Australian Academy of Science

THE RISKS TO AUSTRALIA OF A 3°C WARMER WORLD

AUSTRALIAN ACADEMY OF SCIENCE

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ACKNOWLEDGEMENT OF COUNTRY

> The Australian Academy of Science acknowledges and pays respects to the Ngunnawal people, the Traditional Owners of the lands on which the Academy office is located. The Academy also acknowledges and pays respects to the Traditional Owners and the Elders past, present and emerging of all the lands on which the Academy operates, and its Fellows live and work. They hold the memories, traditions, cultures and hopes of Aboriginal and Torres Strait Islander peoples of Australia.

Indigenous families and communities of Australia are custodial and traditional owners that, for tens of thousands of years, have had responsibility for the nurturing of connections, relationships and care we have for our continent. Indigenous Australians recognise that we belong to Country; no one should be separated from the lands, waters, seas and skies that provide life and law. Therefore, to understand this report and recognise, adapt to and mitigate climate change, first we must look to ourselves and our relationships with Country for an honest appraisal of the strength of our connections. By including Indigenous peoples in our responses to climate change, we can begin to develop a shared language that provides mutual benefit for all Australians and work together towards creating a safe and secure place for everyone to conserve our precious places.

— **Dr Emma Lee**, of *tebrakunna* country,
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EXECUTIVE SUMMARY

As the driest inhabited continent, Australia is highly vulnerable to the impacts of global warming. The summer bushfires of 2019–20 in a tinder-dry country, or the three severe coral bleaching events within five years that caused a loss of over 50% of hard coral cover in the shallow waters of the Great Barrier Reef, demonstrate some of the consequences of a warming planet for Australia's people, economy and environment.

Multiple lines of evidence show that the incidence of extreme weather events will increase as the planet warms. Such events are a natural feature of the climate system, but there is strong evidence that many of them, such as heatwaves, bushfires, storms and coastal flooding, have become more frequent and intense in recent times. These extremes and their risks are likely to escalate as global temperatures continue to rise and our capacity to respond becomes compromised as the frequency increases.

The only way to reduce the risk of these unpredictable and dangerous outcomes is for a substantial reduction in the emissions of greenhouse gases into the atmosphere. Our planet's living systems have evolved over thousands of years in a temperature range that includes relatively minor fluctuations around the long-term average. However, most cannot evolve quickly enough to accommodate the rapid increases in average temperatures we now observe and feel.

The total emission reductions currently pledged by the Australian and international governments through the United Nations Framework Convention on Climate Change Paris Agreement (UNFCCC), even if implemented on time, will translate as average global surface temperatures of 3°C or more above the pre-industrial period by 2100 (see Figure 1, page 18).

Given this situation, we must consider the vulnerability, risks and costs of Australia's policies and strategies for responding to climate change. In particular, we need to understand the comparative risks and costs of not improving our current commitment to reducing greenhouse gas emissions.

The planet is well on the path to devastating climate change. In 2019, Australia's warmest year on record, average surface temperatures were 1.1°C above the pre-industrial period. Australia has warmed on average by 1.4°C since national records began in 1910. Current global and Australian policies to reverse this trend are inadequate. We must plan to do better and prepare for the worst.

Predicting how Australia will change at or beyond 3°C of global warming is challenging. However, by using multiple lines of evidence, such as computer modelling of the climate system, observed changes, and historical paleoclimate studies, we can develop an understanding of future temperatures as well as where we may reach irreversible 'tipping points'—passing thresholds that trigger sudden and accelerating changes in larger climate systems—and how to mitigate those risks.

The report synthesises the observed impacts of climate change on Australia and the risk to our future of the current global trajectory of greenhouse gas emissions. It focuses on the consequences of 3°C of global warming in the absence of greater mitigation strategies for four areas of importance to Australia's future: our ecosystems, food production, cities and towns, and health and wellbeing. The impacts of those changes on the lives and wellbeing of Australians are discussed in detail.

The precautionary principle

This report is a risk assessment based on peer-reviewed scientific literature. Our approach is to include those risks where there is evidence for a link to climate change, even if there is currently some debate about the probability of the impact occurring or the strength of the climate change response. We adopted the precautionary principle: if a potentially damaging effect cannot be ruled out, it needs to be taken seriously.

The global context

There is no scientific doubt about the source, reality and consequences associated with the current level of unmitigated climate change. Human activities, such as the burning of fossil fuels and the destruction of forests, are rapidly changing Earth's climate. The rate of these changes in atmospheric greenhouse gases such as carbon dioxide (CO_2) and methane are unprecedented in millions of years, driving growing impacts on natural and human systems across the world.

If the international community fails to meet the emission reduction targets under the UNFCCC Paris Agreement, this will result in a global mean surface temperature increase of approximately 3°C or more by mid to late century. This level of warming is well above the targets considered manageable under that agreement.

This increase in global average surface temperature lies between the Intergovernmental Panel on Climate Change projections for the 'medium-high' and 'high' greenhouse gas emissions scenarios (Collins et al. 2013). The 3°C temperature rise also corresponds with the average of the projected temperature rise by 2100 (2.7–3.1°C) if current climate policies around the world continue (Climate Action Tracker 2020).

Limiting climate change to 1.5°C is now virtually impossible. A rapid transition to net zero greenhouse gas emissions is required if the international community is to limit warming to "well below 2°C" in line with the Paris Agreement. As with the COVID-19 pandemic, acting early and urgently reduces the scale of the impacts and can save many lives and livelihoods. This also has significant potential benefits in terms of health and regional development and embracing the new economic opportunities associated with a move to net zero greenhouse gas emissions.

Australia's ecosystems in a changing climate

Australia's natural resources are directly linked to our wellbeing, culture and economic prosperity. Yet our ecosystems have already been transformed due to a global increase of 1.1°C in average temperature since the late 19th century, with severe consequences for thousands of species.

Heat stress has impacted marine and coastal ecosystems, destroying habitats and reducing biodiversity. Land-based environments have been affected by drought, fire, extreme heatwaves, invasive species and disease, leading to large-scale mortality of trees, birds and tree-dwelling mammals. Many species are shifting where they live, but cannot keep up with the rate of change, especially given the geography of Australia. Rising sea levels are amplifying storm impacts, damaging coastal ecosystems such as coral reefs and mangrove forests, and causing increasing issues for human health and wellbeing in coastal areas.

The conservation of Australia's unique ecosystems has ramifications for Australian industries such as tourism and recreation. For example, the Australian tourism industry contributed $54.7 billion to the economy in 2016–17, with the top five attractions for international visitors being nature-based: beaches, wildlife, the Great Barrier Reef, wilderness areas and national parks. All of these are at risk from climate change, along with ecosystems that support forestry, agriculture (particularly bee-pollinated crops) and fishing industries.

Critical thresholds in many natural systems are likely to be exceeded as global warming of 1.5°C above pre-industrial levels continues. These impacts will increase as global warming reaches 2°C and beyond, with iconic ecosystems such as the Great Barrier Reef and the World Heritage-listed Kakadu National Park being severely affected.

At 3°C of global warming, many of Australia's ecological systems would be unrecognisable. The decline of Australia's natural resources would accelerate through changing distributions or loss of thousands of species and disrupted ecological processes such as habitat maintenance.

Australian agriculture, forestry, fisheries and food security

Australian agriculture and food security are already exposed to increased risk from drought, heatwaves, fires, floods and invasive species.

Impacts from declining rainfall and more frequent droughts for areas such as south-eastern and south-western Australia would intensify under 2°C or more of global warming. Declining river flows would reduce water availability for irrigated agriculture and increase water prices. Future water resource availability would be affected by the combined changes in rainfall and global surface temperature increases.

Heat stress is a significant issue for livestock systems due to impacts on animal welfare, reproduction and production. Projected temperature and humidity changes suggest an increased number of heat stress days per year. At the same time, more frequent storms and heavy rainfall would likely lead to worsening erosion of grazing land or loss of livestock from flooding.

Impacts for primary producers and rural communities include lost profitability for Australian farms, reduced water availability and elevated heat stress affecting land use for crops. For example, broadacre crops such as wheat and barley have seen reductions in profitability by up to 22% since 2000. Decreasing farm profitability is leaving many Australians in rural and regional communities at risk of declining health and economic wellbeing.

Forestry faces growing pressures from a warming and drying climate. Increased fire risks, changes in rainfall patterns and species-specific pest impacts are likely to threaten forests in the hotter, drier regions of Australia such as south-western Australia, although cooler regions such as Tasmania and Gippsland may see increased production. Existing plantations would change substantially with 3°C of warming.

Fisheries and aquaculture industries are impacted by ocean acidification and warming, which affects species distribution, reproduction and overall health of stock. Decreasing stock levels would cause a decline in profitability, and many aquaculture fisheries enterprises may cease to exist, change fundamentally, or move to other locations if these impacts become worse.

Changes to supply chains and ongoing vulnerabilities to extreme weather events may cause higher rates of unemployment, mental health issues, suicides and heat-related health conditions in some regions of Australia. Strategic planning to create new business opportunities in these regions has the potential to reduce some of these risks.

Australian cities and towns

Close to 90% of Australians live in cities and towns and will experience climate change impacts from the perspective of an urban environment. The risks of extreme events such as heatwaves, severe storms, major floods, bushfires and coastal inundation from sea level rise continue to increase and will be more intense and frequent as temperatures exceed 2°C of warming.

Global sea level continues to rise, posing severe risks to properties, infrastructure and ecosystems. An estimated 160,000 to 250,000 Australian properties are at risk of coastal flooding with a sea level rise of 1 m by the end of the century. Strategies for managing the impacts of sea level rise involve reducing or ceasing building in high-risk areas, adjusting infrastructure planning and maintenance, protecting coastal land with structures such as sea walls and ecosystems such as sand dunes and mangroves, or abandoning assets at risk.

The energy security of many Australian cities and towns is at risk from climate change-driven impacts. Extreme heat conditions, bushfires and storms put strain on power stations and infrastructure while simultaneously increasing demand for energy supply as reliance on air conditioning increases. Much of Australia's electricity generation relies on ageing and increasingly unreliable coal-fired power stations. Oil and gas industries are also vulnerable to delays in operations or damaged infrastructure from extreme weather events. Exploring options for diversifying energy sources and improving existing energy infrastructure will be important to ensure a reliable energy supply into the future.

Changing perceptions of climate risk and exposure are also capturing the attention of the insurance and financial sector. Insurance firms face increased claims due to climate-related disasters, including floods, cyclones and mega-fires. Under some scenarios, one in every 19 property owners face the prospect of insurance premiums that would be effectively unaffordable by 2030. A 3°C world would render many more properties and businesses uninsurable.

Cities and towns, however, can also be part of the climate solution. High-density urban living translates to a lower per capita greenhouse gas emission 'footprint', and innovative solutions are easier to implement in urban environments.
Urban planners can utilise designs that consider passive cooling techniques to reduce city temperatures, such as incorporating more plants and street trees during planning; however, these strategies may require changes to stormwater management and can take time to be effective.

Health and wellbeing of Australians

More frequent and intense weather events such as heatwaves, droughts, cyclones, bushfires and floods have direct and indirect impacts on human health, livelihoods and communities. The elderly, young, unwell, and those from lower socio-economic backgrounds are at increased risk.

Heatwaves on land and sea are increasing in length, frequency and intensity. These changes affect human health through physiological heat stress and by worsening existing medical conditions. Bushfire-related health impacts are increasing, causing direct loss of life and exacerbating pre-existing conditions such as heart and lung disease. Fire conditions in the spring and summer of 2019–20 were classified as 'Catastrophic' for the first time in many parts of Australia. These extreme conditions will increase at 2°C and further at 3°C, and would have direct and indirect health impacts such as economic hardship and ongoing mental health challenges.

The availability of water is also linked directly and indirectly to human health and wellbeing. As climate change increases to 2°C above the pre-industrial period, many communities in eastern and south-western Australian regions will need to consider alternative water supply options if declining rainfall trends continue. This would likely impact local economies and lead to displacement for many people living in rural communities. Climate-sensitive infectious diseases, such as Ross River virus and other vector-borne diseases, will shift in their geographical distribution and intensity of transmission as weather patterns change. Diseases normally considered to be a concern in tropical climates may spread to more temperate areas across Australia, including major population centres.

Strategies such as improving early warning systems for extreme weather events, assessing the climate resilience of healthcare services, implementing nature-based solutions (such as increasing green spaces in urban areas) and reducing energy use in healthcare facilities would help Australia adapt to the impacts of climate change on the health of its citizens.

The way forward: staying well below 2°C and avoiding 3°C

Policy actions for a positive future

Reaching net zero emissions by mid-century is an absolute minimum if we are to avoid the worst impacts of climate change. Australia is well positioned to meet this challenge, with a skilled workforce, industrial base and renewable energy resources facilitating easier emission reductions compared to many other countries. States and territories such as the Australian Capital Territory, South Australia and Tasmania are leading the way in the renewables race, and Victoria, New South Wales and Queensland are showing promise with recent announcements on renewable energy projects. Australia has enormous potential to be a clean industrial powerhouse.

However, Australia should develop a more substantial interim emissions reduction goal than its current Nationally Determined Contribution under the Paris Agreement—and we need to act quickly. Given the threats we face, Australia must revisit its emission reduction commitments and provide the leadership and collaboration required to place the world and Australia on a safer climate trajectory.

To achieve net zero, Australia will need to:

- remove greenhouse gas (GHG) emissions from electricity generation and distribution
- electrify the transport sector
- increase energy efficiency and reduce emissions from industrial activities and buildings
- reduce non-energy related GHG emissions from industrial processes and agriculture
- implement negative emissions options through biosequestration and technological means
- stop deforestation and land degradation, and accelerate revegetation of cleared and degraded land
- shift energy export industries to zero emissions as a matter of urgency.

Australia can become a clean energy exporter and potentially a global renewable energy superpower. We have a relative advantage with our abundant natural resources for solar and other renewable energy generation, as well as significant deposits of new economy minerals critical for developing batteries and other low-emission technologies.

Transitioning to net zero

Acting early to transition to net zero emissions would reduce the scale of climate change impacts and have significant potential benefits for human health and regional development, as well as creating new industrial opportunities.

Sector-by-sector transition policies and support for regional economies will need to be designed to support vulnerable groups, including to ease the change for communities, workers and businesses that currently depend on high emissions of GHGs.

The most immediate requirement is a phase-out of coal-fired energy generation in favour of cheaper and cleaner renewable generation and storage technologies, a process that has already started and needs to accelerate. Similarly, any expansion of the gas industry is incompatible with achieving the Paris Agreement targets. Phasing out fossil fuels should be accompanied by electrification of transport, heating and industrial energy use. Significant opportunities also exist in making our homes and buildings more energy efficient.

The emission reduction commitments of the Paris Agreement cannot be met without also managing emissions from the agricultural and land sectors, including stopping deforestation and increasing investment in restoration and carbon sequestration in soils. Many of these actions will have significant co-benefits in addition to reducing GHG emissions, such as better air quality, biodiversity, employment and health outcomes.

Accelerated investment in clean energy, zero-GHG emission industrial installations, electric transport and more energy efficient housing and public buildings can enhance productivity and improve living standards. Public investment during and after the COVID-19 pandemic offers a chance for economic recovery that is consistent with long-term low-emissions outcomes.

REPORT RECOMMENDATIONS

Current international commitments to greenhouse gas (GHG) emission reduction, if unchanged, would result in average global surface temperatures that are 3°C or more above the pre-industrial period. The evidence presented in this report indicates that this would have serious consequences for Australia and the world.

To rectify this situation, we recommend the following 10 actions for Australia:

1 **Join global leaders in increasing actions for tackling and solving climate change as a matter of urgency.** Australia lags far behind the best practice demonstrated by many countries. Given how much Australia stands to lose if GHG emissions are not reduced, we also recommend that Australia accelerates its transition to net zero GHG emissions over the next 10 to 20 years.

2 **Develop strategies to meet the challenges of extreme events that are increasing in intensity, frequency and scale.** Extreme events at 1.1°C of global warming are placing Australian lives and livelihoods at increasing risk, with concern that 3°C of global warming would not be sustainable. We also recommend a broad-ranging investigation of Australia's readiness for meeting the growing number of climate-related disasters, such as droughts, fires, floods, storm surges, heat stress and ecological damage, that would occur with global temperature increases of 3°C or more.

3 **Improve our understanding of climate impacts, including tipping points, as well as the compounding effects of multiple stressors at global warming of 2°C or more.** The current understanding of abrupt and compounding changes and their consequences for Australian human and natural systems is at an early stage. We also recommend further investigation into effective adaptive responses in preparation for rapid and complex changes.

4 **Systematically explore how our food production and supply systems should prepare for the challenges of climate change.** Australian agriculture and food security are exposed to increasing risk from droughts, extreme high temperatures, coastal inundation, floods, invasive species and fires. We also recommend that Australia prepares for potential interruptions to its food import and export systems driven by global environmental, social and economic changes.

5 **Expand our understanding of the impacts and risks of climate change for the health of Australians.** Climate change already seriously affects the health of Australians and improved strategies need to be developed to reduce these growing risks. We also recommend an in-depth study on the potential impacts of 3°C global warming on health and wellbeing, particularly how impacts can be reduced.

6 Introduce a suite of policies that would deliver deep and rapid cuts in emissions across the economy. In the current absence of an economy-wide carbon price, there will need to be comprehensive sector-by-sector approaches. We also recommend that policies are developed to support the economic and social transition to a low GHG emission outcome, especially in regions where fossil fuel-based industries are currently prominent. This includes the development of strategies to halt further deforestation and land degradation while facilitating carbon storage.

7 Scale up the development and implementation of next-generation low to zero greenhouse gas technologies. If Australia is to argue for increasing international action, greater commitment is required to implement zero to low emissions technologies and the rapid phase-out of fossil fuels by mid-century. We also recommend the development of a strategic plan that maps out the markets and investment opportunities for Australian industries in areas such as offshore renewable energy, green hydrogen fuels, minerals for low GHG emission technologies, mass-scale storage, embedded renewable energy, and more efficient and low GHG emission transport systems for aviation, shipping, road and rail transport.

8 Review Australia's capacity and flexibility to take up innovations and technology breakthroughs for transitioning to a low GHG emission future. We also recommend greater support for innovation and technology breakthroughs by way of a dedicated facility for supporting broad-based applied research on the removal of GHG emissions from the economy, which is consistent with meeting and exceeding current commitments to emission reduction under international agreements.

9 Develop a better understanding of climate solutions through dialogue with Aboriginal and Torres Strait Islander peoples, particularly strategies that have helped people manage Australian ecosystems for tens of thousands of years. We also recommend a meaningful dialogue between all Australians regarding the steps needed to avoid global warming of 3°C by 2100.

10 Continue to build adaptation strategies and greater commitment for meeting the challenges of change already in the climate system. While the major theme of this report is about the urgency of action needed to mitigate GHG emissions, we also recommend increasing efforts to build and implement adaptation strategies and actions to meet the challenges of climate that will continue to change until mid-century and beyond.

1. INTRODUCTION

The atmospheric concentrations of greenhouse gases (GHG) such as CO_2 and methane are increasing, primarily due to burning fossil fuels and land use change (IPCC 2013a; Smith et al. 2014). As a result, global mean surface temperature (GMST) has increased by 1.1°C since the beginning of the Industrial Period (1850–1900) (IPCC 2018). This warming has contributed to the frequency and severity of extreme weather events, which have broad impacts on natural and human systems worldwide (Christoff 2014; IPCC 2013b, 2014a, 2018; Reisinger et al. 2014). If emissions are not rapidly reduced within the next 10 years, impacts from climate change will become so severe that living systems may be unable to adapt to them (IPCC 2018).

Five assessment reports have been produced by the United Nations Intergovernmental Panel on Climate Change (IPCC 2014b, 2007, 2001, 1996, 1990) that have identified a growing number of large-scale climate-related impacts and risks (Hoegh-Guldberg et al. 2018). These include record-breaking heatwaves, warming and rising seas, increasingly longer and more severe fire seasons, challenges to agriculture, human health impacts, and ecosystem transformation (Christoff 2014; Reisinger et al. 2014). Increased levels of atmospheric CO_2 have been absorbed in the upper layers of the ocean, driving ocean acidification and associated impacts on marine organisms and ecosystems (Hoegh-Guldberg et al. 2007). There is increasing concern that both the speed and impacts of the changing climate may have been underestimated (Torn and Harte 2006; Zscheischler et al. 2018).

The United Nations established the Framework Convention on Climate Change (UNFCCC) at the Earth Summit in 1992 as a first step towards addressing the climate change challenge. The aim of the Convention was to prevent "dangerous" human interference in the climate system. In 1997, 192 countries adopted the Kyoto Protocol (ratified in 2005), aiming to limit GHG emissions in developed countries. In 2015, the Paris Agreement (ratified in 2016) set out the core goals of limiting "the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognising that this would significantly reduce the risks and impacts of climate change" (UNFCCC 2015). This comprehensive agreement has been signed by 197 and ratified by 188 countries so far, including Australia. All parties to the Paris Agreement have submitted Nationally Determined Contributions (to 2030) to be reviewed every five years from 2020 for their effectiveness in achieving the Paris goals, and increased if required (but never decreased). The next Conference of the Parties meeting, at which emissions reduction pledges will be discussed, has been delayed until 2021 due to the COVID-19 pandemic.

> If the Paris Agreement pledges are not strengthened, constraining the global mean surface temperature to an increase of "well below 2°C" becomes extremely difficult and temperatures of 3°C more likely

The extent to which the international community is successful in meeting the goals of the Paris Agreement has very important implications for Australia and the rest of the world. If the Paris Agreement pledges are not strengthened, constraining the global mean surface temperature to an increase of "well below 2°C" becomes extremely difficult and temperatures of 3°C more likely. This amount of change could have potentially catastrophic impacts. To put these changes into historical context, the difference in global mean surface temperature between the last glacial period (the Ice Age that ended 20,000 years ago) and today is only 5°C, yet a quarter of Earth's land area was covered by ice, sea levels were more than 100 m lower, and ecosystems were markedly different in their distribution and composition.

The difference in global mean surface temperature between the last glacial period ... and today is only 5°C, yet a quarter of Earth's land area was covered by ice, sea levels were 100 m lower, and ecosystems were markedly different

This report explores Australia's response in light of current commitments by the international community to stabilise GHG concentrations (akin to 'flattening the curve' in the global response to the COVID-19 pandemic) such that the global mean surface temperature stabilises at a temperature well below 2°C above the pre-industrial period. Events early in 2020, such as the unprecedented bushfire season and mass mortality of corals on the Great Barrier Reef, demonstrate how rapidly and fundamentally our global environment is changing with only 1.1°C of global warming. Accelerating the energy transition and establishing a stable global temperature well below 2°C should be an urgent national and international priority.

An Indigenous perspective on issues and responses to climate change

Dr Emma Lee, *tebrakunna* country, Tasmania, Australia

This report introduces us to a world in great flux and demonstrates clearly that, without relief towards abating GHG emissions, the fabric of our continent is at risk of irreparable loss and damage. For Indigenous peoples, such as myself, this impedes our ability to care for Country according to our laws, protocols, practices and knowledges that have profoundly shaped our continent for over 50,000 years and perhaps up to 120,000 years (Bowler et al. 2018). Our ancient physical, spiritual and bio-cultural relationships with Country are reflected in our bodies: our genetic histories show that our families have resided in their same territories continuously through mass climatic changes, such as desertification or sea level rise, and sustainably adapted to new conditions and resources over tens of thousands of years (Nagle et al. 2017; Tobler et al. 2017).

Colonisation has, however, interrupted our sovereign rights to govern, manage and care for Country and these effects will continue to have tangible (and intangible) negative impacts, especially in how we will experience and adapt to a 3°C world (Reynolds 1987; Roös 2015; Tschakert et al. 2019; Veland et al. 2013). Our methods of managing Country often struggle for 'fit' within government funding and national priorities for action, which results in Indigenous knowledges and communities being excluded in policies, programs and research (Ens et al. 2015; Head et al. 2014; Nursey-Bray et al. 2019; Race et al. 2016). There is danger in conflating vulnerability, program failure or lack of participation that often characterises Indigenous engagement in climate change studies with the structural barriers of discrimination and lack of land and sea tenure that prevent inclusion, benefit and opportunities for us (Howitt et al. 2012; Tran et al. 2014; Wensing et al. 2014).

For many of our peoples still subject to colonising structures, climate change is less an ecological shift and more an intrusion into the totality of our lives and how we reconcile our relationships with Country (Carmichael et al. 2018; Hunter 2009; Lennon 2016; Potter 2013). Modern climate change is articulated by us as an intensification and imposition upon our rights to enjoy, define and benefit from Country, and among other things, our identity, heritage, culture, education, health, housing and employment (Bardsley and Wiseman 2012; Campbell et al. 2008; Pearce et al. 2015; Petheram et al. 2010).

And yet there is hope that as relationships between researchers and Indigenous peoples improve, so too does the quality and depth of science and its application in preventing further harm and increasing favourable opportunities. For example, our deep bio-cultural knowledges of Country are beginning to influence national policies for fire management according to understanding of seasonal calendars, implementation of carbon reduction and capture ecosystem services, and culturally-based fire economies surrounding care for Country (Altman Jon 2005; Fitzsimons et al. 2012; McKemey et al. 2020; Menyhart 2018; Molyneux et al. 2011; Catherine J. Robinson et al. 2016; Cathy J. Robinson et al. 2016; Robinson et al. 2014). We have certainly changed the conservation landscape of Australia, where over 67 million hectares of lands are managed and governed according to Indigenous bio-cultural knowledges under the Indigenous Protected Area (IPA) scheme and which the Australian Government wholly adopted in 2016 to benefit the nation (tebrakunna country et al. 2019).

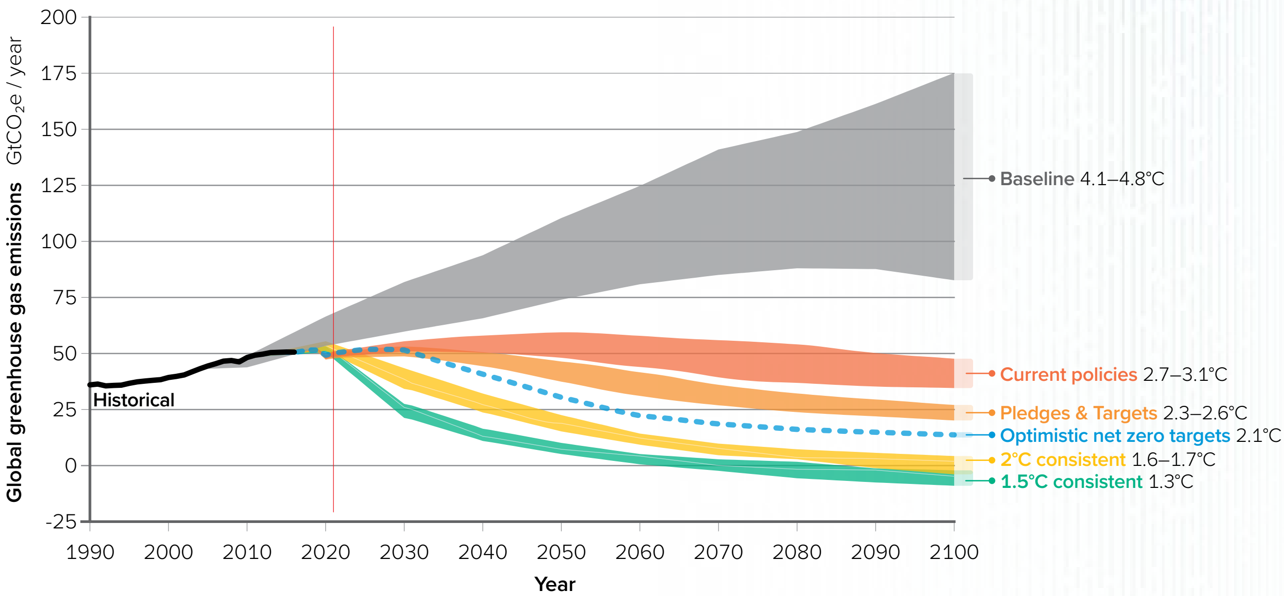
We assert our agency in self-determined climate change statements and declarations (Morgan et al. 2019) and are leaders in building both adaptation and adaptive capacity to keep Country strong. We demonstrate a talent to work together with scientists, to bridge knowledge gaps and respect multiple worldviews that deeply engage with caring for Country as a belonging to each other as Indigenous and other Australians (Adams 2013; Bawaka Country et al. 2013; Ens et al. 2015; Green et al. 2012; Nursey-Bray et al. 2019; Nursey-Bray and Palmer 2018). We can now do better in the future, because today we have stronger relationships between us.

2. IMPACTS OF CURRENT GLOBAL EMISSION REDUCTION COMMITMENTS

To fully appreciate the impact of 3°C warming on Australia, it is important to understand the global context. The current global response to the climate crisis is inadequate. Total emission reduction pledges (up to 2030) are less than those needed to constrain global temperatures to well below 2°C. Multiple lines of evidence (e.g. IPCC 2014, 2018, 2019) indicate that this amount of global warming would have extremely negative consequences for most natural and human systems.

The parties to the Paris Agreement have developed emission reduction commitments drawn from a range of mitigation strategies and technologies (Ghezloun et al. 2017). However, the combined Nationally Determined Contributions (NDC) commitments of the international community will not deliver the global emission reduction needed to meet the goals of the Agreement. The modelled outcome of the current combined emission reduction policies shows that GMST could increase to a median warming of 2.7–3.1°C above pre-industrial levels by 2100 (Climate Action Tracker 2020; Revill and Harris 2017; Rogelj et al. 2016; UNEP 2019).

Figure 1. Projected warming by 2100 under various scenarios



Projected warming by 2100 under various scenarios from top to bottom (Climate Action Tracker 2020; Revill and Harris 2017): 'Baseline' models assume no action on reducing GHG emissions while 'current polices' are based on current commitments and policies made by the international community. 'Optimistic polices' include additional pledges that governments have made as of December 2019. 'Pledges and Targets' are conditional and have not yet been implemented. Pathways for '1.5°C' and '2°C' are scenarios based on models run for IPCC Special Report on 1.5°C (IPCC 2018). Temperatures of each scenario are shown as a range arising from different climate models.

2.1. The urgency of immediate action: remaining global emission budgets for 1.5°C and 2°C

The 'GHG emission budget' presented here (Table 1) illustrates the challenges ahead and the limited time left to reduce GHG emissions at rates required by the Paris Agreement (Collins et al. 2013). The scientific assessment of the level of risk of sudden and large-scale change in the Earth System (interactions between physical, chemical and biological processes across the planet) is steadily increasing (Figure 2).

The GHG emission budget is based on the approximately linear relationship between the cumulative amount of CO_2 (plus non-CO_2 GHG gases, e.g. methane) emitted from all human sources since the beginning of industrialisation and the increase in global temperature (IPCC 2013b). Once the GHG emission budget has been 'spent' (i.e. emitted into the atmosphere), then all subsequent emissions need to be net zero: any further emissions must be balanced by removal of as much CO_2 and other greenhouse gases from the atmosphere as is going in.

Key areas of uncertainty that influence the GHG emission budget include the likelihood of remaining below the temperature target (higher probabilities lead to lower budgets); accounting for other non-CO_2 greenhouse gases; and accounting for carbon cycle feedbacks in the Earth System, such as permafrost thawing and forest dieback (IPCC 2018; Steffen et al. 2018a). The IPCC Special Report on 1.5°C of global warming (IPCC 2018) developed a carbon budget analysis for both the 1.5°C and 2.0°C Paris Agreement targets; Table 1 shows this budget, adding estimated carbon feedbacks (IPCC 2018; Steffen et al. 2018a).

Table 1. Global greenhouse gas emissions budget

Budget Item/Process	Gigatons of carbon (Gt C) 1.5°C	Gigatons of carbon (Gt C) 2.0°C
Base budget from 1 Jan 2018	155	360
Accounting for non-CO_2 greenhouse gases (Estimated from Table 2.2 of IPCC 2018)	-25	-25
Historical emissions for 2018 and 2019	-20	-20
Carbon cycle feedbacks (Steffen et al. 2018b)	-70	-110
Remaining budget to net zero emissions	**40**	**205**

Global greenhouse gas (GHG) emissions budget for a 66% probability of restricting temperature rise to no more than 1.5°C, or no more than 2.0°C, based on the IPCC Special Report on 1.5°C of global warming (SR1.5, IPCC 2018)

Table 1 shows how uncertainties in budget components, such as carbon cycle feedbacks, have a large effect on small remaining emission budgets. The 70 Gt C estimated for emissions from feedbacks in Table 1 consists of approximately 30 Gt C from melting permafrost (IPCC 2018) and approximately 40 Gt C from boreal and Amazon forest dieback (Steffen et al. 2018a, see Supporting Information for methodology). The remaining budget from the beginning of 2020 then becomes 135 Gt C, or about 12 years of emissions assuming they are capped at 2018–2019 (pre-COVID-19) levels.

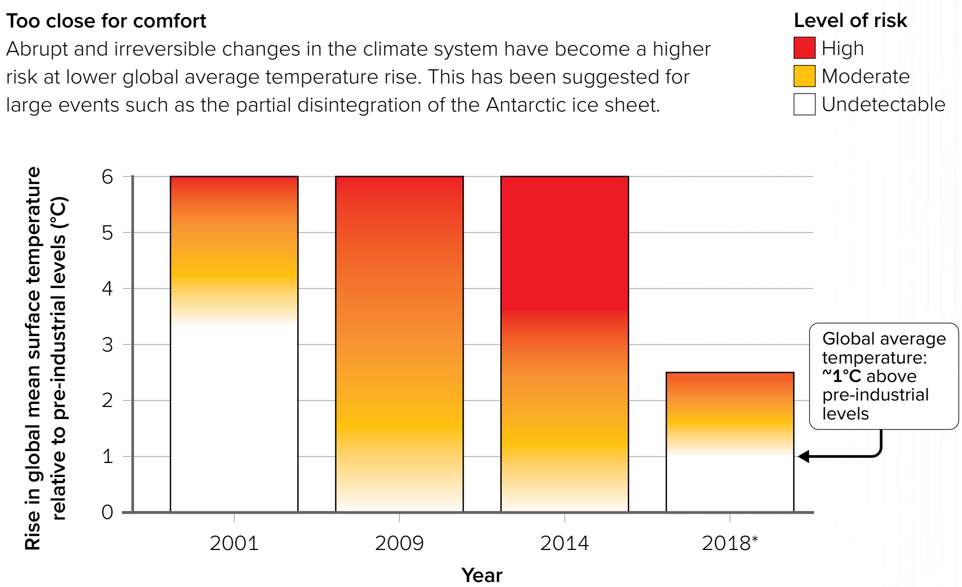
After decades of insufficient action to reduce GHG emissions, the emission budget for the 1.5°C target has shrunk to a range of 40–135 Gt C. Limiting the temperature rise to the lower Paris Agreement target (1.5°C) is exceedingly difficult, and with only three or four more years of emissions at current levels remaining, the target has become virtually impossible to achieve.

For the upper target of 2°C (note that this is 2°C, not "well below 2°C" as specified under the Paris Agreement), the remaining budget is around 200 Gt C (730 Gt CO_2), or about 17 years of current rates of emissions. The remaining budget is broadly consistent with reaching net zero emissions around 2050 if a linear emission reduction trajectory is assumed. Any delay in starting to reduce emissions means even more ambitious reductions later (Figueres et al. 2017). A delay of only five years would mean it would be economically and technologically impossible to find an emission reduction trajectory to meet the 2°C target.

A GHG emission budget for a 3°C target consistent with current international emission reduction pledges (Figure 1) means an increasing risk that planetary systems will fail, irreversibly pushing Earth towards a much hotter state with an increasing risk of rapid and effectively irreversible changes (Figure 2; Lenton et al. 2019).

Any delay in starting to reduce emissions means even more ambitious reductions later

Figure 2. Summary of IPCC assessment of the relative risk of tipping points from 2001 to 2018



Summary of IPCC assessment of the relative risk of tipping points from 2001 to 2018. As knowledge of tipping points improves, the estimate of the probability (risk) of tipping has become much higher for lower levels of increase in global mean surface temperatures (Lenton et al. 2019). The 2018 IPCC special report on Global Warming of 1.5°C is focused on the temperature range up to 2.5°C.

2.2. Increasing risks of tipping points as global temperature increases

> The urgency to act on greenhouse gas emissions is heightened by the increasing risk of sudden and accelerating changes to the conditions on our planet, referred to as 'tipping points'. Many of these include abrupt changes that have the potential to trigger severe impacts for human and natural systems; for example, sudden and large-scale increases in fire risks (Adger et al. 2009; IPCC 2018).

A 'tipping point' is defined as a large-scale component of the Earth System that might reach a critical threshold at which a small change leads to a significantly larger change, qualitatively altering the state or development of a system (IPCC 2018; Lenton et al. 2008; Steffen and Griggs 2014). Once the threshold is crossed, intrinsic processes within the system can accelerate the rate of change via self-reinforcing ('positive') feedbacks. Within the Earth System, tipping points are one of three types: major biomes, such as the Amazon rainforest, boreal forests or coral reefs; polar ice masses, such as Arctic sea ice or the West Antarctic ice sheet; or major circulation systems in the atmosphere or ocean, such as the Atlantic Meridional Overturning Circulation (AMOC) or the northern hemisphere jet stream (Lenton et al. 2008).

An example of a self-reinforcing feedback within a tipping point is the Greenland ice sheet, which is already losing mass at an accelerating rate (Adger et al. 2009), with a total loss of 28.3 million km^2 from 2000–2019 (NSIDC 2019). Recent climate modelling indicates that warming GMST greater than 2°C results in a multi-metre sea level contribution from Greenland alone (Gregory et al. 2020). Beyond a certain threshold, melting is effectively irreversible: the elevation of ice mass is lowered as the ice sheet melts, leading to further melting as the ice surface is exposed to warmer air at lower elevations (Lenton et al. 2019).

Internal feedbacks are important when a tipping point is destabilised by direct human action, such as for the fires and deforestation in the Amazon rainforest (Lovejoy and Nobre 2018). As humans convert rainforest into cropping or grazing lands, the internal recycling of moisture via evapotranspiration (release of water from leaves) of the forests is reduced, causing further stress and increasing vulnerability to disturbances such as fire. These disturbances further reduce the area of forest and evapotranspiration rates, continuing the cycle.

Individual tipping points do not act in isolation. Many tipping points are linked, where the destabilisation of one tipping point may contribute to the tipping of another point (Figure 3). For example, melting Arctic sea ice intensifies regional warming (because darker ocean water absorbs more solar radiation than reflective sea ice), which in turn increases the rate of melting of the Greenland ice sheet. These linkages among individual tipping points could lead to a worldwide 'tipping cascade' or domino effect where humans are no longer able to influence the climate trajectory (Lenton et al. 2019; Steffen et al. 2018b).

> Many tipping points are linked, where the destabilisation of one ... may contribute to the tipping of another

Figure 3. Global tipping point connectivity

Evidence is accumulating that many Earth System tipping points are already active, leading to an increasing risk that interactions among tipping points could lead to a global cascade or domino effect of irreversible impacts. Figure based on Lenton et al. 2019; Steffen et al. 2018b.

The two most important and implicit assumptions in analyses of climate change risks are:

1. the level of warming has a roughly linear relationship with the cumulative emission of greenhouse gases by human activities, and
2. the climate system will eventually stabilise at a level that is determined by the total cumulative emissions, once human emissions have achieved net zero.

However, rapid intrinsic and sudden changes in the Earth System may play an increasingly important role in the trajectory of the system as human influence increases, with the potential of a 'cascade' to become the dominant driver of the trajectory (Nicholls et al. 2020; Steffen et al. 2018a). Furthermore, the IPCC (2018) warns that a wide range of impacts will worsen if the Paris climate targets are exceeded, with fundamental and largely irreversible changes to the ocean and cryosphere (Adger et al. 2009; Bindoff et al. 2019).

> Multiple lines of evidence strongly suggest that exceeding the Paris Agreement targets and moving to a 3°C world (and beyond) will result in a vastly different biosphere, hardly recognisable compared to the conditions of the past 10,000 years in which humans have thrived, and one that would present significant challenges even for the technologically advanced society of today. There is a substantial risk that inhabiting many areas of our planet would be extremely challenging for humans at 3°C or more of global warming.

The policy challenges of tipping points

Tipping points present a formidable challenge for the science–policy interface, given the inherent degree of uncertainty around many aspects of tipping points but also the very serious consequences if they are reached.

Although the science of tipping points is rapidly advancing, large uncertainties will undoubtedly remain for some time. Yet critical decisions on societal responses to climate change must be made now or in the very near future if the climate is to stabilise anywhere near a 2°C temperature rise. Decisions relating to tipping points will need to be made based on risk assessments, rather than on the more established science-policy approach where 'robust science' with a high degree of certainty is required before policy action is taken.

The future of the Amazon rainforest is a good example of the need for a risk assessment approach leading to a cautious policy. There is a high degree of uncertainty around where the tipping point lies for the conversion of the rainforest into a savanna or open woodland (Hirota et al. 2011; Jones et al. 2009; Lovejoy and Nobre 2018). A combination of human deforestation and increasing drought, perhaps related to changes in Atlantic Ocean circulation, are already triggering an increase in wildfires (Brienen et al. 2015; Feldpausch et al. 2016;), a key element for activating the tipping process. But we may never know with a high level of certainty precisely where the Amazon tipping point lies. Given this uncertainty, Carlos Nobre, former chair of the International Geosphere-Biosphere Programme and an expert on Amazon forest dynamics, and Thomas Lovejoy argue for a margin-of-safety policy: "… there is no point in discovering the precise tipping point by tipping it." (Lovejoy and Nobre 2018). We cannot wait for a high level of scientific certainty before developing policy to protect the Amazon rainforest.

The concept of a tipping cascade (Figure 3) is even more challenging for the science-policy relationship to deal with. A tipping cascade carries more uncertainty than Amazon rainforest dynamics but also a very high risk for a catastrophic outcome at the global level. A recent observation-based analysis shows that many of the processes that form the basis for a potential global tipping cascade are being activated (Lenton et al. 2019). Here a risk-averse approach is the only one that makes sense. As Lenton et al. argue: "If damaging tipping cascades can occur and a global tipping point cannot be ruled out, then this is an existential threat to civilization … we need to change our approach to the climate problem."

There is considerable growing evidence that abrupt, nonlinear changes in the Earth System, such as tipping points and cascades, represent a credible risk (see Figure 2). Furthermore, "the current speed of human-induced CO_2 change and warming is nearly without precedent in the entire geological record, with the only known exception being the instantaneous, meteorite-induced event that caused the extinction of non-bird-like dinosaurs 66 million years ago." (Lear et al. 2021). This combination of rate and magnitude of human pressure on the Earth System and potential catastrophic outcomes represents a serious risk for humanity. It requires urgent and careful consideration in terms of the policy response.

3. OCEANS AND CLIMATE CHANGE

The oceans play a critical role in determining global weather patterns and Australia's drought and flood cycle. Many of these processes are beginning to change at regional scales with serious consequences for ecosystems and people.

At a global scale, the Atlantic Meridional Overturning Circulation (AMOC) is changing. The AMOC transports warm water northwards and is a major factor determining global climate, including a warmer European climate than expected for similar latitudes. Sea surface temperature observations from 2004–2017 indicate that the AMOC has weakened relative to 1850–1900 (Caesar et al. 2018), consistent with climate model projections (Collins et al. 2019). The AMOC is projected to weaken further during the 21st century, with the rates and magnitudes of the changes smaller for a 1.5°C warming than for 3°C warming (Bindoff et al. 2019; Collins et al. 2019). A similar but less well-understood overturning occurs in the southern hemisphere.

The El Niño Southern Oscillation (ENSO) is another source of interannual variability in ocean and land conditions. El Niño and La Niña events are projected to increase in frequency and intensity over the 21st century with drier or wetter trends and extremes (Cai et al. 2014; 2015). Extreme El Niño events are projected to occur more often in the 21st century than in the 20th century (Cai et al. 2014). However, there are large natural variations in the strength and spatial pattern of ENSO and confidence in any specific projected change has been low (IPCC 2013b). More detailed recent analysis has shown with greater confidence that extreme El Niño and La Niña events are projected to increase in frequency, along with the intensity of existing hazards, with drier or wetter responses over several regions globally (Collins et al. 2019; Karamperidou et al. 2020).

El Niño and La Niña events are projected to increase in frequency and intensity over the 21st century

3.1. Ocean warming, circulation and oxygen depletion

The temperatures of Australia's coastal waters and oceans have broken instrumental records every year for the past 10 years (Cheng et al. 2020). For example, in 2020 the Great Barrier Reef experienced the hottest February since records began (Deacon 2020). The oceans will continue to warm through to 2100 under all potential emission scenarios and for centuries after GHG concentrations and surface temperatures have been stabilised. This will have profound long-term consequences for ecosystems, coastal infrastructure, food production, and the health and wealth of Australians everywhere.

With 3°C of global warming by 2100, oceans are projected to absorb five times more heat compared to the observed amount accumulated since 1970 (Bindoff et al. 2019; Church et al. 2013a), leading to an increasing frequency and intensity of marine heatwaves (Bindoff et al. 2019). The stratification (separation into layers) of the upper ocean (0–1,000 m) is projected to increase, reducing surface ocean mixing and the vertical distribution of nutrients, CO_2 and oxygen. Ocean oxygen concentrations are projected to decline at shallower depths as oceans warm in a 3°C world, affecting the distribution of oceanic life. In the Australian region, the ocean surface has warmed by over 1°C since 1910. This has contributed to more extreme marine heatwaves (Spillman 2020) and associated impacts on marine ecosystems (Hoegh-Guldberg et al. 2019).

3.2. Sea level rise, intensifying storms and coastal inundation

For 3°C of global warming, sea level will rise by 0.4–0.8 m by 2100 and by many metres over subsequent centuries. These changes will cost hundreds of billions of dollars over coming decades as coastal inundation and storm surges increasingly impact Australia's coastal communities, infrastructure, and businesses.

Sea level is rising due to the expansion of ocean waters as they warm and from the melting of land-based glaciers and ice sheets (mainly Greenland and Antarctica). Decreases in the volume of Earth's ice sheets and glaciers indicate that they contributed 14 mm to global sea level from 2003 to 2019. The rate of sea level rise is accelerating, from 1.4 mm per year between 1901 and 1990 to 3.6 mm per year between 2006 and 2015 (Oppenheimer et al. 2019; Smith et al. 2020). Anthropogenic climate change has been the dominant cause of sea level rise and its acceleration since 1970 (Church et al. 2013b; Slangen et al. 2016).

The higher the level of global warming, the greater the probability of tipping points that trigger large, rapid and ongoing contributions from Greenland and Antarctic ice sheets (DeConto and Pollard 2016; Golledge et al. 2019). The potential impacts can extend for millennia into the future: for 3°C warming or more, the increase in sea level will likely exceed 2 m by 2300, continuing to rise by many metres over subsequent centuries (Clark et al. 2016), with Greenland alone contributing more than 4 m to global sea level (Gregory et al. 2020). Loss of Antarctic ice shelves, as has recently occurred on the Antarctic Peninsula, has the potential to destabilise parts of the Antarctic ice sheet. Near-term emission reductions that achieve the "well below 2°C" long-term temperature goal of the Paris Agreement will be needed if we are to limit future sea level rise (Mengel et al. 2018; Nauels et al. 2019).

Rising seas amplify the effect of coastal storm surges. For many locations, including in Australia, historical 1-in-100-year coastal flooding events are occuring more frequently and are likely to occur annually by 2100 under most scenarios (Oppenheimer et al. 2019). Coastal flood area is projected to expand by approximately 33,200 km^2 across Australasia under the RCP4.5 scenario (Arnell et al. 2019). Wahl et al. (2017) found similar trends under the RCP4.5 scenario for Australia, with the time between what are currently 1-in-100-year events likely to decrease. This will have increasing impacts in densely populated areas on the east and south-east coasts of Australia, both along the coast and in nearby estuarine areas (Hanslow et al. 2018). Increased sea level is very likely to amplify related risks such as coastal erosion, flooding and salinisation, which will significantly increase by 2100 within Australia's coastal settings. Sea level rise associated with 3°C of warming will transform Australia's coastal regions with severe impacts on natural ecosystems, urban infrastructure and rural settlements, putting the health and wellbeing of many people and societies at increasingly severe risk (Oppenheimer et al. 2019).

> For many locations, including in Australia, historical 1-in-100-year coastal flooding events are beginning to occur more frequently and are likely to occur annually by 2100 under most scenarios

Representative concentration pathways (RCPs)

Representative concentration pathways, or RCPs, are scenarios that show how different levels of greenhouse gas emissions and aerosol concentrations, as well as land use, lead to different global warming trajectories and associated impacts over time. Four RCPs are used in the Fifth IPCC Assessment (IPCC 2014b) as a basis for climate predictions and projections that cover plausible global warming scenarios. This report discusses three of them:

RCP2.6 represents the most ambitious mitigation scenario and is likely to keep global warming to below 2.0°C by 2100, relative to the pre-industrial period.

RCP4.5 is an intermediate pathway associated with global warming between 2°C and 3°C by 2100. RCP4.5 is the closest pathway that would result if current Nationally Determined Contribution commitments (NDCs) are met and continue beyond 2100.

RCP8.5 assumes little mitigation of greenhouse gas emissions and is associated with global warming of 4°C or more above pre-industrial levels by 2100. Up to now, anthropogenic emissions have tracked the RCP8.5 pathway most closely (Schwalm et al. 2020).

RCP6, not discussed in this report, falls between RCP4.5 and RCP8.5.

3.3. Ocean acidification: chemical changes that will last for thousands of years

Increased concentrations of CO_2 are fundamentally changing the chemistry of the ocean (Hoegh-Guldberg et al. 2007; Pelejero et al. 2010). The ocean takes up about a third of the CO_2 that is emitted to the atmosphere by human activities. As sea water absorbs atmospheric CO_2, concentrations of hydrogen ions increase, causing an increase in acidity of the water column, particularly in the upper 1,000 m (Bindoff et al. 2019). Many effects are not fully understood, but ocean acidification takes thousands of years to reverse (Hoegh-Guldberg et al. 2007).

The ocean takes up about a third of the CO_2 that is emitted to the atmosphere by human activities

Acidity is measured using the pH scale, where lower numbers correspond to higher acidity. Ocean surface pH has declined by 0.017–0.027 pH units per decade since the late 1980s, with the decrease in ocean pH likely to be greater than background natural variability for more than 95% of the ocean surface area. Continued uptake of CO_2 will further decrease the open ocean surface pH by around 0.2 pH units by 2100 (Bindoff et al. 2019; IPCC 2014b). The pH scale is not linear and a decrease of this size (from pH 8.1 to 7.9) represents a 150% increase in acidity.

The capacity for absorbing CO_2 is reduced as oceans warm and acidify (McNeil and Matear 2008). This leads to an increased risk of becoming undersaturated for carbonate ions in polar and sub-polar oceans by 2100. At CO_2 levels associated with the current international set of emission reduction pledges (3°C by 2100), the pH of the upper ocean will decrease by approximately 0.3 pH units by 2081–2100, with the concentrations of key ion species such as carbonate also decreasing. This has substantial impacts for marine species, especially those with calcareous bones and shells that rely on carbonate ions, and that are part of ocean food webs (Doney et al. 2020; Hoegh-Guldberg et al. 2014; IPCC 2018, 2014a; Kroeker et al. 2013).

Many of these conditions can be avoided this century if global warming is limited to well below 2.0°C.

4. CLIMATE CHANGE AND THE AUSTRALIAN CONTINENT

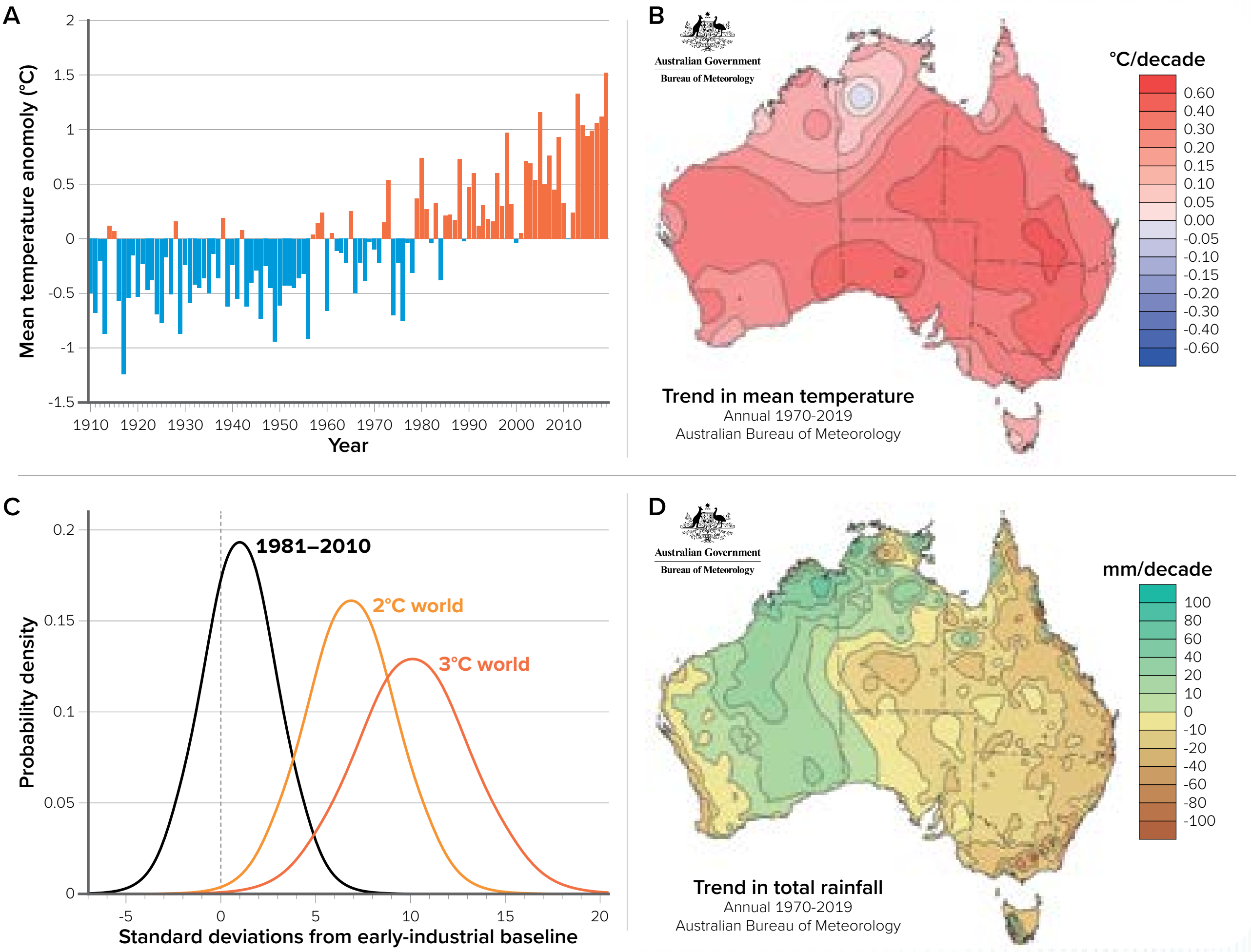
Australia is warming rapidly and recently reached 1.4°C above 1910, when measurements began

Australia is warming rapidly and recently reached 1.4°C above 1910, when measurements began (Figure 4A,B; BOM 2020; CSIRO & BOM 2020; Grose et al. 2020, under review). As Australia has warmed, the continent has experienced more hot extremes as well as fewer cold extremes (Alexander and Arblaster 2017; Lewis and King 2015; Whetton et al. 2014) and changes to rainfall patterns with increases in the north-west and declines in the south-west and south-east. Periods of frost are decreasing (along with snow cover in mountains) during winter in many areas but the risk of late frosts has increased in southern Australia (Crimp et al. 2016; Dittus et al. 2014; Whetton et al. 2014). Increasing dryness and droughts increase the likelihood of dust storms, placing an added burden on air quality (Goudie 2014) along with increased smoke from fires. Australia's coasts and oceans are changing rapidly as they experience acidification, rising sea level, coastal inundation and erosion (Adger et al. 2009; IPCC 2014a; Whetton et al. 2014). These physico-chemical changes are expected to continue, driving increasing impacts and risks as the global mean surface temperature increases and exceeds 3°C (Whetton et al. 2014).

As GHG emissions continue to rise, Australia will become hotter and many regions will continue to become drier due to reduced seasonal rainfall coupled with higher rates of potential evapotranspiration (Table 2; Whetton et al. 2014). Some regions will experience increasing rainfall. The magnitude of these changes over time will depend on whether Australia and the global community can chart a course consistent with the well below 2°C goal of the Paris Agreement. The impacts on peak temperature, seasonal rainfall and evapotranspiration for a series of Australian regions are shown in Table 2.

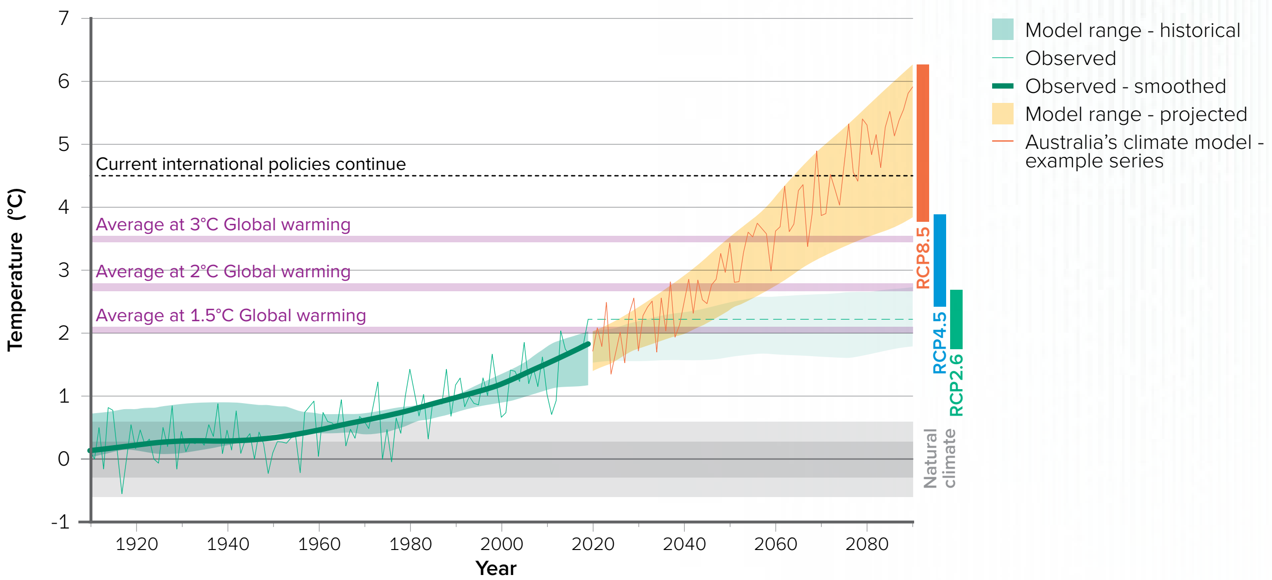
> As more and more energy is trapped by the Earth System due to increasing concentrations of greenhouse gases, the probability of large-scale extreme events such as severe storms, floods, droughts, heatwaves and other similar climate-related events increases rapidly.

Figure 4. Australia's changing climate



(a) Annual mean temperature anomaly since 1910, (b) regional changes in mean temperature from 1970 to 2019, (c) Australian seasonal temperature anomalies in a recent climate and warmer worlds as a departure from an early-industrial climate. Distributions of standardised seasonal-average Australian-average temperature anomalies from climate model experiments 1850–1900 are shown for a recent historical period (1981–2010), a 2°C warmer world and a 3°C warmer world. (d) Rainfall trends over last 50 years (BOM 2020).

Figure 5. Historic and projected average global surface temperatures for Australia under three pathways ranging from RCP2.6 (~1.5°C) to RCP8.5 (~3–5°C) climate change scenarios



Note that Australia's mean temperature anomaly is 1.4 times higher than the global average, which explains the slight differences to Figure 1. (Figure provided by Michael Grose; modified from CSIRO & BOM 2020)

Table 2. Annual temperature, rainfall and evapotranspiration changes at end of century for different climate scenarios (RCP2.6 low; RCP8.5 high scenarios).

		Region			
					
RCP scenario	**Variable**	**Southern**	**Eastern**	**Northern**	**Rangelands**
	Annual temperature	2.7 to 4.2°C	2.8 to 5°C	2.7 to 4.9°C	2.9 to 5.3°C
	Annual rainfall	-26 to 4%	-25 to 12%	-26 to 23%	-32 to 18%
	Summer rainfall	-13 to 16%	-16 to 28%	-24 to 18%	-22 to 25%
RCP8.5 (~3°C)	Autumn rainfall	-25 to 13%	-33 to 26%	-30 to 26%	-42 to 32%
	Winter rainfall	-32 to -2%	-40 to 7%	-48 to 46%	-50 to 18%
	Spring rainfall	-44 to -3%	-41 to 8%	-44 to 43%	-50 to 23%
	Evapotranspiration	8 to 17%	9 to 18%	8 to 17%	6 to 16%
	Annual temperature	0.5 to 1.4°C	0.6 to 1.6°C	0.5 to 1.6°C	0.6 to 1.8°C
	Annual rainfall	-15 to 3%	-19 to 6%	-12 to 3%	-21 to 3%
	Summer rainfall	-22 to 6%	-20 to 13%	-16 to 4%	-22 to 8%
RCP2.6 (~1.5°C)	Autumn rainfall	-17 to 11%	-25 to 15%	-18 to 11%	-26 to 18%
	Winter rainfall	-9 to 4%	-24 to 9%	-32 to 13%	-31 to 12%
	Spring rainfall	-23 to 4%	-26 to 11%	-32 to 13%	-32 to 15%
	Evapotranspiration	2 to 5%	3 to 7%	2 to 6%	0 to 4%

Differences projected to occur by 2090, relative to 1995, averaged over the four regions shown. Modified from CSIRO & BOM 2016a.

5. EXTREME WEATHER EVENTS IN RESPONSE TO GLOBAL WARMING OF 1.1°C

While extreme weather events are a natural feature of the climate system, they are increasing in intensity and frequency due to the atmosphere, land and surface ocean containing significantly more heat (and hence energy) today compared to the 1950s (Braganza et al. 2014; Bruyère et al. 2019; Trenberth 2012).

5.1. Heatwaves

Periods of extreme heat (known as heatwaves) are increasing in length, frequency and intensity on land and in coastal and oceanic waters (Braganza et al. 2014; IPCC 2014b; King et al. 2017; Perkins-Kirkpatrick and Lewis 2020; Perkins and Alexander 2013; Smale et al. 2019; Trancoso et al. 2020). Heatwave intensity and frequency increase with increasing average global temperature. This is consistent across all global regions, though the relationship differs depending on the region (Perkins-Kirkpatrick and Lewis 2017). The global average frequency of marine heatwaves increased by 34% and the global average duration increased by 17% between 1925–1954 and 1987–2016 (Oliver et al. 2018). Marine heatwaves have had major impacts on ecosystems such as the Great Barrier Reef and mangrove forests across northern Australia (Babcock et al. 2019; Duke et al. 2017; Hoegh-Guldberg 1999; Hughes et al. 2018b).

5.2. Extreme rainfall and destructive storms

Cyclones in the Australian region have increased in intensity but decreased in frequency over the past 30 years. Slow-moving and larger cyclones are projected in the future, leading to more extreme rainfall events and flooding. The height of storm surges and resulting coastal damage will continue to be exacerbated by sea level rise (BOM 2018; Oppenheimer et al. 2019).

> Cyclone activity is increasing in south-east Queensland, northern New South Wales, and some West Australian sites

Cyclone activity is increasing in south-east Queensland, northern New South Wales, and some West Australian sites (e.g. Shark Bay), demonstrating a southward shift (Sharmila and Walsh 2018). Compared to the eastern coast, the southward shift in cyclone activity in the west is expected to be smaller due to the relatively cooler waters off the west coast. These waters are projected to continue warming until at least 2100 (Bruyère et al. 2019). Bureau of Meteorology data for summer cyclone density between 1950–2018 indicate that the frequencies of cyclones are increasing in the form of heat lows for west Pilbara to west of the Gascoyne region of Western Australia and tropical lows over the Arnhem Land region of the Northern Territory. Risks from southward-shifting cyclone activity are expected to increase mostly in the south-east Queensland and north-east New South Wales regions, followed by coastal areas located in the south of Shark Bay in Western

Australia (Bruyère et al. 2019; IAG 2019). The increased strength and prevalence of heat lows due to global warming may alter tropical cyclone characteristics in future, but further research is needed to fully understand such changes.

Globally, the world is seeing a doubling of economic and insured losses from strengthening tropical cyclones every 15 years (Bruyère et al. 2019). However, not all of the increase in cyclone damage for Australia is due to climate change (Chand et al. 2019; Patricola and Wehner 2018).

Some characteristics of cyclones are likely to change in response to climate change. The average lifetime of a cyclone is likely to extend by 12 to 24 hours as GMST increases from 2°C to 3°C of global warming (Dowdy et al. 2019a; Lavender and Walsh 2011; Sharmila and Walsh 2018). These shifts in cyclone activity would have increasingly damaging consequences for people, ecosystems and industries, especially in areas less prepared for the scale of the impacts (e.g. at high latitudes where storms increasingly penetrate). Windspeed at landfall is projected to increase by 25–30%, while cyclone rain intensity at landfall is projected to increase by approximately 27% by 2100 under the RCP8.5 scenario (4°C) over eastern Australia (Parker et al. 2018).

Multiple models exhibiting warming from 2.5°C to 3.7°C by 2090 indicate increases in the intensity of 1-in-20-year extreme rainfall events in most regions

Apart from tropical cyclones, the impacts of extreme rainfall and storm systems are also likely to increase as global temperature exceeds 2°C above the pre-industrial period. Multiple models exhibiting warming from 2.5°C to 3.7°C by 2090 indicate increases in the intensity of 1-in-20-year extreme rainfall events in most regions (Braganza et al. 2014).

5.3. Hailstorms

Hail associated with extreme storms is very costly and represents a growing risk to people, infrastructure and the environment. There is some evidence that large hailstorms are shifting southward with impacts and risks decreasing in Queensland and south-western Western Australia but increasing in New South Wales and Victoria (Braganza et al. 2014; Bruyère et al. 2019).

Our understanding of how hail will change is developing but is limited by current modelling capacity. Without a better understanding of processes resulting in large hail and the tools to study this phenomenon, projections of hail events in Australia will remain speculative. However, changes in hail involve factors incorporated into coarse-resolution global climate model simulations, providing some insights into future hail-related impacts (Allen et al. 2014a, 2014b). The studies found that severe thunderstorm environments will increase in northern and eastern Australia over the present century under the RCP8.5 (>3°C) climate scenario. The increase is in response to increasing convective available potential energy which is likely to be a consequence of climate change (Gensini and Mote 2015; Prein et al. 2017; Romps et al. 2014). Rising levels of melting ice in thunderstorms are likely to decrease the incidence of hail in near-tropical areas.

5.4. Interactions between multiple stressors drive even larger impacts

Stressors rarely act in isolation and often interact to produce impacts that are greater together than on their own. For example, the combination of record temperatures, dryness and wind patterns disproportionately increases the risk of forest fires over and above each factor alone, with increasing risk for natural and human systems (IPCC 2018, 2014b). Similarly, elevated sea level when amplified by stronger storms exposes hundreds of thousands of people, infrastructure, agricultural production and coastal environments to significantly greater damage than either sea level rise or storms alone (Braganza et al. 2014; IPCC 2013b; Steffen and Griggs 2014; Whetton et al. 2014). These additional risks place a growing burden on Australian communities and businesses, with the potential to overwhelm the management and insurance of infrastructure (IAG 2019; IPCC 2018).

Case study: Extreme bushfires—the new norm?

In 2019–20 Australia experienced devastating bushfires: 33 lives were lost (Royal Commission into National Natural Disaster Arrangements 2020) and 429 people died of conditions worsened by toxic smoke inhalation (Johnson et al. 2020). Over 3,000 homes were lost and over 24 million hectares were burnt. The national financial impact of the fires is estimated to be in excess of $10 billion (Royal Commission into National Natural Disaster Arrangements 2020). An estimated 3 billion vertebrate animals were either killed or displaced (WWF 2020), while 80% of the Blue Mountains World Heritage Area and 50% of Gondwanan rainforests were burnt (Royal Commission into National Natural Disaster Arrangements 2020).

The unprecedented scale and severity of the 'Black Summer' bushfires in 2019–20 is an example of how climate change drives extreme events, underscoring the complex relationship between climate change, natural systems and the wellbeing of Australians. Severe bushfire risk is increased by high temperatures, as well as by the dryness and relative abundance of fuels (i.e. dead or dry foliage). The long-term trend towards hotter and often drier conditions (Table 2; Figure 4), plus longer and hotter heatwaves (Trancoso et al. 2020), increases the risk and impacts of fire (Hughes et al. 2020; Jyoteeshkumar Reddy et al. 2021; IPCC 2018).

Climate change has already accelerated bushfire risk across south-east Australia with 'Very High' fire danger days increasing in number, and fire seasons starting earlier and ending later (Hughes et al. 2020). Fire risk factors (heat, dryness and fuel) are amplified by other factors such as lightning strike frequency and wind strength and direction (Di Virgilio et al. 2019; Dowdy et al. 2019b), as well as dry-lightning storms which may become more frequent in some areas (e.g. south-east coast) as the climate warms (Dowdy 2020). For example, the 2009 Black Saturday fires in Victoria, in which 173 lives were lost, were preceded by a decade-long drought with a string of record hot years combined with a severe heatwave in the preceding week. Weather conditions broke temperature records on 7 February as maximum temperatures reached 23°C above the February average in Victoria (BOM 2009, Bannister 2009).

The McArthur Forest Fire Danger Index (FFDI) is a tool used by emergency services to assess the risk of fire on a particular day, given prevailing conditions (McArthur 1967). It was originally developed as a scale from 0 to 100, with 50 to 100 being categorised as 'Extreme'. During the Black Saturday fires, the FFDI ranged from 120 to 190, and included the highest values ever recorded (Karoly 2009). After the exceptional conditions of the 2009 Black Saturday bushfires the scale was revised to include 'Severe' (50–75), 'Extreme' (75–100), and 'Catastrophic' (100+, also known as Code Red in Victoria). Fire authorities now warn that even well-prepared homes may be impossible to defend under Catastrophic conditions, with escalating mortality risks for people. Yearly cumulative FFDI has increased by 42% across all sites (CSIRO & BOM 2016b) with the greatest changes occurring in south-east Australia, a probable consequence of elevated temperatures and a drying climate, both strongly influenced by climate change (CSIRO & BOM 2020).

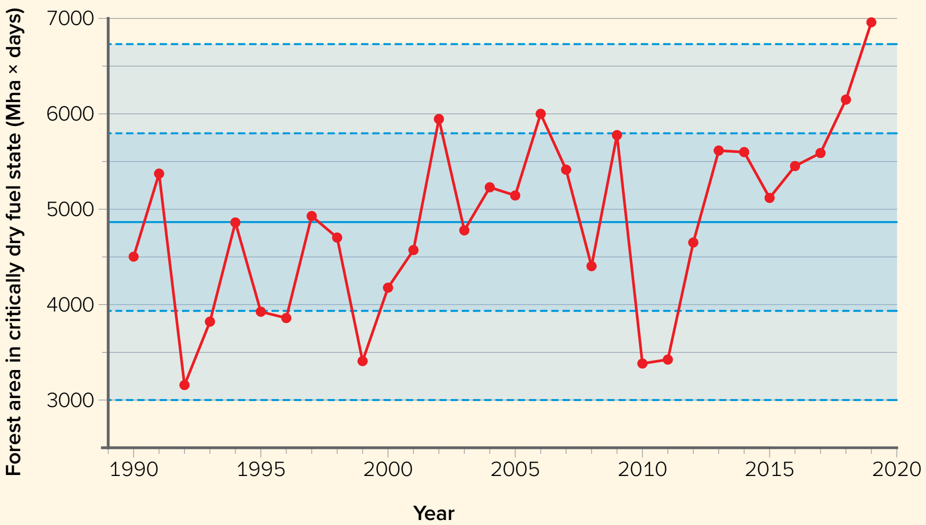
FFDI ratings for the most extreme 10% of fire weather days across Australia have increased in the last 30 years, especially in southern and eastern areas where the amount of forest area in critically dry fuel state has been increasing (CSIRO & BOM 2020). Further, there is increasing risk of pyroconvection in some regions of southern Australia. Pyroconvection occurs when there is a violent release of latent heat in the fire's plume which acts like an extraction fan above a fire, increasing the coupling between the fire and the atmosphere, potentially accelerating fire severity by generating high windspeeds, rapid ember dispersal and lightning strikes, often called a 'fire storm' (Dowdy et al. 2019b).

The human, environmental and economic costs of the 2019–20 bushfires were enormous: 33 people died as a direct result of the fires, with estimated additional deaths of 429 people from smoke-induced respiratory problems, more than 4,000 hospital admissions for respiratory and cardiovascular conditions were recorded (Borchers Arriagada et al. 2020) and an estimated 11 million

Australians were affected by bushfire smoke (Duckett et al. 2020). The fires burnt an estimated 24 million hectares, equivalent to three-and-a-half times the size of Tasmania (Royal Commission into National Natural Disaster Arrangments 2020), causing the deaths or displacement of nearly 3 billion mammals, birds, reptiles and frogs (WWF 2020). Nearly 6,000 buildings (including over 3,000 homes) were destroyed (Royal Commission into National Natural Disaster Arrangements 2020; Hughes et al. 2020). Recent insurance estimates of the total claims from the 2019–20 bushfires were well in excess of $4.4 billion in claims from the Black Saturday fires in 2009 (Butler 2020). Economic losses of at least $4.5 billion have been estimated for the tourism sector alone (Hughes et al. 2020).

The scale and destructive impact of the 2019–20 bushfire season was unprecedented but not unexpected and will most likely happen again. The long-term escalation of bushfire risk means that far greater resources and strategic planning across all levels of government are needed to increase preparedness, upgrade emergency service capabilities and build community resilience to this escalating threat (ELCA 2020).

Figure 6.1. Forest area in critically fuel dry state, Eastern Australia 1990–2019



Boer et al. 2020.

Figure 6.2.

Fire haze near Oberon from Blue Mountains mega-fire in December 2019

6. AUSTRALIA AFTER 3°C OR MORE OF GLOBAL WARMING

Understanding how Earth's climate system will change as global warming reaches 3°C or more above the pre-industrial period is challenging but essential given our current trajectory and poor understanding of sudden changes, synergies, and other non-linear responses (Christoff 2014). Some insights, however, can be drawn from trends established over the last 50–100 years, mechanistic understandings from observations, global circulation models (IPCC 2013b) and other types of mathematical models (Braganza et al. 2014; Hoegh-Guldberg et al. 2018; Whetton et al. 2014). A large body of research has examined the impacts of global warming since the Paris Agreement in December 2015 (Hoegh-Guldberg et al. 2018; IPCC 2019, 2018), including for extreme weather, at 1.5°C and 2°C above pre-industrial levels both in Australia (King et al. 2017; Lewis et al. 2017) and around the world (Dosio et al. 2018; Lee et al. 2018) with much of that work summarised in the IPCC Special Report on Global Warming of 1.5°C (IPCC 2018).

We focus here on changes associated with 3°C or more of warming above the pre-industrial period given that would be the outcome of current policy commitments (Rogelj et al. 2016; UNEP 2019). In doing so, we focus on information and scenarios that are close to 1.5°C (i.e. up to RCP2.6) and those that resemble 3°C (i.e. up to the lower range of RCP8.5). The latter may exceed 3–5°C by the end of the century but may underestimate warming given that these scenarios generally don't include the increasing probabilities of feedback loops (Hoegh-Guldberg et al. 2019a; Lenton et al. 2019, 2008; Steffen et al. 2015).

There is a growing understanding of how conditions are likely to change as Earth's average surface temperature increases by 1.5°C, 2.0°C and higher above the pre-industrial period. As in other areas of the world, more frequent, longer and more intense heatwaves are projected for Australia at 3°C global warming relative to 1.5°C and 2°C (Perkins-Kirkpatrick and Gibson 2017; Trancoso et al. 2020). Global warming of 2°C may lead to days above 50°C in Sydney and Melbourne (Lewis et al. 2017b). Although still rare at 2°C global warming, these days are very likely to be regular occurrences at 3°C global warming. The number of days above 35°C, for example, is projected to be three times greater by 2070 as compared to today in 15 towns and cities (Braganza et al. 2014).

Global warming of 2°C may lead to days above 50°C in Sydney and Melbourne

A more recent study using high resolution climate projections (Trancoso et al. 2020) explored how heatwave characteristics are likely to change under 1.5°C, 2.0°C, and 3°C of global warming across all of Queensland's local government areas. Under 1.5°C of global warming, heatwaves would occur three times a year with each event lasting on average 7.5 days. With global warming of 2°C, heatwaves would occur at least four times a year, on average lasting 10 days. At 3°C of global warming, heatwaves would happen as often as seven times a year, with events lasting 16 days on average (Figure 7). Achieving the Paris Agreement targets would be very beneficial in reducing the number of heatwave events over arid and subtropical regions and decreasing heatwave duration over tropical and equatorial regions.

Figure 7. Impact of global warming for Queensland local government areas

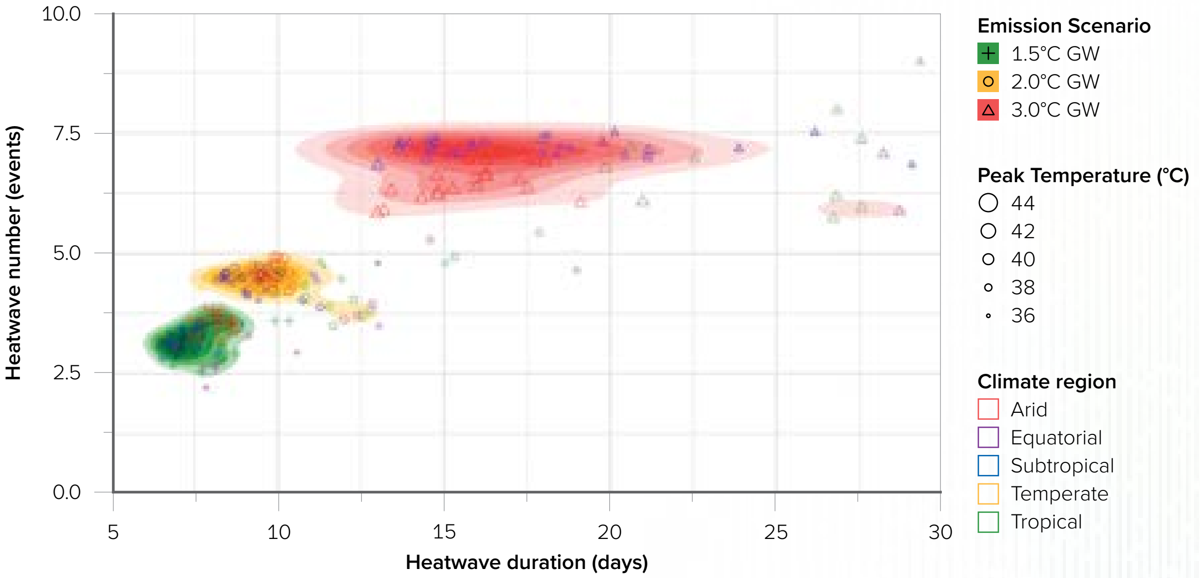


Figure 7. Impact of global warming of 1.5°C, 2°C, and 3°C above the pre-industrial period on peak temperature, heatwave duration and number across Queensland's local government areas (Trancoso et al. 2020, reprinted with permission of authors).

Weather systems are likely to be more energetic with further global warming. Associated wind speed will be higher although cyclones are likely to move at slower speeds, delivering greater volumes of water than they do today (Patricola and Wehner 2018). Higher sea level will exacerbate levels of coastal inundation associated with storms, which is highly likely to increase relative to today. Short-duration extreme rainfall would increase at 3°C global warming and above relative to the present day for much of Australia. Large hailstorms may increase in frequency and size in the southern regions of Australia (Braganza et al. 2014; Bruyère et al. 2019). Risks from bushfires will increase substantially with moderate confidence that the number of extreme fire days will double for global warming of 3°C (Clarke and Evans 2019; Di Virgilio et al. 2019; Dowdy et al. 2019b) and large decreases in seasonal rainfall will occur in southern Australia (Table 3). Similarly, fire risk (driven by record heat, dryness, and fuel, see case study, p.34) will increase by 30% or more in south-eastern Australia (Sharples et al. 2016).

Table 3. Examples of extreme events in Australia's changing climate

Extreme events	Metric	Benchmark	Climate change variable (Australia)				References
			Present climate	1.5°C (Global)	2.0°C (Global)	3.0°C (Global) and above	
East Coast lows (ECL)	Frequency of damaging ECL	Since 1860	Increased damaging ECL, decrease in other ECL includes large natural variability (medium)	Increased damaging ECL, decrease in other ECL includes large natural variability (medium)	Increasing frequency of intense ECL impacts (low)	Increasing frequency of intense ECL impacts (low)	(Bruyère et al. 2020)
Heatwaves (land)	Days	Since 1950	Historical changes show a general increase in heatwave days, from 1950 onwards.	Increased intensity and frequency e.g. Queensland: at 1.5°C of global warming, heatwaves would occur 3 times a year with each event lasting on average 7.5 days.	Increased intensity and frequency e.g. Queensland: at 2°C of global warming, heatwaves would occur 4 times a year with each event lasting on average 10 days.	Increased intensity and frequency e.g. Queensland: at 3°C of global warming, heatwaves would occur 7 times a year with each event lasting on average 16 days.	(Perkins-Kirkpatrick et al. 2016; Perkins-Kirkpatrick and Gibson 2017; Trancoso et al. 2020)
Heatwaves (marine)	Days	since 1990	Three-fold longer than 1990	Increased: heatwave intensity and frequency scale with increasing global temperature.	Increased further: heatwave intensity and frequency scale with increasing global temperature.	Heatwaves will be hotter and longer	(Arafeh-Dalmau et al. 2020; Babcock et al. 2019; Oliver et al. 2018)
Extreme rainfall	Annual maximum one-day rainfall intensity	1986–2005	Regularly variable generally slightly upward	Regularly variable ~10% increase (medium-low)	Regularly variable ~13–15% increase (medium-low)	Potentially 40% increase for +4°C (medium)	(Bruyère et al. 2020)
	20-year return level of 1-day rainfall	1986–2005	Variable, generally slightly upward (medium-high)	Variable, generally slightly upward (medium-high)	Between 15–20% increase dependent on the region (medium-high)	Between 10–60% increase dependent on the region (medium-low)	
Large hail	Frequency of hailstones greater than 2 cm diameter	~2000	Marked increasing trend in east and south-east Australia (medium-high)	Increasing trend in south-east Australia, decrease in central, north Queensland (medium)	Increasing trend in south-east Australia, decrease in Queensland (medium)	Potential increases in New South Wales and southern regions, decreases elsewhere (low)	
Bushfires	McArthur Forest Fire Danger Index	1973–2010	Increasing in all Australian regions especially in the south-east (high)	15–65% increase in number of extreme fire days (FFDI > 50) for +1°C (medium)	Further increase is typically < 10% (medium)	Increases > 30% in southern and eastern Australia (high); further increases in other regions (medium); 100–300% increase in the number of extreme fire danger days (FFDI > 50) for +3°C (medium)	
Tropical cyclones	Peak wind speeds	Variable between 1973–2007	~5% increase (high)	< 10% increase (medium-high)	10–20% increase (medium-high)	5–10% increase for every +1°C (medium-high)	
	Latitude of maximum intensity	1989	Poleward shift 1-6 km per year (high)	Further poleward shift (medium)	Further poleward shift (medium)	Possible further poleward shift (low)	
	Proportion of Australia CAT 4–5	1975	~100% increase between 1975–2010 (high)	Small increase from 2010–2015 (medium)	Further small increase from 2010–2015 (low)	Minimum further increase (low)	
	Intense precipitation (> 600 mm) within 500 km of tropical cyclone centre	1960s	~60% increase (medium)	~10% further increase (medium)	Further increase (medium)	~20% further increase (medium)	
	Frequency		Small decrease (medium)	~15% decrease (medium)	Further decrease (medium)	~30% further decrease (medium)	
	Average gale force winds	1973–2007	No information	~50% increase (low)	~100% increase (low)	Further increase (low)	
	Storm surge frequency/ coastal inundation	Since 1900	Increase (high)	Further increase (high)	Further increase (very high)	Possible substantial increase (very high)	

From expert assessment in peer-reviewed report from NCAR/IAG (Bruyère et al. 2020) except where noted. The table describes change from benchmarks under three future global temperature scenarios (average temperature increase since the pre-industrial period) with confidence in different changes indicated in brackets (low, medium, high, very high). 'Present climate' represents the observed state for the last two decades.

7. AUSTRALIA'S ECOSYSTEMS: CURRENT IMPACTS AND PROJECTED RISKS AT 3°C

The goods and services provided by natural ecosystems are inextricably linked to human wellbeing, providing food and fibre, regulating the climate, protecting coastlines, reducing the impacts of natural hazards, maintaining the quality of our air and water, pollinating our crops, providing medicines and pest control, sequestering CO_2 and holding important spiritual and cultural values (Díaz et al. 2018). Human activities, however, have taken an enormous toll on these vital resources. Deterioration of ecosystems and species extinction is occurring at an unprecedented rate (Steffen et al. 2015; Woinarski et al. 2019). Around 1 million animal and plant species are threatened with extinction, many within decades (Brondizio et al. 2019); Australia has one of the worst records of species extinctions of any continent, with nearly 50% of the world's known mammal extinctions in the last 200 years (Hughes 2014). The many stresses facing species and ecosystems globally, such as invasive species, overharvesting, and habitat loss and fragmentation, are all being exacerbated by a rapidly changing climate (Creswell and Murphy 2016).

> The many stresses facing species and ecosystems globally, including invasive species, overharvesting, and habitat loss and fragmentation, are all being exacerbated by a rapidly changing climate

7.1. Global warming of 1.1°C is already seriously affecting Australia's ecosystems

Many of Australia's terrestrial, freshwater and marine ecosystems have already suffered from climate change over the past few decades. Atmospheric and ocean warming, accompanied by changes in the distribution and seasonality of rainfall, and the frequency and intensity of extreme events such as heatwaves, droughts, bushfires and floods, are associated with unprecedented, rapid and potentially irreversible ecosystem impacts (Babcock et al. 2019; Bergström et al. 2019; CCA 2019).

In marine and coastal ecosystems, these impacts include heat stress and mortality, destroying the habitats of tens of thousands of species (Babcock et al. 2019; Hoegh-Guldberg 1999; Hughes et al. 2018b, 2018a). Coral reefs, seagrass and kelp beds are affected, and there has been widespread mortality of mangroves and the loss of freshwater wetlands in the Northern Territory due to saltwater intrusion.

In terrestrial environments, a combination of drought, extreme heatwaves, disease and insect herbivores has caused large-scale mortality of trees in forest and woodland ecosystems; bushfires have destroyed Gondwanan forests in Tasmania and tropical rainforests in Queensland; and woody shrubs are encroaching into alpine grasslands (Bergström et al. 2019; Hoegh-Guldberg et al. 2018; IPCC 2018). Rapid warming of parts of Australia's Antarctic and sub-Antarctic regions, together with increases in wind speed and evapotranspiration, has caused extensive dieback of cushion plants and mosses on Macquarie Island and East Antarctica (Robinson et al. 2018).

Palaeoclimate records reveal that Australia has experienced severe droughts in the past (Freund et al. 2017). Droughts may become more frequent and intense in future (Ukkola et al. 2020), but there is some uncertainty in current drought projections, which will require additional study (King et al. 2020). Ongoing drought and high temperatures have been associated with mass fish kills (AAS 2019; Vertessy et al. 2019) and the loss of river red gums in freshwater systems such as the Murray-Darling.

Recent heatwaves have caused high mortality in groups of species such as birds, flying foxes and tree-dwelling mammals (CCA 2019). Warming is associated with increasing 'feminisation' of green turtles in the northern Great Barrier Reef with potential long-term population consequences (Jensen et al. 2018). Dramatic declines in Bogong moth populations due to drought in larval habitats have had subsequent impacts for alpine species such as the endangered mountain pygmy possum (*Burramys parvus*) (CCA 2019). Storm surge and coastal inundation exacerbated by rising sea level in the Torres Strait are responsible for the extinction of the Bramble Cay melomys (*Melomys rubicola*), the first documented climate change-driven mammalian extinction globally (Gynther et al. 2016). The effect of recent unprecedented fires in 2019–20 on Australian ecosystems and species is still being analysed and is expected to include the death or displacement of approximately 3 billion amphibians, reptiles, birds and marsupials as well as the transformation of vast areas of vegetation (WWF 2020).

Storm surge and coastal inundation exacerbated by rising sea levels in the Torres Strait are responsible for the extinction of the Bramble Cay melomys, the first documented climate change-driven mammalian extinction globally

7.2. Risks of exceeding thresholds for ecosystems increase as global temperatures warm by 2°C, 3°C and more

The majority (approximately 70–90%) of the world's tropical coral reefs are projected to disappear at even low levels of warming of 1.5°C (IPCC 2018). The outlook for the state of the Great Barrier Reef is considered 'very poor' with climate change seen as the major driver, primarily through more frequent and intense heatwaves and cyclones (GBRMPA 2019).

Substantial losses in ocean productivity, ongoing ocean acidification, and the increasing deterioration of coastal systems such as mangroves and seagrasses (Babcock et al. 2019) are projected to occur if global warming exceeds 2°C above the pre-industrial period (Hoegh-Guldberg et al. 2018). The accompanying loss of ecosystem services and the release of GHG from sediments are likely to drive positive feedbacks involving climate change (Hoegh-Guldberg et al. 2014).

Rising sea level will continue to amplify storm impacts, damaging coastal ecosystems such as mangroves, seagrass beds, rocky intertidal zones and estuaries. The World Heritage-listed Kakadu National Park in the Northern Territory has an average elevation above sea level of only 0.5 m, placing it at extreme risk of saltwater intrusion into its unique freshwater ecosystems in a region where sea level has been rising at approximately twice the global average, partly due to climate change and partly due to natural variability (Pettit et al. 2018).

Freshwater ecosystems, already considered among the most threatened globally, will continue to suffer from rising air and water temperatures, reduction in flows in drought-affected regions, declining water quality and disruption to hydrodynamics. Inland freshwater wetlands that provide breeding habitat for birds, especially those in the Murray-Darling Basin, will continue to decline (Kingsford et al. 2017).

Ongoing transformational impacts in terrestrial ecosystems will likely include increasing desertification; woody shrub encroachment into alpine herb fields and savannas; loss of rainforests, accelerated by the increasing frequency, intensity and extent of bushfires; and forest dieback (especially in areas affected by clearing and drought) as a result of pest outbreaks affecting species already under stress (Hoegh-Guldberg et al. 2018; Hughes 2014). Declining ecosystem health is likely to reduce carbon stocks in soil and vegetation, creating positive feedbacks to climate change (Settele et al. 2015).

The current global rate of species extinction (100 to 1,000 times higher than the background rate estimated from the fossil record) will likely accelerate as the global mean surface temperature exceeds 2°C. Species distribution modelling studies indicate that thousands of plant and animal species globally (Warren et al. 2018), and hundreds of species in Australia (Williams et al. 2003), are likely to suffer substantial losses of suitable habitat with a warming of 1.5°C, and these impacts are considerably greater at 2°C and beyond. Given that such habitat loss is a risk factor for extinction, it is reasonable to predict that accelerating loss of species will accompany warming (Urban 2015) with recent estimates of around 1 million animal and plant species being threatened with extinction, many within decades, from a combination of climate change and other factors (Brondizio et al. 2019; Díaz et al. 2018). These types of projections, however, do not consider altered interactions between species, natural or anthropogenic barriers to dispersal, or the impacts of extreme events such as heatwaves, so should be considered very conservative.

The current global rate of species extinction (100 to 1,000 times higher than the background rate estimated from the fossil record) will likely accelerate as the global mean surface temperature exceeds 2°C

7.3. Species are shifting where they live but most are not keeping up with climatic change

Observations of distribution and life cycle changes indicate that some species are partially adjusting to the climatic change of the past few decades (Chambers et al. 2013; Poloczanska et al. 2013; Steffen et al. 2015). At least some of these responses to changes, such as the movement of sea urchins to Tasmanian kelp forests from New South Wales coastlines due to the southward incursion of the East Australia Current, are having negative impacts on other species through altered species interactions such as predation, grazing and competition (Ling et al. 2009). Likewise, mismatches between plant and pollinator species will lead to loss of ecosystem function (Settele et al. 2015).

Studies of the global rates of species movement indicate that the rapid pace of climate change exceeds most species' capacity to adapt by shifting their geographic ranges (Hughes 2014; IPCC 2014a; Poloczanska et al. 2013). Barriers to the adaptative movement of terrestrial and freshwater ecosystems include Australia's low topographic relief (flatness), arid interior, and fragmented native vegetation (Burrows et al. 2014). Species already at elevational or southern limits, as well as those on small islands, face greater challenges. These types of responses to ocean warming are also affecting the distribution of many key commercial marine species and fisheries (Lindegren and Brander 2018).

> **Australia's unique ecosystems have already been seriously affected by the 1.1°C increase in global temperature since the late 19th century. As conditions have warmed, species have shifted their distributions and many have also decreased in abundance. In some cases, entire ecosystems (e.g. coral reefs, forests) have declined, with major impacts on biodiversity and ecosystems services. These changes have serious implications for nature and human wellbeing as global temperatures head toward 3°C and above.**

7.4. Conservation of Australia's unique ecosystems in a 3°C warmer world

The prospect of ongoing species loss as the climate changes rapidly has focused much-needed attention on how protection and management of landscapes and seascapes might increase species resilience and reduce vulnerability. Many complementary strategies have been proposed including:

- reduction of non-climatic stresses such as: pollution, over-allocation of water for human uses, over-fishing, invasive species, nutrient and sediment runoff, over-exploitation, unsustainable coastal development and land clearing (Anthony et al. 2015; Hoegh-Guldberg et al. 2018; Mcleod et al. 2019)
- restoration, revegetation, reforestation and habitat creation (terrestrial, freshwater and marine) to actively increase viable habitat in existing or new locations and sequester carbon (Jellinek et al. 2020; Keith et al. 2014; Mackey et al. 2013; Roxburgh et al. 2006; von Holle et al. 2020), subject to issues regarding cost (Bayraktarov et al. 2019)
- identification and protection of climate refugia and pathways: places in the landscape that are projected to provide buffered habitat for current species or where species may adaptively migrate (Beyer et al. 2018; Hoegh-Guldberg et al. 2014; Hoegh-Guldberg et al. 2018; Hoeppner and Hughes 2019)
- management of fire regimes, where possible, including creating buffer zones around fire-sensitive vegetation, and small-scale habitat alteration to reduce exposure to or impact of warming or drying (Clarke et al. 2016; Sharples et al. 2016)
- assisted evolution: large-scale genetic modification, captive breeding and release of organisms with enhanced stress tolerance; and translocation of vulnerable species to habitats projected to be more climatically suitable in the future (Heller and Zavaleta 2009; Hoegh-Guldberg et al. 2008; van Oppen et al. 2017).

There remain significant barriers to effective ecosystem adaptation measures. Despite more than three decades of research literature and a growing number of climate adaptation plans available, most adaptation action to reduce species loss and manage ecosystem transformation in the face of a rapidly changing climate remains small-scale and relatively passive, with few active interventions, such as translocation or habitat creation, being implemented in Australia (Hoeppner and Hughes 2019). There is, however, growing recognition that ecosystem transformation is inevitable and that new interventionist approaches to conservation and natural resource management will become increasingly necessary to meet the challenge at 1.5°C and higher (Bowman et al. 2017).

Many potential approaches to reducing the climate risk for ecosystems have demonstrable co-benefits for human communities and wellbeing, as well as contributing to mitigation efforts and sustainable development more broadly. Nature-based solutions (sometimes referred to as Ecosystem-based Adaptation, EbA), such as preserving and restoring mangroves, deliver multiple benefits including coastal protection, carbon sequestration and habitat provision, reducing vulnerability and building resilience to climate change for both human and natural systems (IUCN 2017). However, the potential for some human adaptation measures (such as shifting agricultural patterns, creating bushfire buffer zones, and building dams and sea walls) to have negative impacts on species and ecosystems may rival the direct impacts of climate change (Maxwell et al. 2015).

Many potential approaches to reducing the climate risk for ecosystems have demonstrable co-benefits for human communities and wellbeing

7.5. The decline of Australia's ecosystems has serious implications for human health, wellbeing, food security, culture and economic development

In most cases, future impacts are difficult to quantify accurately but some examples follow. In 2014–15, the value of honeybee pollination services was estimated at around $14.2 billion (Karasiński 2018). Decline of honeybee populations threatens these services, affecting more than a million hectares of crops in Australia. The tourism industry, which in 2016–17 accounted for 3.2% of GDP and contributed $54.7 billion to the economy, is largely nature-based, with the top five attractions for international visitors being beaches, wildlife, the Great Barrier Reef, wilderness areas and national parks. All of these attractions are at increasing risk from climate change. Very high rates of sea level rise in the Gulf of Carpentaria, due to natural variability and climate change, are affecting shoreline stability and mangrove communities, which provide nurseries for fish and commercially important invertebrates including crabs and prawns, supporting a fishing industry worth approximately $30 million per year (Duke et al. 2017b).

The deterioration of the kelp communities that make up the Great Southern Reef along Australia's southern coast and Tasmania due to warming waters and changes in the distribution of marine herbivores such as sea urchins, combined with other human impacts such as sediment and nutrient runoff, threatens a loss of up to $10 billion per year (Bennett et al. 2016). Drinking water for 4.5 million people in Melbourne comes from catchments dominated by Mountain Ash forests that are the most carbon-dense forests on Earth, but are threatened by bushfires combined with logging (Lindenmayer 2016).

> Our ability to conserve Australia's unique ecosystems in a world that is 3°C warmer than the pre-industrial period is in doubt. The impacts of unrestrained warming to 3°C and more on Australia's unique flora and fauna will be severe. Failure to meet the Paris Agreement targets will have serious implications for human health and the prosperity of Australia. Encouraging the international community to act effectively on climate change is therefore very much in Australia's national interest.

8. AGRICULTURE, FORESTRY, FISHERIES AND FOOD PRODUCTION

Australian agriculture, forestry, fisheries and food systems are being negatively impacted by climate change, with serious risks unfolding over the coming decades (Reisinger et al. 2014; Smith et al. 2014). Climate factors affect the choice of agricultural production system, potential productivity, its variability, and product quality. They also influence which areas are to be planted and preferred soil types, management systems and technologies, as well as input levels and their costs, product prices, and natural resource management (including water). These systems support human health, the social fabric of rural communities, businesses, value chains and regional economies. These elements have been, and will be, affected to various extents as the climate changes.

Rural and regional communities are particularly vulnerable to increasing droughts, bushfires and heatwaves. Climate change acts as a 'threat multiplier', exacerbating existing threats and issues via changes in average temperature, temperature extremes, rainfall patterns, storm and hail risk, potential evaporation and sea level rise (Reisinger et al. 2014; Smith et al. 2014; Stokes and Howden 2010). Climate change is an issue for the sector to deal with right now: it has already resulted in the reduced profitability of Australian broad-acre farms by an average of 22% since 2000 (Hughes et al. 2019).

Climate change is an issue for the sector to deal with right now: it has already resulted in the reduced profitability of Australian broad-acre farms by an average of 22% since 2000

Land use in Australia has already been impacted by climate change, with negative impacts such as reduced water availability and elevated heat stress projected to increase with further increases in global average temperature (see Tables 2 and 3). Climate changes may alter the most productive, profitable or sustainable land use in a given location and this may give rise to adaptations via land use change. For example, with ongoing increases in temperature and decreases in cool season rainfall, the 'dry' margin of the Australian grain growing belt is likely be replaced by grazing-only land use, whereas the 'wet' margin of this belt is likely to expand into the high rainfall grazing zones (Nidumolu et al. 2012) due to changing relative profitability (Moore and Ghahramani 2013). The overall area of land under grain cropping is likely to shrink. Land uses that require active outdoor labour are likely to be increasingly difficult as heat stress days increase in frequency and severity, particularly in northern Australia. Some proactive land use changes such as moving viticulture operations to high elevations or southward can generate benefits now and in the future (Vermeulen et al. 2018).

8.1. Australian grain, fruit and vegetable production has already been impacted

Climate change has already affected cropping activities in Australia, particularly the broadacre crops such as wheat and barley that have seen reductions in yield potential of up to 27% (Hochman et al. 2017; Hughes et al. 2017), reducing profitability by around 22% (Hughes et al. 2019). There have also been changes in dryland cropping systems in south-eastern Australia, particularly at the dry margins of the grain belt (Howden et al. 2014). Reductions in river flows have affected water availability for irrigated agriculture, decreasing the available volumes of water and increasing prices, resulting in efforts to improve water use efficiency. Many of the above changes have been exacerbated by the recent severe droughts, which are increasing as seasonal rainfall declines while temperatures and evaporation rates increase (Table 2).

Climate change has already affected cropping activities in Australia, particularly the broadacre crops such as wheat and barley that have seen reductions in yield potential of up to 27%

Grain, fruit and vegetable crops are crucial for our food and nutritional security, but they are already negatively affected by climate change, with further change likely as average global surface temperature increases to 3°C or more above pre-industrial levels.

Climate change is likely to exacerbate drought impacts with projected decreases in cool-season rainfall across many regions of southern Australia (Feng et al. 2019; Table 2). Given that crop production is often water-limited in Australia, these shifts in rainfall along with rising temperatures pose a challenge to the sustainability of broadacre crop yields in south-western and south-eastern Australia, particularly at the dry margins of the grain belt (Howden et al. 2014). For example, a 3°C global temperature increase would reduce yields of key crops by between 5 and 50% depending on crop and location (Anwar et al. 2015) with more severe reductions in the drier locations. Declines in rainfall result in corresponding reductions in crop yield due to reduction in plant growth. Increases in temperature reduce the duration of accumulation of plant biomass after flowering, reducing grain yield.

Yields of fruit and vegetable crops are likely to be reduced due to decreases in irrigation water availability and increases in temperature that reduce both quality and quantity of produce (Reisinger et al. 2014). Changes in growing season attributed to global warming are projected to decrease maize production in Queensland (at 1.5°C) and wheat and soy yield in the Australian east coast when global warming exceeds 2°C (Ruane et al. 2018). Significant reductions are also expected in oil seeds (35%), wheat (18%), fruits and vegetables (14%), plant fibres (7%) and other fibres (11%) in Australia under severe climate warming of 3°C and more (Dellink et al. 2019).

Flowering and fruit set of apples and stone fruit may be affected in some areas by the reduction of winter chilling conditions due to higher temperatures. In other areas of southern Australia, viticulture and horticulture may be affected by increasingly late frosts (Crimp et al. 2019, 2016) that interact with earlier budburst and flowering due to higher average temperatures, substantially increasing the damage to grape, fruit and cereal crops (van Leeuwen and Darriet 2016).

There are many adaptation options possible. These include incremental agronomic changes such as changing planting dates, breeding crops with increased vigour that mature faster and have more effective root system architecture, or adoption of zero-tillage to more effectively manage soil moisture. There are also systemic changes such as including grazing animals into cropping systems and transformative changes such as relocation (for example, exploration of rice cropping in the Northern Territory due to reductions of water availability and increased prices in the Murray-Darling Basin; Stokes and Howden 2010). Collectively, these adaptive changes are anticipated to reduce, but not remove, the impacts of climate change.

8.2 Rising heat stress has negatively affected extensive and intensive livestock systems

Heat stress is a significant issue for many livestock enterprises via impacts on animal welfare, reproduction and production (Lees et al. 2019). In Australia, where dairying is primarily pasture-based and relies on the efficient conversion of pastures into milk, the effects of extreme events are likely to have significant negative impacts beyond those of climate change alone (Harrison et al. 2016). Projected temperature and relative humidity changes for the Murray dairy region suggest up to 37 additional days of heat stress if the 'high' GHG emission scenario is realised, reducing production (Nidumolu et al. 2014). Similar reductions in productivity due to heat stress are projected for beef cattle in northern Australia, which will interact with other climate impacts on feed availability and feed quality.

Grazing with domestic livestock (mainly sheep and cattle) is the major land use of Australian grasslands and rangelands and long-term declining trends in forage production due to declining and more variable rainfall would create problems in many areas as graziers attempt to maintain livestock numbers, profitability and soil cover (McKeon et al. 2009). Maintenance of soil cover is critical to protect often-scarce soil nutrients from erosion arising out of extreme rainfall and wind events. Extreme events such as flash flooding can impact grazing herds (Crowley and Preece 2019) as was seen in early 2019 when around half a million beef cattle died in tropical Queensland from a combination of cyclonic flood rains and lack of feed from the prior drought.

Climate change scenarios of 3°C or more are likely to be very challenging for livestock systems. For example, across the top third of Australia, almost every day will be a heat stress day, affecting livestock and the people who manage them. There will also be impacts on water demand, pasture quality and quantity, and fire management (Stokes and Howden 2010). Across southern Australia, large declines in rainfall will reduce both dryland and irrigated production bases for livestock.

Climate change scenarios of 3°C or more are likely to be very challenging for livestock systems. For example, across the top third of Australia, almost every day will be a heat stress day, affecting livestock and the people who manage them

Adaptation options include improvements in the management of the feed production base, especially through improved water use efficiency, maintenance of soil cover, selection of livestock breeds for heat resistance and productivity, moderation of temperature extremes via shade, provision of adequate, clean drinking water and the enhanced management of pests, diseases and weeds (Stokes and Howden 2010).

8.3. Forestry is under rapidly growing pressure in a warming and drying climate

Regional impacts on forests include potential increases in production in the southern temperate regions but decreases in hotter areas, including increased fire risks overall (see case study, p.34) and species-specific pest impacts. Changes in rainfall will be critical for the distribution and growth of forests across Australia, particularly in the drier regions and in south-western Australia which may be most at risk. In hotter regions, plantations will be increasingly limited by high temperatures. In cooler temperate regions (e.g. Tasmania and Gippsland), increased production may be expected as temperatures warm due to climate change (Battaglia and Bruce 2017).

There remains significant uncertainty as to the effects of elevated CO_2 on growth and how climate scenarios will interact with local conditions such as soil depth. Forestry plantations are likely be exposed to higher fire danger in a drier and warmer climate in the future, particularly in inland Victoria and south-western Western Australia (Pinkard et al. 2014; Ruthrof et al. 2016). Projected warmer temperatures may result in increased pest incidence such as chewers and sap suckers through improved survival rates in winter (Pinkard et al. 2014).

In order to sustain plantation productivity into the future, the forest industry may need to use new provenances of currently planted species or alternative species that are better adapted to hotter and drier environments (Bush et al. 2018). Risks can be reduced through variation in tree planting density, tree species and provenance and via appropriate fire and fertiliser management.

Complex ecosystems such as forests may be exposed to climate impacts that are reached at or below 2°C global warming (Leadley et al. 2010; Scheffer et al. 2009). In a 3°C Australia, these impacts are likely to manifest at an accelerated pace. For example, a species-rich tropical rainforest of the Cairns region could be transformed into a savanna woodland, such as that in Jabiru in Northern Territory, as global mean surface temperature warms to 3–4°C (Whetton et al. 2014).

A species-rich tropical rainforest of the Cairns region could be transformed into a savanna woodland ... as global mean surface temperature warms to 3–4°C

8.4. Fisheries in a rapidly changing ocean

Ocean warming and acidification is affecting marine organisms that are the basis of fisheries and aquaculture. Fisheries and aquaculture have been estimated to provide 20% of the protein needs of 3 billion people across the planet (FAO 2020). Australia depends on its fisheries and aquaculture as part of its food system and exports, earning an estimated $3.06 billion in 2016–17 (Steven et al. 2020).

There is considerable risk from a broad range of impacts for these valuable industries. For example, changes in sea surface temperature are driving range shifts with many species moving hundreds of kilometres towards higher latitude locations as oceans warm (Burrows et al. 2014; Hoegh-Guldberg et al. 2014). Ocean acidification and warming is affecting the success of aquaculture through the failure of fertilisation and early development for species such as oysters (Bindoff et al. 2019; Fleming et al. 2014; Lindegren and Brander 2018), and the changing distributions of disease and invasive species (Hoegh-Guldberg et al.

2014). These changes and many others associated with climate change are increasing industry costs and decreasing productivity of fisheries and aquaculture. Given the changes so far for 1.1°C, there is concern that these industries are facing serious impacts as warming increases above 1.5°C (Hoegh-Guldberg et al. 2018, 2019b).

Australia depends on its fisheries and aquaculture as part of its food system and exports, earning an estimated $3.06 billion in 2016–17

8.5. Food value chains are likely to be increasingly affected by climate disruptions

As we move towards a 3°C world, extreme events will increasingly become part of the norm, disrupting systems, changing landscapes and causing significant structural damage to logistical routes, processing facilities and storage hubs. Food value chains, which are intrinsically linked to landscape geography and connect rural to urban communities, will be exposed to such systemic shifts. As climate changes, decision makers should disentangle day-to-day risk management from longer-term climate trends (Lim-Camacho et al. 2019, 2017). However, while there is a growing level of concern about changing climatic impacts on value chains, there is still minimal guidance for managers across the value chain to understand and act on potential risks as they become increasingly complex.

Value chain approaches provide a systems perspective of risk management, which is critical in considering adaptation options across a collective group of actors in a chain and understanding where adaptations will be most effective (Lim-Camacho et al. 2015) . For example, in the case of seafood value chains, where gross value was estimated at $3.06 billion for fisheries and aquaculture in 2016–17 (ABARES 2018), the direct impacts of climate change (extreme weather events, changes in volumes and location of fish stocks, and increased temperature) were perceived to impact the harvest end of the supply chain the most (Fleming et al. 2014). Increased complexity of value chains via strategic inclusion of additional nodes and linkages can help reduce problematic climate impacts (Lim-Camacho et al. 2017). Given the large projected increases in the variability of food production over the coming decades due to climate changes (Porter et al. 2014), such adaptations will be needed on an ongoing and increasing basis if food and nutritional security is to be maintained.

8.6. The growing vulnerability of Australia's rural and regional communities

Rural employment, including self-employed people such as farmers, those employed to support rural sectors (such as in agriculture, fishing or wine industries) and those living in rural towns (teachers, retail, medical personnel) will be affected by climate change in multiple ways (Edwards et al. 2009; Howden et al. 2014). Rural and regional communities are vulnerable to increasing droughts, hailstorms, bushfires and heatwaves being driven by climate change, which acts as a threat multiplier, exacerbating other existing threats and issues (Hughes et al. 2016).

With an increase of 3°C, climate change impacts on profits and business viability are likely to cause increased unemployment and possibly higher suicide rates (Hanigan et al. 2012), mental health issues (Horton et al. 2010; O'Brien et al. 2014) and health issues relating to heat stress (Mora et al. 2017). Rural communities also face increasing livelihood difficulties by taking on debt to cope in poor years, insurance losses from emergency events and more challenging work conditions resulting from climate change (Alston 2011; Hughes et al. 2016). Aboriginal and Torres Strait Islander communities are likely to suffer increased disadvantage especially in relation to health. Businesses, including tourism, will potentially face greater levels of absenteeism and loss of work productivity, difficulties in attracting and retaining staff, increased insurance premiums and increased costs, affecting employment in rural regions. Impacts on the transport sector will have ripple effects in rural regions, creating higher costs for employers and diminished capacity to offer ongoing employment.

Strategically building new and alternative regional businesses as part of a national climate response would provide employment opportunities in rural regions that are not strongly affected by climate variation. These investments would have the potential to build community social and other assets as well as the formation of support and information networks that create and grow adaptive capacity (Dowd et al. 2014). In other places, transformational adaptation, such as via the relocation of rice and cotton growing, may buffer potential impacts on employment and create new opportunities (Mushtaq 2018).

Strategically building new and alternative regional businesses as part of a national climate response would provide employment opportunities in rural regions that are not strongly affected by climate variation

8.7. Food security: can Australia and the world provide enough food on a 3°C warmer planet?

Australia is currently considered to be food secure, although there are parts of the population that are not (Friel et al. 2020; Friel and Baker 2009; Lindberg et al. 2015). In this context, being food secure is when people have physical, social and economic access to sufficient, safe and nutritious food in order to meet their dietary needs and food preferences for an active and healthy life (Ingram 2020; Pérez-Escamilla 2017). The perception of food security in Australia appears to be based on several livestock (such as beef, lamb and to a lesser extent, dairy) and cereal commodities, the production of which grossly exceeds domestic consumption (on average), leading to significant exports.

However, this picture disguises some significant emerging food security issues. For example, historically, the value of imports and exports of vegetables was approximately equal. However, the Millennium Drought in the early 2000s, combined with the high Australian dollar, pushed exports down while imports accelerated (Howden et al. 2014). Currently, the value of imports (over $1 billion per year) is about 2.5 times that of exports, reflecting a degree of potential food insecurity in relation to vegetables even though increased consumption of vegetables is being emphasised as critical for improved health. Future water stress in key catchments from climate change is likely to increase this gap. A similar situation applies to fruit although the gap has closed recently. Similarly, the value of dairy exports in the past grossly outweighed imports but these are now almost at parity.

These sorts of potential food gaps are manageable provided that:

- Australia has enough international currency to purchase imports
- the required foods are available internationally for trade
- issues such as biosecurity restrictions or social concerns regarding GHG footprints don't constrain these imports.

Climate change can influence all three considerations through major negative impacts on food production in many regions worldwide, which raises significant questions about global food security (Porter et al. 2014).

While total wheat production (the most important grain in Australia) has almost doubled since the mid-1970s, domestic use has increased by a factor of 3.5: in recent drought years, consumption is now 70% of production and rising. When this exceeds 100% in a given year, Australia will either have to rely on stored grain or imports. Scenarios that combine population growth with climate change suggest that this situation is very likely over the forthcoming decades especially under scenarios of 3°C or more temperature increase (Howden et al. 2014). Recent trends indicate the closing stocks of wheat in a given year (which roughly equates to storage) are only about half a year's national consumption whereas a few decades ago they were almost two years' worth. Consequently, it is possible that food security in Australia related to cereal consumption may not be guaranteed—a situation that would have been hard to contemplate historically. If we consume the full amount of domestic production, our export earnings will fall, reducing our capacity to purchase and import other food such as vegetables which may be in short supply due to irrigation water shortages.

In contrast, beef production has increased by 50% since the 1970s despite significant climate changes (which includes positive impacts in the north-west), exports have increased by about 25% and domestic consumption as a proportion of production has halved (ABARES 2020). It is therefore unlikely that climate change will cause risks to this component of food security. However, this industry may come under pressure to reduce its GHG footprint especially in the absence of research and development to reduce methane emissions.

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Climate change and water in Australia

Australia is the world's driest inhabited continent. While the water cycle is always variable, climate change will impact water resources in multiple ways: southern Australia at 3°C will be hotter, drier and more water stressed. These stresses will have impacts on water security, availability, quality, economies, human health and ecosystems.

Impacts overview

Depending on the region, climate-driven changes may increase the length and severity of droughts, decrease rainfall and increase temperatures (Cheng et al. 2014; Steffen et al. 2018c). In wetter places, there may be an increase in extreme rain events in the short term. There will also be declines in runoff, soil moisture, streamflow, dam inflow, and groundwater recharge, which will exacerbate and amplify natural variability. Climate impacts on water will be amplified by their interrelation with each other. For example, floods will impact water infrastructure; industries such as coal, gas and hydro power that need immense quantities of water will be negatively affected by drought; and bushfires will adversely affect catchment water supplies (Steffen et al. 2018c).

Availability

Decreases in precipitation, increased vegetation water use and loss of soil moisture will reduce water availability (Cheng et al. 2014) and balance (Ali et al. 2012; Pokhrel et al. 2021). This will impact agriculture, urban water supplies and mining. For example, warming of 2.5°C, a rainfall decrease of 20%, and associated decreases in winter runoff and soil moisture will intensify reductions in water availability in eastern Australia (McFarlane et al. 2012; Zhang et al. 2019).

Evaporation and increased temperatures will mean that the total water storage capacity of open water reservoirs in south-east and south-west Australia will decline substantially (Pokhrel et al. 2021). Cities in Australia will have less water and will increasingly have to seek it elsewhere (e.g. desalination). Perth and Adelaide are at highest risk, Melbourne could lose up to 35% of the water that currently flows into dams, and Sydney water supplies will be reduced. In the Murray-Darling Basin, models show that average catchment rainfall decreases of 13–21% would reduce runoff by up to 45% in wetter catchments and up to 64% in drier and hotter ones, demonstrating that climate changes would cause significant impacts to natural resource management (Austin et al. 2010). This includes groundwater supplies, 79% of which would experience reduced recharge capacity due to their dependence on annual rainfall (Barron et al. 2012). For example, Rottnest Island in Western Australia has experienced reductions in freshwater, primarily due to a reduction in recharge to the freshwater lens (layer) caused by a 20% decline in winter rainfall in the south-west Western Australian region (Bryan et al. 2016). Climate sensitivity that causes changes in river flows and diversions has implications for water allocation and management (Kirby et al. 2014).

Quality

Water quality will be affected by future climate impacts. These will include increased incidences of algal blooms (eutrophication) and acidification. Contaminant mobilisation in drying Australian wetlands leads to generation of acidic soils (Shand et al. 2017). For example, water levels fell below sea level in the Lower Lakes at the mouth of the River Murray during the Millennium Drought, causing soil acidification and the release and mobilisation of a range of contaminants in many parts of the lake, highlighting what will happen in the future (Shand et al. 2017). A scenario analysis of the semi-arid Millbrook catchment-reservoir system that supplies drinking water to north-eastern suburbs of Adelaide, South Australia and hosts a range of viticultural and horticultural land uses, shows high likelihood of significant eutrophication effects in the reservoir (Nguyen et al. 2017). Extreme events such as bushfires affect water quality, generating ash that enters waterways and contaminates water sources, and when followed by heavy rainfall events causes flooding and nutrient runoff (Bodí et al. 2014). Extreme flood events also increase turbidity, changes to water colour and incidence of organisms such as giardia and algal blooms (Khan et al. 2016).

Security

Australia's water security will be significantly influenced by climate change (Arnell et al. 2019b). Changes to the global water cycle are likely to cause regional conflict, particularly in the Asia–Pacific region. Food security in Australia would also be affected as climate change will limit the capacity to export food. Despite its relatively small contribution to total global food production, Australia's contribution to international trade in wheat, meat and dairy products is substantial and could affect global food prices. Furthermore, Australia's agricultural exports are very important within the South- and South-East Asian and Oceania regions (Ejaz-Qureshi et al. 2013).

Ecosystem impacts

Future climate scenarios show water-dependent ecosystems and species will be affected (Barron et al. 2012; Shand et al. 2017). For example, species modelling indicates turtle species loss in the Murray-Darling, north-east coast and Gulf of Carpentaria regions (James et al. 2017). The viability of freshwater fish species will be impacted, causing ecosystem and social impacts (Koehn et al. 2011). Habitats sensitive to changes in water regimes will be affected by changes to the life history processes of amphibian, reptile and mammal species including migration habits and the flowering–fruiting regimes of various plant systems (Capon et al. 2013). Ecosystems are sensitive to weed invasions after extreme events such as floods or fire, and invasion of feral species such as the mosquito fish or common carp, which cope better with higher temperatures and can out-compete native fish. Long-term reductions in rainfall combined with drought and bushfire events can lead to the destruction of key habitats, such as the destruction of the Tasmania World Heritage area in the 2016 bushfires (Steffen et al. 2018b).

Cultural impacts

Indigenous water rights are at significant risk due to climate change and will compound existing problems. Many Indigenous communities rely on natural flows to maintain the health of waterways and surrounding ecosystems (Australian Human Rights Commission 2009). Declining river system quality affects water sites that hold deep cultural significance and are sources of food and medicine. Climate-related water impacts will also compromise Indigenous opportunities for economic development and empowerment. For example, in the Torres Strait, reduced freshwater availability compromises opportunities for Islanders to enjoy basic human rights (Green et al. 2010b, 2010a). In the Murray-Darling region, home to 40 autonomous Indigenous nations, a lack of flow has already severely impacted food sources and caused significant damage to spiritual sites.

Economic impacts

The total revenue from the sale of water services in Australia during 2016–17 was $17.8 billion (ABS 2019). Economic impacts on various land uses will be significant. For example, in the Murray–Darling Basin, while impacts will be variable, wheat yields will decrease by 2070 due to drying and warming of up to 3°C but with substantial variation by location and soil type (Wang et al. 2011). A combination of climate change impacts has already reduced national farm profits by 22% at only 1°C above pre-industrial global temperatures. That has been most pronounced in cropping with a profit reduction of about 35%—a national level economic impact of 8% or $1.1 billion per year (ABARES 2019; Hughes et al. 2019).

Social impacts

In rural communities, drought-related stress caused by sustained negative economic effects will exacerbate and increase psychological stress leading to mental health issues, increased levels of suicide and financial hardship (Austin et al. 2018). Drought stress will also have differential impacts related to gender (Alston 2014). Impacts on human health will include an increased risk of water-borne diseases like dengue fever and Ross River virus resulting from climate-related flood events (Cann et al. 2013).

Adaptations

A range of technical, practical and policy adaptations could help respond to water climate issues. Deficit irrigation could be used to increase the efficiency of water use and reduce fruit size, and conserve soil moisture through weed control for horticulture. New irrigation and water storage infrastructure could be built, including desalination plants. Water allocations could be restructured and various water trading markets instituted. Installation of water tanks in cities can assist rainfall capture.

9. AUSTRALIAN CITIES AND TOWNS IN A HOT FUTURE

Most Australians live in towns and cities and will experience climate change from an urban environment perspective. The greatest risks to urban populations are likely to come from increasing temperatures: we expect more frequent, longer and more intense heatwaves in the future (Figure 4; Table 4; Trancoso et al. 2020). Increasing periods of extreme heat will likely increase human mortality and morbidity, especially among vulnerable members of the population: the socio-economically disadvantaged, outdoor workers, those with pre-existing medical conditions, infants and the elderly (Cowan et al. 2014; Toloo et al. 2015). There will be subsequent impacts for social and health services: for example, emergency departments may struggle to cope with large influxes of people experiencing heat stress (Sun et al. 2019). Power outages may occur as electricity supply companies struggle to meet demands for air conditioning during increasing stress events.

Changes in rainfall will also have serious implications for Australia's cities. Urban areas are characterised by hard, often impermeable, surfaces: concrete, tarmac and packed soil. During heavy rainstorms, runoff is high with potential for flooding. If rainfall becomes more intense as a result of global warming, floods will be more common and more severe in terms of the area affected, speed of onset and depth (Schreider et al. 2000). Conversely, drought impacts will be exacerbated by climate change, including water shortages and rationing, as well as structural impacts such as damage to building foundations when clay soils dry out and crack.

Higher temperatures and lower rainfall increase the risk of bushfires. The outer suburbs of cities and large towns will be at increasing risk as temperatures rise (Buxton et al. 2011). Estimates of future climate change show a clear trend towards more dangerous fire weather conditions for Australia (Jyoteeshkumar Reddy et al. 2021), as well as increased pyroconvection risk factors for some regions of southern Australia. Pyroconvection has the potential to accelerate the severity of bushfires by generating high windspeeds, rapid ember dispersal and lightning strikes (Dowdy et al. 2019b).

Table 4. Average number of days per year with maximum temperature above 35°C

	1981–2010	2090 RCP2.6 (~1.5°C)	2090 RCP8.5 (~3°C)
Sydney	3.1	4.5 (3.9 to 5.8)	11 (8.2 to 15)
Melbourne	11	14 (12 to 17)	24 (19 to 32)
Perth	28	37 (33 to 42)	63 (50 to 72)
Brisbane	12	27 (21 to 42)	55 (37 to 80)
Darwin	11	111 (54 to 211)	265 (180 to 322)

RCP2.6 corresponds to around 1.5°C warming over Australia and RCP8.5 corresponds to 3°C warming over Australia (Watterson et al. 2015). Figures in brackets are the 10th and 90th percentiles.

It is interesting to note that the estimates in Table 4, calculated in 2015, have already underestimated the rates of change in southern Australian cities. Days greater than 35°C for Perth have already occurred more than 36 times over the last ten years 2010–2019 for the current 1.1°C of global warming (Karoly D., personal communication).

9.1. Australia's coastal living: vulnerability to changing sea level

Many of Australia's cities and towns are highly vulnerable to sea level rise, which increases the risk of inundation and coastal erosion. Between 160,000 and 250,000 properties are estimated to be at risk of coastal flooding with a sea level rise of 1 m by the end of this century.

Global average sea level has risen by more than 20 cm since the 19th century at an accelerating rate (Church et al. 2013a; Church and White 2006; see also Section 2). The changes that have taken place in Australia are similar to global changes and have resulted in an increase in the frequency of high sea level by about a factor of three between the first and second halves of the 20th century (Church et al. 2006).

Sea level will continue to rise for the foreseeable future. Estimates for the Australian coastline suggest that the rate of future sea level rise will reach close to 12 mm per year by 2100 for RCP8.5 and 6 mm per year for RCP4.5 (McInnes et al. 2015). Some estimates of future sea level rise for Australian locations under three different climate scenarios are shown in Table 5.

More than 85% of Australia's population lives along the coast, with the majority being in the coastal capital cities. As sea level rises, the risk of coastal flooding during high tides and surges (usually associated with windstorms such as cyclones) increases. It has been estimated that more than $226 billion in commercial, industrial, road, rail and residential assets are potentially at risk of inundation from a 1.1 m sea level rise by 2100 (DCC 2009; DCCEE 2011; Steffen et al. 2014). Some low-lying areas of high population density are at particular high risk. South-east Queensland, without adaptation, is exposed to damages of around $1.1 billion to residential buildings due to risks associated with 1-in-100-year coastal flooding events. A similar flooding event with a 0.2 m rise in sea level would increase the damages to around $2 billion, and with a 0.5 m rise to $3.9 billion (Steffen et al. 2014). The impact of sea level rise is not confined to the open coast. For 1 m sea level rise, the number of properties along New South Wales estuaries impacted by a 1-in-100-year storm surge would triple to 74,700 (compared to 24,300 for current sea levels).

It has been estimated that more than $226 billion in commercial, industrial, road, rail and residential assets are potentially at risk of inundation from a 1.1 m sea level rise by 2100

Rising sea level poses severe risks to coastal and estuarine ecosystems (Hanslow et al. 2018). A phenomenon known as 'coastal squeeze' can lead to coastal ecosystems such as mangroves and sea grass beds moving inland as sea level rises, coming up against human infrastructure and leading to their local elimination (Mills et al. 2016). However, this can be mitigated by taking into account these future shifts in coastal ecosystems in the design of coastal solutions. Saline waters will mix with groundwater and further upstream in estuaries, affecting salt-sensitive plants and animals. Corals may be unable to grow quickly enough where sea level is rising rapidly and where their physiology is compromised by ocean warming and acidification as well as local stresses such as pollution (Dove et al. 2013; Steffen et al. 2014).

Strategies to manage sea level rise in coastal areas fall into four categories:

- **Avoid:** identify future no-build areas and use planning regulations to prevent new development in areas of high risk now and in the future
- **Accommodate:** continue to use the land but accommodate change, such as by raising roadbeds, building on piles or relocating essential infrastructure
- **Protect:** use hard structures such as sea walls, or soft solutions such as dunes and vegetation (or some mixture of the two), to protect the integrity of coastal land. Note that hard structures raise environmental concerns and are likely to be cost-effective only in areas of very high land value or population density, and prohibitively expensive in the long term
- **Retreat:** withdraw or abandon assets at risk; allow ecosystems to retreat inland.

Land managers in Australia such as coastal councils now take sea level rise into account in their decision-making about land use in the immediate coastal zone. The decision as to which strategy, or mix of strategies, to employ is complex and should consider costs and benefits, conflicting interests, threatened ecosystems, and the long-term inevitability of sea level rise. Under high levels of warming and sea level rise, retreat is likely to be the only feasible long-term strategy (Grace and Thompson 2020). Disputes between local government, residents and developers are common (Cradduck et al. 2020). Despite these difficulties, it is essential that decision-making for coastal land use in Australia takes account of plausible long-term scenarios of sea level rise and of the vital roles played by ecosystems and their services.

Table 5. Future sea level rise in Australia

Stations	Scenarios	2050		2090	
		Sea level rise (m)	Allowance (m)	Sea level rise (m)	Allowance (m)
Darwin	RCP2.6 (~1.5°C)	0.21 (0.13–0.28)	0.21	0.38 (0.22–0.55)	0.43
	RCP4.5 (>2°C)	0.22 (0.14–0.30)	0.23	0.46 (0.29–0.65)	0.52
	RCP8.5 (>3°C)	0.25 (0.17–0.33)	0.26	0.62 (0.41–0.85)	0.71
Port Hedland	RCP2.6	0.20 (0.13–0.28)	0.21	0.38 (0.22–0.55)	0.43
	RCP4.5	0.22 (0.14–0.30)	0.23	0.46 (0.28–0.64)	0.52
	RCP8.5	0.24 (0.16–0.33)	0.26	0.61 (0.40–0.84)	0.70
Fremantle	RCP2.6	0.21 (0.13–0.29)	0.22	0.39 (0.22–0.56)	0.47
	RCP4.5	0.22 (0.14–0.30)	0.24	0.46 (0.28–0.65)	0.56
	RCP8.5	0.24 (0.16–0.33)	0.26	0.61 (0.39–0.84)	0.76
Port Adelaide	RCP2.6	0.21 (0.13–0.29)	0.24	0.39 (0.23–0.55)	0.50
	RCP4.5	0.22 (0.14–0.30)	0.25	0.46 (0.29–0.63)	0.59
	RCP8.5	0.25 (0.16–0.33)	0.28	0.61 (0.40–0.84)	0.81
Sydney	RCP2.6	0.22 (0.14–0.29)	0.24	0.38 (0.22–0.54)	0.48
	RCP4.5	0.24 (0.16–0.31)	0.26	0.47 (0.30–0.65)	0.59
	RCP8.5	0.27 (0.19–0.36)	0.30	0.66 (0.45–0.88)	0.84
Mackay	RCP2.6	0.21 (0.14–0.29)	0.22	0.38 (0.22–0.55)	0.43
	RCP4.5	0.23 (0.16–0.31)	0.24	0.47 (0.30–0.64)	0.53
	RCP8.5	0.26 (0.18–0.35)	0.28	0.64 (0.44–0.87)	0.73

Shown are median values and the 5–95% model range of projected regional sea level rise and 'allowances' for 2050 and 2090 relative to 1986 to 2005 under RCP emission scenarios 2.6 (~1.5°C), 4.5 and 8.5 (~3°C) for selected locations along the Australian coastline (full list in Table 1 of McInnes et al. 2015). 'Allowances' are for future periods (2050 and 2090) and represent the vertical distance that an asset needs to be raised in the case of rising sea level so that the present likelihood of flooding does not increase. The 5–95% model range, with the lower value (where 5% of projections are lower) and the upper value (where 95% of projections are lower), corresponds to the likely range of global mean sea level rise.

9.2. Water for Australian cities and towns in a changing climate

Water for many towns and cities across southern Australia is already in short supply and water availability faces increasing challenges in the coming years as global temperature rises. Many locations in Australia at global warming of 3°C would be very difficult to inhabit due to projected water shortages.

The climatic aspects of water security depend not only on rainfall, but also on temperature and evaporation: even if the amount of rainfall stays the same, water availability will decline because of greater potential evaporation and increasing atmospheric dryness (Pokhrel et al 2021, Yuan et al. 2019). Other climatic effects such as hotter temperatures, bushfires and flood events can affect water quality through risks of bacterial and blue-green algal outbreaks (Carolyn 2012).

Australian rainfall is highly variable and strongly influenced by weather patterns such as El Niño and La Niña events plus other long-term drivers of climate (e.g. Indian Ocean Dipole, Pacific Decadal Oscillation). Australia has a history of severe rainfall events (intense rainfall leading to catastrophic floods) and long droughts, with devastating impacts on livelihoods and the natural environment. In addition to this variability, there is evidence of long-term trends in rainfall in recent decades: a drying trend across south-western and south-eastern Australia during April to October and wetter conditions throughout the year across Northern Australia (CSIRO & BOM 2020). A higher proportion of total annual rainfall has come from heavy rain days (CSIRO & BOM 2020). Since the mid-20th century, the severity of droughts such as the Millennium Drought has also been increased by climate change (Steffen et al. 2018c; see also 'Climate change and water in Australia', p.51).

Federal and state governments are already taking steps to manage the decline in water security that has emerged in recent years. On the supply side, many regions have installed desalination plants to augment the domestic piped water supply. On the demand side, consumers are encouraged to reduce their piped water use through, for example, installation of tanks to collect rooftop water and the introduction of drought-tolerant gardens.

Long-term trends in water availability are less certain although the decline in cool season rainfall is likely to continue across southern Australia, with more years spent in drought than not (Steffen et al. 2018c), and with increased intensity of episodic rainfall events (CSIRO & BOM 2020). Water security is expected to decline further with less water for agriculture, urban water supply, and ecosystems, while the risk of short-term extreme flooding may increase.

Australia is experiencing these water challenges at 1°C of global warming. 3°C warming by 2100 could result in severe water security challenges with far-reaching impacts on land, urban, energy and industrial systems (Steffen et al. 2018c).

9.3. Climate change and Australia's energy security

The energy security of many cities and towns is at risk from climate change. Power stations and transmission lines are affected by extreme heat conditions and storm events, and may fail as a result. These events can put strain on energy systems and drive up peak demand (Emodi et al. 2018). Some recent failures include severe storms in September 2016, which knocked down 22 transmission towers in South Australia, and heatwaves in January 2019, which led to blackouts in South Australia and Victoria. These types of stresses and impacts will increase as Australia becomes hotter and drier.

Australia's electricity generation is particularly vulnerable because it is dominated by ageing, inflexible and polluting coal-fired power stations. Within a decade, half of Australia's coal-fired power stations in the National Electricity Market will be over 40 years old (CCA 2014; Finkel 2017). These power stations are technically already obsolete and are increasingly unreliable. Recent reports by the Australian Energy Market Operator (AEMO) have highlighted the risk posed by ageing fossil fuel power stations to Australia's energy supply, particularly during extended heatwaves (AEMO 2017).

Australia's electricity generation is particularly vulnerable because it is dominated by ageing, inflexible and polluting coal-fired power stations

Demand rises during extreme heat as people turn to air conditioning. Variations in heating and cooling demand, as well as global temperatures that exceed 3°C warming above the pre-industrial period, are projected to increase energy demand by 135% in Darwin, 213% in Alice Springs and 350% in Sydney, while Hobart and Melbourne are projected to have a decline in energy demand of 48% and 14% respectively, compared to the base year of 1990 (Wang et al. 2010). With projected increases in the frequency of heatwaves across Australia, rapid responses to power disruption in the future will be vital to reduce the indirect effect of extreme heat on electricity consumers (Weller 2018). Projections by AEMO reveal that consumption of grid-supplied electricity will remain relatively flat over the next 20 years but increase beyond that time (AEMO 2020a, 2017; Chang et al. 2020). Considering only climate-related causes, electricity demand is likely to increase across Australia and outstrip supply by the end of the century under severe climate scenarios (Ahmed et al. 2018; Emodi et al. 2019a) due to more prolonged and intense heat, which will increase peak demand and reduce power generation efficiency.

Energy consumers also face an uncertain future under rapid climate change, partly due to rising costs as power companies and retailers pass the increased cost of electricity to consumers (Richardson 2019). Renewable energy technologies already play a role in reducing energy costs for consumers and CO_2 emissions from thermal power plants. However, renewables such as hydropower and wind energy are themselves vulnerable to climate change impacts (Emodi et al. 2019b). For example, south-eastern Australia is expected to be drier with higher evaporation and reduced rainfall (Table 2), and this is projected to reduce electricity generation from existing hydropower by 18% under RCP8.5 by 2100 (Van Vliet et al. 2016). Extreme wind speeds can cause damage to wind turbines (Chen et al. 2016; Rose et al. 2013) or interrupt power generation when turbines shut down at high wind speeds to avoid damage (Sohoni et al. 2016). Oil and gas industries are also vulnerable to climate change as a result of intense cyclones, extreme rain, floods, bushfires and extreme temperatures that can cause delays in operations, damage to infrastructure, increased cost of distribution to meet higher construction standards and risks of pipeline leaks and explosions (Smith 2016).

Climate change poses a significant risk to the energy sector and its impact is expected to be greater in the future (Gerlak et al. 2018). Therefore, there is a need to identify policy options that involve exploration of new energy sources such as 'green' hydrogen (generated without fossil fuels) to increase energy diversification, demand-side management, battery storage systems to reduce intermittency, improved power system reliability and resilience using smart grid systems. The rapid reduction in GHG emissions and energy system transition remains the most viable solution to mitigate GHG emissions and adapt to a changing climate (Gielen et al. 2019). This will have an indirect effect on the economy through the provision of green jobs and the environment through GHG emission reduction.

9.4. Impacts on the mining and export sector

The mining sector is a vital part of Australia's economy, with mineral exports worth $248 billion in 2018–19 (Tunnicliffe 2019) and was projected to reach $282 billion in 2019–20 (Thurtell et al. 2019). Despite the economic importance, knowledge of climate change impacts on the mining sector is very limited (Mavrommatis et al. 2019). Mining operations are not immune to climate change as most Australian mining operations are exposed to extreme weather events, including elevated temperatures and heatwaves, sea level rise, cyclones, floods, erosion and landslides (Hodgkinson et al. 2010; Odell et al. 2018). These events are expected to cause disruption to mining operations through impacts such as drainage issues and reduction in worker productivity as a result of heat-related stress, illness and absenteeism (McTernan et al. 2016; Street et al. 2019).

Climatic events can also affect the transportation, processing and storage of mineral resources in ways that increase operating costs to mine operators, increase the risk of environmental pollution and reduce the rate of rehabilitation of old mine sites (Cahoon et al. 2016; GATF and OECD 2019; Metcalfe and Bui 2017). This presents the most significant impact climate change poses on the mining sector as obtaining approvals for mining projects and securing funds for mining activities become more difficult, leading to job losses and decline in government revenues (NSW 2018).

9.5. Vulnerability of Australian financial and insurance sectors

> Climate change is already affecting the Australian financial sector and a 3°C world would render many properties and businesses uninsurable.

Climate change poses a significant investment risk to businesses and the financial sector. Insurance firms are already facing substantially increased claims, many of which are partially or fully a result of climate-related impacts. One in every 19 property owners face the prospect of insurance premiums that will be effectively unaffordable by 2030, costing 1% or more of the property value per year (Steffen et al. 2019). However, increased claims can also arise from non-climate drivers such as expansion of dwellings and businesses into hazardous settings (such as flood plains) and increasing personal wealth (that is, people can afford insurance).

> One in every 19 property owners face the prospect of insurance premiums that will be effectively unaffordable by 2030

Properties and other financial assets located along coastal areas in Australia are at a 5% (2.8–13%) risk of river flooding per year under a RCP8.5 climate scenario, which includes average global surface temperatures of 3°C or more later this century (supplementary material, Arnell et al. 2019). This has encouraged investors to consider climate risk and bank directors and supervisors to legally disclose climate risk associated with financial transactions and opportunities (UNEP and Acclimatise 2018). Extreme weather events often lead to higher insurance costs, declining property values and difficulties in loan repayments. The property market is projected to lose $571 billion in value by 2030 due to climatic events and the losses will continue if emissions are not reduced (Steffen et al. 2019). For example, the Commonwealth Bank of Australia estimates that 0.01% of properties in their overall mortgage portfolio are classified as having high climate-related credit risk. If there are no changes to that portfolio and no mitigating actions taken by the year 2060, the proportion of high-risk properties may increase to 1%. Meanwhile, capital losses incurred by home loan customers due to climate-related impacts under a RCP8.5 scenario could increase by 27% by 2060 (CBA 2018).

Some Australians living in low-lying properties near rivers and coastlines are particularly at risk, with flood risks increasing progressively and risks of coastal inundation emerging as a major threat around 2050 (Steffen et al. 2019). Homes and infrastructure in the urban–bushland interface also face increased bushfire risk and associated increases in insurance costs (see case study, p.34). Mid-to-end century projections for properties located in flood plains and storm surge zones in south-east Queensland show a 33% increase in tropical cyclone risk under a 3°C global warming scenario (Bruyère et al. 2019; IAG 2019). The costs of these claims will be reflected in increasing premiums over time. In response, Australian homeowners in high risk areas may reduce house and content insurance due to higher financial cost while renters may insure fewer household items (Booth and Tranter 2018; Osbaldison et al. 2019). If warming exceeds 3°C, it is likely that many properties may become effectively uninsurable because of their exposure to climate-related risks.

Many future events associated with climate change are not covered by commercial insurance, including coastal inundation and erosion (Steffen et al. 2019). Insurance companies may also respond by divesting from, and refusing to insure, unsustainable commercial and industrial activities. As evidence of damage becomes clearer, it is possible that insurers covering damage claims will seek to recover damage costs from polluters through 'subrogation' actions (substituting one for another). This would in turn create risk for investors, lenders and insurers associated with polluting projects. The unsustainability of current levels of fossil fuel-based fuel use, along with the future prospect of liability, has already created major difficulties for banks and other financial institutions.

9.6. Urban living in a 3°C world

> Close to 90% of the Australian population lives in urban areas. The impacts of climate change will be felt by most people within urban environments, and it is from those environments that solutions are likely to emerge.

Multiple lines of evidence strongly suggest that the impacts on Australia's urban environments under a trajectory towards 3°C of global warming will be extreme. Broadscale adaptation will be essential and can be expected to drive fundamental changes in how we live in cities and how urban areas function. National policy will be required based on comprehensive nationwide engagement and consultation (Tàbara et al. 2018). The Australian community has shown itself able to rise to the challenge. For example, from being relatively slow to adopt renewables, Australia has become a world leader in the installation of photovoltaic (PV) systems, particularly rooftop solar energy systems. From a 2009 baseline of around 66 MW, installed PV capacity in Australia increased 10-fold by 2011, quadrupled between 2011 and 2016, and tripled between 2016 and 2019, reaching a total of 16,089 MW in December 2019 (APVI 2019).

> Incorporating plants such as street trees can greatly reduce urban temperatures, as will green roof plantings that reduce glare, create shadows and have a strong cooling effect

The bushfire season will continue to lengthen and extreme fire days will be far more common (Clarke et al. 2016), with the risk that fires will penetrate more deeply into our cities, as demonstrated by the devastating 2019–20 fire season (Gergis and Cary 2020). The trade-offs between safety and amenity are likely to be debated, although the unprecedented events of the 2019–20 summer demonstrated how rapidly the levels of risk are increasing. Penalties for starting fires will increase, as will expenditure on firefighting personnel and equipment. Over time, perception of bushfire risk may lead to a move away from low density outer suburbs and small regional and remote towns, with the population becoming more concentrated in large, dense urban environments.

Water resource management strategies in areas of reduced supply require integrated demand-side approaches, combining measures such as metering, variable pricing, restrictions on garden watering, leakage reduction, and recycling (Wu et al. 2017). Flood reduction measures include installation of more permeable surfaces and stormwater drainage systems. However, some water management strategies may be outside the control of cities, such as where upstream flood mitigation works are required, and will require careful and possibly lengthy negotiations.

Urban planners can do much to improve urban climates, with designs that consider how to use passive cooling via shade and air movement, and the ability of a material to absorb and store heat energy, known as thermal mass (Norton et al. 2015). Incorporating plants such as street trees can greatly reduce urban temperatures, as will green roof plantings that reduce glare, create shadows and have a strong cooling effect. Unfortunately these strategies can also have a high water requirement and be hostile environments for plant growth because of shallow substrate depths, high temperatures and wind exposure (Raimondo et al. 2015). Appropriate selection of materials (waterproof and anti-root membrane, protection, filter, drainage layers, substrate and vegetation) based on geographical locations can improve performance of green roofs in damping extremes (Cascone 2019). Despite all these approaches, it is likely that many activities will move to, or be further concentrated in, indoor air-conditioned environments. The requirement to shift to low GHG emission electricity generation becomes critical if strategies to adapt to climate change impacts are not to add to the burden of atmospheric greenhouse gases (Magnan et al. 2016).

10. HEALTH AND WELLBEING IN A HOTTER AND MORE DANGEROUS WORLD

Rapid human-driven changes to Earth's climate are already undermining the health and safety of people and their enterprises. Due to the long life of CO_2 in the atmosphere, none of these threats can be stabilised until mid-century, which emphasises the need for understanding and limiting the impacts of climate change as much as possible. Failure to reduce global warming to well below 2°C has very serious consequences for the health and wellbeing of Australians.

The increasing frequency and intensity of extreme weather events such as heatwaves, cyclones, droughts, bushfires and floods are already having direct impacts on human health and wellbeing, livelihoods and communities (Table 3). For example, direct health effects of extreme heat include heat stroke and the exacerbation of pre-existing conditions such as heart and kidney disease. Indirect health impacts include, for example, the mental and psychological repercussions arising from loss of livelihoods due to a flood event (Beggs et al. 2019; Berry et al. 2010; McMichael 2015). Importantly, these health effects will not be felt equally, with those at higher risk including the young, the elderly, those with pre-existing or chronic illnesses, and those from lower socio-economic backgrounds (Bindoff et al. 2019; IPCC 2018, 2014b).

Climate change can also affect health by changing the severity, frequency and distribution of climate-sensitive infectious diseases, such as malaria, dengue fever and Ross River virus. As extreme heat events become more intense and frequent due to climate change, the risk of adverse human health impacts grows. In addition, health and emergency services are under ever greater demand (AAS 2015) and will continue to be increasingly exposed to extreme weather events due to their key roles in emergency management and response.

10.1. Impacts of climate warming on human health so far

Climate change is already having serious impacts and risks for people across Australia, and many of these health risks would become much worse as global temperatures exceed 1.5°C and approach the temperatures that are the result of current policy (i.e. 3°C). Health impacts of climate change in Australia include an increase in mortality and morbidity arising from extreme weather events including heatwaves, bushfires, floods, droughts and storms. Climate-sensitive infectious diseases are also projected to change their distribution and transmission risk as the climate changes. Many health impacts will be indirect, arising via other more complex pathways such as the water and agriculture sectors. Health impacts will encompass both physical and mental aspects, so it is important to assess and respond to risks and impacts in an integrated manner.

Heat stress

If global mean surface temperature exceeds 3°C above the pre-industrial period, the Australasian region is projected to experience more frequent and more intense heatwaves. The likelihood of a major heatwave occurring in any given year will rise to about 78.6% (64.5–91.1%), up from the 1.7% chance recorded in 2010 (supplementary material, Arnell et al. 2019). For Queensland, recent modelling reveals hotter, longer and more frequent heatwaves, ranging from events lasting 7.5 days occurring 3 times a year at warming of less than 1.5°C, to events that last 16 days and occur 7 times a year at warming of 3°C (Trancoso et al. 2020). Heat-related health impacts are more severe in urban areas (Fagliano and Diez Roux 2018) due to the urban heat island effect (Maheng et al. 2019). The increasing frequency and intensity of heatwaves will also adversely affect the productivity of outdoor workers and others working in non-airconditioned environments (Perčič et al. 2018; Zander et al. 2015; Zhang et al. 2018).

Of increasing concern is Australia's ageing population, with 23–25% of Australians being older than 65 by 2056. This age group is vulnerable to heat stress and the increasing frequency of extreme heat events places this group at greater risk of temperature-related morbidity and mortality (Schneider and Breitner 2016). Other vulnerable groups include very young people, Indigenous groups, those who work outdoors, people with pre-existing or chronic medical conditions, people living with a disability, breastfeeding women, socio-economically disadvantaged, and socially isolated groups (AAS 2015). Often these groups are exposed to heat stress due to economic challenges and limited access to culturally and linguistically diverse information.

Bushfires

> **Bushfire-related health impacts are increasing, including direct loss of life and exacerbation of pre-existing conditions such as lung and heart disease due to air pollution from prolonged and more severe fire seasons. Around 429 people died from smoke and respiratory problems due to the catastrophic 2019–20 fires.**

A large proportion of the Australian population is at risk from the health impacts of bushfires which can cause health complications and mortalities (Johnston 2009). Poor air quality caused by bushfire smoke, as seen in the extraordinary fires of the 2019–20 summer, are associated with an increase in ambulance callouts and emergency hospital admissions (see case study, p.34; also Haikerwal et al. 2015; Martin et al. 2013; Morgan et al. 2010). An increase in the frequency and intensity of bushfires will have immediate impacts on people with respiratory conditions, and delayed impacts on people with heart conditions (Edwards et al. 2018; McMichael 2015; Salimi et al. 2017).

The fire conditions of 2019–20 that were classified as 'Catastrophic' for the first time in New South Wales and the equivalent 'Code Red' in Victoria emphasised the highly concerning and changing nature of fire and associated weather conditions (see case study, p.34). The increasing frequency and intensity of bushfires and dust storms will heighten particulate matter levels (Dean and Green 2018) and exacerbate pre-existing lung and heart diseases in vulnerable groups (Liu et al. 2015; Morgan et al. 2010). With severe fire weather conditions projected to rapidly increase, the capacity of firefighting agencies to contain bushfires and prevent fire-related increases in human mortality rates will be stretched. The increasing length and severity of fire seasons will place additional professional burdens on emergency services staff (fire, ambulance, traffic services), with potential occupational health and safety implications. In addition to physical health impacts, the trauma and stress of experiencing a bushfire can increase depression, anxiety and other mental health issues after the traumatic event (Sim 2002; Whittaker et al. 2012).

10.2. Risks to health from reduced access to food and water

Threats to food and water security have a broad range of health impacts, including those associated with declining economic livelihoods and social cohesion. Decreasing water availability over the past 50 years in south-eastern and south-western regions of Australia is exemplified by decreasing total rainfall (see Section 6; Table 2). If these trends continue as global warming increases beyond 1.5°C as projected, many communities will have pushed into what would have been considered 'last resort' options only a few decades ago, such as access to water supplies from desalination and water being transported into areas of low supply. This is likely to impact local economies due to increased operating expenses and may trigger the movement of people to areas where water is more abundant. At higher temperatures (beyond 1.5°C), fire seasons become longer and more intense; when combined with increases in the severity of drought conditions, this would lead to displacement of people from many parts of rural Australia due to decreasing water availability, health risks, declining agricultural productivity and negative impacts on rural incomes (Kiem and Austin 2013).

10.3. Impacts of infectious disease and global temperature

There is substantial evidence that many climate-sensitive infectious diseases are likely to shift their geographic range, seasonality and intensity of transmission in response to the changing weather patterns associated with climate change, with risks being greater in a warmer world (Cann et al. 2013; Ebi et al. 2018). Changes in rainfall in Australia will affect the distribution of infectious diseases. Ross River virus (RRV) is the most common vector-borne disease in Australia and the Pacific Islands (Yu et al. 2014). While there are a range of vectors carrying RRV, changes in temperatures have an impact on its transmission rate into sites at higher latitude. RRV is expected to spread to temperate areas across Australia (Shocket et al. 2018), with projections indicating an increase of 45% in RRV cases in Hobart by 2079 (Herold et al. 2018). This implies that climate warming will likely extend the distribution of vectors. Further, the adaptability of *Aedes* mosquitoes to a changing climate might result in an underestimation of transmission risk and amplify its impact across Australia. Other climate-sensitive infectious diseases include vector-borne diseases such as dengue fever, chikungunya, Zika, West Nile virus and Lyme disease (Ebi et al. 2018).

10.4. Impacts and risks on mental health and wellbeing of Australians

Research is increasing the understanding of individual and community mental health impacts of a changing climate. These impacts arise from acute stressors, such as bushfires, cyclones and floods, as well as chronic stressors, such as drought and long-term drying. Mental health impacts include post-traumatic stress disorder (PTSD), generalised anxiety, and at the extreme scale, suicide. Particular attention should be paid to heatwaves: in warmer states and territories, higher mean annual maximum temperatures predict elevated suicide rates (Zhang et al. 2018). Further, droughts are associated with increased distress among farmers, especially young rural farmers facing financial challenges (Austin et al. 2018). Given that heatwaves and droughts are projected to intensify under changing climatic conditions, it is important to recognise and respond to mental health challenges.

Adapting to climate impacts on health: a national imperative

There is no national climate change and human health adaptation plan for Australia. Queensland is the only state with a comprehensive standalone health adaptation plan. Victoria has included climate change as one of its top priorities in its recently-released health strategic plan, Tasmania is developing an adaptation plan and Western Australia recently held an inquiry into the impacts of climate change on health (Weeramanthri et al. 2020). Adaptation options to consider are provided below.

Early warning systems for heatwaves, floods and other extreme weather events

Effective early warning systems alert individuals and communities of upcoming emergency events, with sufficient time to plan and respond to the specific threat. Many states have early warning systems for heatwaves; however, these are implemented at the local government level by necessity and support is often needed to ensure that the policies can be appropriately rolled out.

Audit of climate-resilient health infrastructure

Tertiary hospitals, primary health care facilities and rural and remote health services should be assessed for their climate resilience in the face of changing climate hazards and should be re-designed if necessary. For example, infrastructure that is situated on low-lying coastal areas may be vulnerable to storm surges and long-term sea level rise.

Supporting nature-based solutions

Nature-based solutions, including green and blue spaces, help to protect the natural environment by acting as carbon sinks. They also have many other benefits, including providing shade and cooling, promoting physical and mental health, and enabling greater social connection. Re-establishing mangroves and other coastal ecosystems for defending coastlines can provide multiple co-benefits such as improving fisheries habitats and reducing coastal erosion. Supporting nature-based solutions, particularly in built-up urban areas, has the potential to be a strong and effective approach to reduce health impacts of climate change.

Clean and green hospitals and healthcare facilities

There is an opportunity for the health sector to lead a rapid reduction in the GHG emissions associated with its services, beginning with an assessment of where the largest energy emissions originate. Importantly, the economic gains from reducing energy consumption, shifting to renewable energy provision and minimising waste have the potential to be significant and are a vital reason to act quickly.

Strengthening social networks in rural communities

Strengthening social networks in rural communities can improve and mitigate the distress experienced by local farmers. With prolonged drought projected across southern Australia, maintaining social connections in rural communities can be an effective strategy to reduce the higher risks of mental health impacts and suicide.

11. THE WAY FORWARD: STAYING WELL BELOW 2°C AND AVOIDING 3°C

A global transformation is needed to rapidly reduce global GHG emissions and limit warming to well below 2°C as envisaged under the Paris Agreement. Depending on the trajectory that global emissions take over time and the extent of warming targeted, global emissions will need to decrease to at least net zero (and lower in some scenarios) by the middle of the century (IPCC 2018).

To achieve net zero emissions globally, developed countries will need to achieve net zero earlier than developing and industrialising countries that are still building up their infrastructure and that have fewer resources to contribute towards the transition to low-GHG emissions in the short term. A commensurate contribution by Australia to a strong global climate change response implies the rapid removal of GHG emissions from Australia's economy.

Transforming to a global energy supply that is based on a low-GHG emissions mix is a first-order priority that will require substantial investments in additional energy supply infrastructure (IPCC 2018; Lane et al. 2016). In addition to removing GHG emissions from the energy sector, Australia should transform its transport, agricultural and waste systems as well as its built environment in a similar way and lay the groundwork for massive drawdown of previously emitted GHG emissions (Alfredsson et al. 2018; IPCC 2014a). Ready access to the necessary raw materials, engineering skills, design capability, capital, enabling supply chains and stable policy and regulatory settings will also be needed, along with an extent of 'cultural change' that reduces preferences for lifestyles that are materially and energy intensive (Alfredsson et al. 2018; Cohen et al. 2017). No single step will be sufficient if taken in isolation from the others.

Transforming to a global energy supply that is based on a low-GHG emissions mix is a first-order priority

> **While the challenge is enormous, the science underpinning the urgent need to deeply reduce GHG emissions is clear, with evidence demonstrating that it costs much less to reduce the emissions of the global economy than it costs to adapt to the impacts of unrestrained global warming, with the benefit-cost ratio increasing with additional global warming (Garnaut 2014, 2011; Hoegh-Guldberg et al. 2019; Kompas 2018; Stern 2007; Tesk 2019). Reducing emissions is possible without compromising future economic growth, in Australia or globally (Denis et al. 2014; Jacobson et al. 2017; Rockström et al. 2017).**

11.1. Deep and rapid cuts in greenhouse gas emissions are possible and necessary

The principles for reducing GHG emissions apply universally in all economies. The application of those principles will differ strongly between countries depending on circumstances, opportunities and preferences (Bataille et al. 2016). A useful characterisation of the pillars for the rapid removal of GHG emissions is as follows:

- remove GHG emissions from electricity generation and distribution
- electrify the transport sector
- increase energy efficiency and reduce emissions from industrial activities and buildings
- reduce non-energy related GHG emissions from industrial processes and agriculture
- implement negative emissions options, through biosequestration and technological means
- stop deforestation and land degradation, and accelerate revegetation of cleared and degraded land
- shift energy export industries to zero emissions as a matter of urgency and produce energy-intensive products using renewable energy.

Earlier analyses have shown that a net zero emissions outcome by 2050 is possible for Australia without compromising economic prosperity (Denis et al. 2014). This would be achieved principally through renewable electricity, electrification, emissions reductions in industry and agriculture, and large-scale afforestation to compensate for remaining emissions.

Remove GHG emissions from the electricity supply

An electricity supply with zero emissions is at the heart of any strategy for reducing GHG emissions across the economy (Sachs et al. 2016). Emissions-free electricity can be achieved through different electricity supply technologies that do not rely on fossil fuels.

Wind and solar continue to be the cheapest sources of new electricity generation in Australia, even when the cost of storage and new transmission network infrastructure is taken into account (CSIRO 2019). Globally, investment in new coal power stations has reduced dramatically (IEA 2020a). No new coal-fired power plants are currently under construction, or proposed, anywhere in North America or Western Europe. The last remaining major project in the European Union (Ostroleka C in Poland) was cancelled in July 2020 (Proctor 2020). Investment in new gas-fired power stations is also declining, particularly in countries with high gas prices (IEA 2020b), as is the case for Australia. Given the highly restricted GHG emissions budget that Australia and the world should adhere to, exploration and development of new gas fields is not recommended.

Existing gas supplies will have a diminishing role in Australia's electricity supply, including balancing the typically variable output from wind and solar power (as is currently the case especially in South Australia). However, the longer-term solution to intermittency is energy storage, with gas likely to play a decreasing role, thereby enabling deeper cuts in the GHG emissions associated with the electricity supply. For example, the Australian Energy Market Operator's Integrated System Plan sets out a range of scenarios for the future of Australia's national electricity market. Under its 'central' scenario, additional energy storage capacity is estimated to be twice as high as additional gas generation capacity by 2040, and six times greater in its 'step change' scenario of a more rapid re-orientation transition of the grid towards renewables (AEMO 2020b). Any expansion of the gas production network would require longer-term infrastructure that has a high risk of becoming a stranded asset.

> Carbon capture and storage for coal-burning plants, once held as a possible solution for the continued operation of coal power stations under emission constraints, is no longer seen as a cost competitive option, at least not in locations where renewable energy is plentiful and relatively cheap as in Australia (Graham et al. 2018).

It follows that as existing coal-fired power plants close, they will be replaced by renewable energy generation. This has been the experience in Australia, with very high levels of deployment of wind and solar power in recent years. Scenarios by the Australian Energy Market Operator (AEMO 2020b) suggest that over half of Australia's remaining coal plants will close down during the 2020s and 2030s. In a 'step change' scenario, half of the remaining capacity would be closed by the early 2030s and three quarters by the end of the 2030s. The pace of transition from coal to renewables affects Australia's cumulative GHG emissions until 2030 and Australia's future contribution to climate change.

Achieving climate goals requires accelerated investment in renewables, storage technologies and transmission, rather than attempts to extend the life of existing coal plants. Incentives for accelerated investment have been a standard element of government policy in response to economic depression, reflecting the fact that accelerated investment generates more economic activity (including employment growth) than extending the life of existing equipment. The cost of accelerated phase-out of coal-fired power plants is the residual value of generation assets at the point of closure. The residual asset value will tend to decline as the share of renewable energy increases, which often means lower operating hours for remaining coal plants and lower market prices for electricity (Mills et al. 2020). Increasing supply from wind and solar installations in Australia has already resulted in lower electricity prices (AEMC 2019). Public investments in utility-scale renewable energy have been historically successful at attracting private financing. An extra $3 of private co-financing could be unlocked for every dollar of public funding (Alphabeta and Climate Council 2020).

Electrification of transport and stationary energy use

Fuel used for transport accounts for 19% of Australia's total annual GHG emissions, and fossil fuels burned in industry (and to a smaller extent in buildings) account for another 19% (DEE 2019). Fuel burned for electricity accounts for around one third, the remainder is mostly from agriculture, industrial processes and fugitive emissions including from gas production. Emissions from direct combustion of fossil fuels can be avoided by shifting to electricity as the energy carrier, and once electricity results in zero emissions, these sectors are then also subject to emissions reduction (Dennis et al. 2016).

Solutions to reducing the emissions of these sectors are varied. In the transport sector, battery-electric engines for cars and many larger vehicles represents the most likely route for reducing associated GHG emissions. On current estimates, lifetime costs of electric vehicles (EVs) are similar to those of conventional internal combustion engine vehicles and are likely to fall further. Large-scale adoption of EVs will require an expanded charging network and significant expansion of renewables-based electricity supply. An EV fleet also offers a large, conveniently decentralised energy storage capacity that can help balance electricity demand and supply on the grid.

An EV fleet … offers a large, conveniently decentralised energy storage capacity that can help balance electricity demand and supply on the grid

In industry, many uses of fossil fuels for energy, such as low-temperature heat or fossil fuel-based motive power, can be electrified. In the building sector, the use of natural gas for heating and cooking can be readily replaced with electricity, and large savings in total energy use can be achieved using electric heat pump technology (Madeddu et al. 2020).

Increase energy efficiency in all sectors

There are substantial opportunities to improve energy efficiency for most energy-using technologies, including transport, buildings, industrial processes and domestic goods. Policies promoting this goal have been pursued in many countries (including Australia) but there are still many opportunities for improvement (NABERS 2020). Policy debate around this issue has centred on the 'rebound' effect, that is, the suggestion that improvements in energy efficiency will be offset by an increase in energy-using activities. IPCC (2014c) addresses the rebound issue, saying: "the size of energy efficiency rebound is controversial, with some research papers suggesting little or no rebound and others concluding that it offsets most or all reductions from energy efficiency policies". The majority of studies yield estimates ranging from 0–60% rebound (Thomas and Azevedo 2013). It is important to keep in mind that a rebound effect means that increased energy efficiency is allowing people to meet needs that were previously unmet.

Industrial processes and agriculture

Industrial processes and agriculture are often referred to as 'hard to abate' sectors, as there is often no ready substitution option for emissions-free inputs or processes (Bataille 2020; Wollenberg et al. 2016). Greenhouse gases (including CO_2, methane, nitrous oxide and others) are emitted from agricultural activities such as livestock farming, cultivation of rice, and fertiliser use, while industrial emission sources include production of cement, chemicals, steel, fertiliser and other products (Butler et al. 2020). In some of these 'hard to abate' applications, solutions for reducing GHG emissions may include development of new technologies, substitution with other products, and incremental improvement to existing processes (Bataille et al. 2018). To achieve net zero GHG emissions, outside of technology innovations (such as use of seaweed to reduce ruminant emissions of methane; Roque et al 2019), remaining emissions will need to be compensated for through negative emissions.

Carbon sequestration and negative emissions

Negative emissions technologies include a variety of options to remove CO_2 from the atmosphere and store it. This can take the form of biological sequestration, for example through afforestation of unforested land, preservation of mangroves and seagrass (Hoegh-Guldberg et al. 2019), or changing vegetation to increase the carbon content in plants and soils. The potential for sequestering carbon in revegetation in Australia is substantial, with some estimates putting the total potential sequestration in the range of Australia's current total annual emissions by mid-century (CSIRO 2019).

There are also a variety of technological options for negative emissions (Fuss et al. 2018). These include technologies such as carbon capture and storage from combustion of bioenergy, enhanced weathering of CO_2-absorbing silicate minerals, and direct capture of CO_2 from the air in energy-intensive chemical processes to produce either liquid fuel alternatives or other high-value products. These are in varying states of technological readiness. Australia has the prerequisites for large-scale deployment of most or all of these technologies, on the basis of the available land mass and practically unlimited potential for renewable energy. Many of these opportunities require national leadership and large investment at scale if they are to develop as viable options for the near future.

11.2. Clean energy export industries

Australia has excellent prerequisites for very large-scale production of renewable energy to not only fulfil most or all of the domestic energy demand, but also power export industries (Garnaut 2020). Such industries are premised on production of energy intensive goods that, in a low emission world economy, will tend to be located in areas where emissions-free energy is plentiful and cheap, and where raw materials are on hand. International trade in emissions-neutral fuels and in emission-free electricity is also likely to develop.

> Australia has excellent prerequisites for very large-scale production of renewable energy

Australia is potentially well-positioned for renewable energy production and export based on its geography and resource endowment, including abundant solar radiation, high wind speeds, land availability, prior experience and reputation for large-scale resource projects, and a stable institutional and investment environment (Commonwealth of Australia 2019). In the medium term, establishment of a hydrogen industry may offer potential, given that some energy importing economies such as South Korea, Japan and Germany see their economies as likely future importers of hydrogen (COAG Energy Council 2019). Germany expects to be an importer specifically of hydrogen made through electrolysis using renewable electricity ('green hydrogen') and Australia is seen as a 'sleeping giant' for supply (Westphal et al. 2020).

The production and export of ammonia for fertiliser or energy is a related opportunity with lower costs of conversion and transport and a more ready market (Burdon et al. 2019). Longer-term, synthetic fuels including for aviation could be produced using hydrogen as an energy source (Rosa 2017).

For hydrogen and hydrogen-based products to be compatible with a shift to a net zero emissions world economy, the hydrogen needs to be produced through electrolysis using zero-emissions electricity ('green hydrogen').

The establishment of a 'green steel' industry, using renewable energy-generated hydrogen rather than coking coal for processing iron ore, is a potentially large long-term prospect for a renewable energy-based industry including in Australia (Gielen et al 2020, Wood et al 2020). Green steel production would likely involve the use of very large amounts of locally-produced green hydrogen.

There may also be opportunities to use renewable energy for export without the production of hydrogen, such as through a rejuvenation of Australia's aluminium smelting industry fuelled by renewable energy, or direct exports of electricity to countries in the Asia–Pacific region via high-voltage direct current (HVDC) cable connections.

The demand for 'new economy' resources (those required for the shift to net zero emissions) is projected to increase dramatically. This is especially so for metals such as aluminium, cobalt, copper, lead, lithium, nickel, manganese, steel, titanium, zinc, cadmium, molybdenum and rare earth elements (Arrobas et al. 2017; Mackey et al. 2013). The production of electric cars, for example, uses roughly five times more of these new economy minerals than a conventional petrol car (IEA 2020). Many of these metals are found in abundance in Queensland. Several, such as aluminium and zinc, are currently refined and processed in Queensland, and represent opportunities for developing new mining and processing methods and value-adding to industries powered by renewable energy.

11.3. Policy responses

An effective removal of GHG emissions will require a wide range of policy responses and an economy-wide framework which respects a set of core principles.

These principles include that they:

- reduce GHG emissions at a trajectory consistent with the Paris Agreement
- are cost-effective
- account for distributional impacts
- do not leave households on low incomes worse off
- are administratively feasible and sufficiently flexible to respond to changed market and technology conditions as they arise
- provide support to workers and communities impacted by the energy transition
- provide policy stability and certainty during transition so that investments can be made with confidence.

Economic theory and evidence suggest that a price-based policy offers the lowest-cost route to reducing emissions in the long term. However, more direct policy interventions to manage the transition are also likely to be effective. Compared to a comprehensive carbon price, separate policy instruments applied to each sector may sacrifice some efficiency for effectiveness, but their benefits overall will outweigh their costs.

A middle path involves a sector-by-sector approach, with capacity for trade within sectors. Examples include support for renewable energy deployment in the electricity sector, incentives for more efficient processes in industry, or fleet-level fuel efficiency targets for motor vehicles. Given the present lack of political consensus on pricing in Australia, a sectoral approach may be more feasible than a comprehensive carbon price.

In other countries, a wide range of climate policy instruments are in operation. At the time of writing, 116 countries have adopted some form of renewable energy target (IEA 2019) and 34 countries have joined the Powering Past Coal Alliance, which is committed to advancing the transition from unabated coal power generation to clean energy (PPCA 2021). Outside of energy systems, 21 countries have also implemented some form of carbon tax and 36 countries have established some form of emission trading (The World Bank 2019). In the transport sector, nearly 80% of new passenger vehicles sold globally are now subject to fuel efficiency or CO_2 emissions standards (IEA 2019; Frankfurt School–UNEP Centre and Bloomberg New Energy Finance 2018; Yang and Bandivadekar 2017).

11.4. Transition

> **A transition away from fossil fuels is inevitable if the world is to achieve the reduction in emissions necessary to achieve the Paris Agreement target ("well below 2°C"). Given the vulnerability of Australia to the impacts of climate change, it should work with other nations to ensure that emissions reduction strategies bring about a rapid transition to a low GHG emission world.**

Even if some countries (such as China and India) continue to generate coal-fired power alongside a rapidly-growing use of renewables, it is likely that they will accelerate efforts to replace imports with domestically mined coal. It follows that a transition away from thermal coal, and ultimately also from metallurgical coal as new smelting strategies move to low carbon alternatives, is inevitable. The primary question facing Australia is whether this transition should start immediately and be managed to protect workers and communities, or delayed until there is a process of disorderly collapse. The latter is occurring in the United States (Jakob et al. 2020), where a sharp decline in production and employment since 2017 has been exacerbated by the COVID-19 pandemic, resulting in the lowest power sector use of coal since 1975 (US Government 2020). A smooth transition requires an immediate halt to new thermal coal mines and coal-fired power stations and a gradual closure of existing mines and power stations.

Successful implementation of such a policy requires a strong and concrete commitment to facilitating employment transitions for workers in the industry (including to alternative jobs and support for early retirement), and equally strong and concrete measures to promote alternative sources of development and employment for regional communities dependent on coal mining (CFMEU 2017; Quiggin 2020).

> **Thermal coal mining is not a major employer in Australia's overall labour market (RMIT ABC Fact Check 2019) and most employees in the industry have skills that make them employable in a wide range of industries (Quiggin 2020).**

A plan to transition away from coal, with plenty of notice to affected workers and communities and with concrete measures to facilitate an orderly transition, could certainly achieve the required shift in Australia's economy while minimising economic and social dislocation. Indeed, given the highly uncertain prospects for this industry even in the absence of necessary climate policies, many coal-dependent workers and communities will be better off under a compassionate, pro-active transition program than by simply carrying on with 'business as usual' (Wiseman et al. 2017).

A plan to transition away from coal, with plenty of notice to affected workers and communities and with concrete measures to facilitate an orderly transition, could certainly achieve the required shift in Australia's economy while minimising economic and social dislocation

Only a small number of communities, mostly in central and northern Queensland, depend critically on coal mining to provide livelihoods for their residents given their reliance on FIFO operations. Specific place-based policies for these communities should be developed.

The key policy requirements are:

- a transition fund to assist workers with specialised coal-related skills in retraining or moving to other parts of the mining sector
- development of utility-scale solar PV and associated transmission infrastructure targeted at communities undergoing a transition from coal mining and coal-fired power generation.

The transition to electric vehicles (EVs) will also require a range of economic adjustments, including in the car servicing and repairs industry. The initial stages of the process should involve the introduction of vehicle fuel efficiency requirements similar to those in other developed countries. This would reduce emissions directly and provide an incentive to add electric vehicles to the range of vehicles on which average fuel efficiency is calculated. Although these measures would benefit consumers by reducing the lifetime cost of vehicle ownership, they have faced resistance from vehicle importers and dealers who would need to change their business models to deal with EVs, and from oil refiners who would need to produce cleaner fuel. These adjustment challenges could be overcome easily enough by a government with a clear commitment to deep reductions in GHG emissions. In the absence of such a commitment, Australia will be left with an inefficient car fleet, dependent on mostly imported oil, for many years to come.

New economic activity will centre around emerging industries, such as renewables-based industries, more than offsetting the loss of employment in industries based on coal and other fossil fuels (Quiggin 2020). There is significant potential for a managed transition within the energy sector from fossil fuels to other parts of the mining sector. In some cases, however, new jobs and business opportunities will be in different geographic regions and will require different skill sets in many cases. The path to economic vitality among the decline of high emitting industries will lie in diversification away from fossil fuel-based energy and resource industries.

11.5. Co-benefits

In addition to the global benefits of reduced GHG emissions, shifting to zero-emissions technologies often has important local or national benefits outside of climate change (Karlsson et al. 2020). The co-benefits that arise from reducing GHG emissions can be substantial, such as improved air quality due to using alternatives to coal and natural gas (Green 2015; Luderer et al. 2019) as well as reduced road congestion, traffic accidents and road damage from shifting to greater public transport use, electric and autonomous vehicles.

Reducing burning of coal would yield substantial health benefits due to reductions in particulate pollution, which is a major source of excess mortality. For example, ending the use of coal would yield net health benefits to the United States even in the absence of concern about GHG emissions (Muller et al. 2011). Coal-fired power generation causes around 300 excess deaths per year in New South Wales alone (Ewald 2018). Other co-benefits can include ecological benefits from afforestation and where land management for higher carbon sequestration also means better environmental outcomes locally, and reduced reliance on imports of critical inputs such as petrol and diesel. Previous sections of the report outline the co-benefits for reducing fossil fuel use for an array of beneficiaries in Australia such as reducing stress on its ecosystems, reducing the loss of agricultural productivity, and improving the health and wellbeing of its citizens.

The co-benefits that arise from reducing GHG emissions can be substantial, such as improved air quality due to using alternatives to coal and natural gas

11.6. Economic impacts

Reducing fossil fuel emissions from the economy is no longer a question of a trade-off between environmental objectives and economic growth. Rather, reducing CO_2 emissions means positioning Australia for prosperity in a low-GHG emission global economy. Conversely, if Australia were to retain high emissions production structures in the longer term, the economy would risk being locked into declining markets. This could take the form of declining investments which ultimately get reflected in lower productivity. It could also have more tangible and immediate adverse effects, such as through trade barriers that could be erected against imports from countries that do not act effectively to reduce emissions (Mehling et al. 2019), a prospect raised recently by the European Union (BCG 2020).

Reducing CO_2 emissions means positioning Australia for prosperity in a low-GHG emission global economy

Some aspects of reducing GHG emissions can be implemented without any additional costs, especially where existing high-emissions installations are replaced with cost-competitive clean technologies at the end of their economic life. Where such a transition is accelerated, or where policy measures bring about investment in zero emissions options that would not be commercially competitive by themselves, it leads to higher business costs, but will not necessarily affect overall economic activity. An accelerated shift to clean technologies means accelerated investment and can bring productivity dividends (Fankhauser and Jotzo 2018). This needs to be considered in government spending for economic recovery following COVID-19. A multitude of opportunities exist for fiscal investments that create jobs and also help to reduce emissions (Hepburn et al. 2020; Forster et al. 2020; Jotzo et al. 2020).

Australia's economy has long been characterised by strong mining and agriculture sectors. The central role played by both sectors in Australia's 'public imagination' and national identity is well documented, with mining and agriculture shaping Australians' understanding of, and relationship with, rural and regional Australia (Robin 2007). The reduction in GHG emissions need not diminish the role of Australia's resource and land-based industries. Indeed, it can strengthen the economic contribution from rural and regional areas, and help establish economically-secure regional communities based on new energy industries, as well as carbon sequestration activities (Hatfield-Dodds et al. 2015).

Australia has much to gain from a zero emissions future. Seizing the opportunities demands an ambitious, whole-of-economy policy framework, developed in partnership with Australian communities, businesses, local governments, Traditional Owners and key stakeholders, and one that is sensitive to Australia's historical development and vulnerable communities.

11.7. International action and Paris Agreement targets

Countries differ greatly in their emission trajectories, ambition to limit and reduce emissions, and effectiveness of efforts to curb GHG emissions growth. Under the Paris Agreement, all countries have provided pledges for their climate change action and a large number of countries across the developed and developing world have put forward measurable targets for emissions by the year 2030 (Climate Change Authority 2019). Under various assumptions about emissions trajectories beyond 2030, current national targets when aggregated globally are projected to result in warming in the order of 2.7–3.1°C above pre-industrial levels by 2100 (Climate Action Tracker 2020; Höhne et al. 2018; Revill and Harris 2017). The level of ambition needed to achieve a 2°C stabilisation is three times greater than current commitments. In order to be on a trajectory compatible with well below 2°C stabilisation, emissions pledges for 2030 would need to be greatly strengthened. Achieving 1.5°C of stabilisation would require a far greater level of ambition still, with this opportunity rapidly closing.

The Paris Agreement foresees a 'ratcheting up' of national contributions to emission reduction over time, with the first round of enhanced emissions pledges planned for the early 2020s (Hermwille et al. 2019). The COVID-19 pandemic has delayed the UN climate change negotiations process and high-level talks and agreements are expected to resume in 2021.

The COVID-19 pandemic is resulting in a pronounced reduction in global GHG emissions due to less energy use for transport, and a recession that is beginning to be reflected in lower industrial and manufacturing output as of mid-2020. While the effects may linger for some time, they are unlikely to result in permanent emission reductions, so the direct effect of COVID-19 on long-term climate change objectives is likely limited or negligible (Forster et al. 2020; IEA 2020c). It underscores the need to support and accelerate the removal of GHG emissions from the Australian economy.

> Australia is facing an extremely challenging future under the current emission trajectory of the international community. If the world continues on this pathway, it will lose many of its vital ecosystems (native forests, Great Barrier Reef, alpine regions), and will place its agriculture and health systems in jeopardy of failing. The argument that Australia doesn't contribute 'significantly' to the GHG emission problem and therefore should not act on climate change ignores the enormous losses that Australia will experience if it doesn't work with the rest of the world to achieve and exceed the Paris Agreement goals.

APPENDIX

Terms of reference

The Australian Academy of Science requested a report on the risks and challenges for Australia under global mean surface temperatures that are 3°C or warmer in 2100 than the pre-industrial period. This increase in global average surface temperature lies between the Intergovernmental Panel on Climate Change (IPCC) projections for the medium-high (2.8°C (2.3–3.2), RCP4.5) and high (4.3°C (3.6–5.0), RCP8.5) greenhouse gas emissions scenarios (Collins et al. 2013). The 3°C temperature rise also corresponds to the mean of the projected temperature rise by 2100 (2.7–3.1°C; see Figure 1) if current climate policies around the world are continued (Climate Action Tracker 2020). Assessing the potential consequences for Australia of a 3°C world is therefore important for understanding the magnitude of the risks and the urgency of the challenge we face over the next decade and beyond in dealing effectively with climate change.

The specific terms of reference (TOR) for this study are:

- **TOR1:** Outline the global challenge under current and future climate change for Australia.
- **TOR2:** Define the impacts of climate change so far on key sectors within Australia, particularly in the context of mean global temperatures increasing by 1.1°C since 1870.
- **TOR3:** Define the risks that are associated with reaching and exceeding average global temperatures of 3°C (as compared to 1.5–2°C) above the pre-industrial period.
- **TOR4:** Review the steps that Australia and the world are taking in order to avoid 3°C of warming by 2100 and define the challenges and opportunities for Australia over next 10 years.
- **TOR5:** Explore the types of actions that Australia might take to keep global warming to well below 2°C as well as strategies for improving the science and policy dialogue, including evidence-informed decision making and partnerships.

Process

The Academy assembled a panel comprising Academy Fellows plus other internationally respected experts. This team drew on the peer-reviewed expert literature, as well as assessments and special reports including those from the Intergovernmental Panel on Climate Change (IPCC). The panel also consulted a wider range of experts on specific issues associated with the terms of reference, which included input from relevant organisations. The authors then synthesised the material into a draft report which was assessed by six expert reviewers who are listed at the front of the report.

Scope of this report

Climate change is affecting an increasing array of natural and human systems. These changes are documented in international peer-reviewed scientific literature and are periodically synthesised into comprehensive reports from the Intergovernmental Panel on Climate Change (IPCC 2014b, 2014a; Reisinger et al. 2015; Stocker et al. 2013), with additional special reports on specific issues (Adger et al. 2009; IPCC 2019, 2018). The present investigation of Australia's changing climate and current international commitments for emission reductions is therefore not intended to be an exhaustive assessment of current and future impacts, risks or solutions to climate change. These can be found in the extensive IPCC reports and other peer-reviewed scientific literature.

The present report is focused on understanding the risks for Australia if the international community continues with its current suite of policies for reducing human derived greenhouse gas emissions. Current policies, if enacted, would result in a global mean surface temperature increase of approximately 3°C or more by mid-to-late century if current emission reduction pledges are not strengthened. This level of warming is well above the targets considered manageable ("safe") by the Paris Agreement of the UN Framework Convention on Climate Change.

TOR1 of this report therefore outlines the global challenge of climate change for Australia, while TOR2 defines the impacts of climate change to date (under 1.1°C of warming) on four key sectors that are important to Australia, namely Australia's ecosystems, food production, cities and towns, and health and wellbeing. The risks for these sectors under global warming of 3°C are the focus of TOR3. TOR4 focuses on the measures needed in Australia and the international community to meet the mitigation and adaptation challenges that we face, many of which will be determined by our actions over the next few years (IPCC 2018). Finally, TOR5 explores how evidence-informed policymaking can be improved to achieve the great commitments and transitions that are required. A list of supporting peer-reviewed literature is available at the end of the report.

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