11

Australasia

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Executive Summary

Observed changes and impacts

Ongoing climate trends have exacerbated many extreme events (*very high confidence*). The Australian trends include further warming and sea level rise sea level rise (SLR), with more hot days and heatwaves, less snow, more rainfall in the north, less April–October rainfall in the southwest and southeast and more extreme fire weather days in the south and east. The New Zealand trends include further warming and sea level rise (SLR), more hot days and heatwaves, less snow, more rainfall in the south, less rainfall in the north and more extreme fire weather in the east. There have been fewer tropical cyclones and cold days in the region. Extreme events include Australia's hottest and driest year in 2019 with a record-breaking number of days over 39°C, New Zealand's hottest year in 2016, three widespread marine heatwaves during 2016–2020, Category 4 Cyclone Debbie in 2017, seven major hailstorms over eastern Australia and two over New Zealand from 2014–2020, three major floods in eastern Australia and three over New Zealand during 2019–2021 and major fires in southern and eastern Australia during 2019–2020. {11.2.1, Table 11.2, 11.3.8}

Climate trends and extreme events have combined with exposure and vulnerabilities to cause major impacts for many natural systems, with some experiencing or at risk of irreversible change in Australia (*very high confidence*) and in New Zealand (*high confidence*). For example, warmer conditions with more heatwaves, droughts and catastrophic wildfires have negatively impacted terrestrial and freshwater ecosystems. The Bramble Cay melomys, an endemic mammal species, became extinct due to loss of habitat associated with sea level rise (SLR) and storm surges in the Torres Strait. Marine species abundance and distributions have shifted polewards, and extensive coral bleaching events and loss of temperate kelp forests have occurred due to ocean warming and marine heatwaves across the region. In New Zealand's southern Alps, from 1978 to 2016, the area of 14 glaciers declined 21%, and extreme glacier mass loss was at least 6 times more likely in 2011 and 10 times more likely in 2018 due to climate change. The end-of-summer snowline elevation for 50 glaciers rose 300 m from 1949 to 2019. {11.3.1.1, 11.3.2.1, Table 11.2b, Table 11.4, Table 11.6, Table 11.9}

Climate trends and extreme events have combined with exposure and vulnerabilities to cause major impacts for some human systems (*high confidence*). Socioeconomic costs arising from climate variability and change have increased. Extreme heat has led to excess deaths and increased rates of many illnesses. Nuisance and extreme coastal flooding have increased due to sea level rise (SLR) superimposed upon high tides and storm surges in low-lying coastal and estuarine locations, including impacts on cultural sites, traditions and lifestyles of Aboriginal and Torres Strait Islander Peoples in Australia and Tangata Whenua Māori in New Zealand. Droughts have caused financial and emotional stress in farm households and rural communities. Tourism has been negatively affected by coral bleaching, fires, poor ski seasons and receding glaciers. Governments, business and communities have experienced major costs associated with extreme weather, droughts and sea level rise (SLR). {11.3, 11.4, 11.5.2, Table 11.2, Boxes 11.1–11.6}

Climate impacts are cascading and compounding across sectors and socioeconomic and natural systems (*high confidence*). Complex connections are generating new types of risks, exacerbating existing stressors and constraining adaptation options. An example is the impacts that cascade between interdependent systems and infrastructure in cities and settlements. Another example is the 2019–2020 southeast Australia wildfires, which burned 5.8 to 8.1 million hectares, with 114 listed threatened species losing at least half of their habitat and 49 losing over 80%, over 3,000 houses destroyed, 33 people killed, a further 429 deaths and 3230 hospitalisations due to cardiovascular or respiratory conditions, AUD$1.95 billion in health costs, AUD$2.3 billion in insured losses and AUD$3.6 billion in losses for tourism, hospitality, agriculture and forestry. {11.5.1, Box 11.1}

Increasing climate risks are projected to exacerbate existing vulnerabilities and social inequalities and inequities (*high confidence*). These include inequalities between Indigenous and non-Indigenous Peoples and between generations, rural and urban areas, incomes and health status, increasing the climate risks and adaptation challenges faced by some groups and places. Resultant climate change impacts include the displacement of some people and businesses and threaten social cohesion and community well-being. {11.3.5, 11.3.6, 11.3.10, 11.4}

Projected impacts and key risks

Further climate change is inevitable, with the rate and magnitude largely dependent on the emission pathway (*very high confidence*[1]). Ongoing warming is projected, with more hot days and fewer cold days (*very high confidence*). Further sea level rise (SLR), ocean warming and ocean acidification are projected (*very high confidence*). Less winter and spring rainfall is projected in southern Australia, with more winter rainfall in Tasmania, less autumn rainfall in southwestern Victoria and less summer rainfall in western Tasmania (*medium confidence*), with uncertain rainfall changes in northern Australia. In New Zealand, more winter and spring rainfall is projected in the west and less in the east and north, with more summer rainfall in the east and less in the west and central North Island (*medium confidence*). In New Zealand, ongoing glacier retreat is projected (*very high confidence*). More extreme fire weather is projected in southern and eastern Australia (*high confidence*) and over northern and eastern New Zealand (*medium confidence*). Increased drought frequency is projected for southern and eastern Australia and northern New Zealand (*medium confidence*). Increased heavy rainfall intensity is projected, with fewer tropical cyclones and a greater proportion of severe cyclones (*medium confidence*). {11.2.2, Table 11.3, Box 11.6}

1 In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

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Climate risks are projected to increase for a wide range of systems, sectors and communities, which are exacerbated by underlying vulnerabilities and exposures (*high confidence*) {11.3; 11.4}. Nine key risks have been identified, based on magnitude, likelihood, timing and adaptive capacity {11.6, Table 11.14}:

Ecosystems at critical thresholds, where recent climate change has caused significant damage and further climate change may cause irreversible damage, with limited scope for adaptation

1) Loss and degradation of coral reefs and associated biodiversity and ecosystem service values in Australia due to ocean warming and marine heatwaves. For example three marine heatwaves on the Great Barrier Reef (GBR) during 2016–2020 caused significant bleaching and loss *(very high confidence)*. {11.3.2.1, 11.3.2.2, Box 11.2}
2) Loss of alpine biodiversity in Australia due to less snow. For example loss of alpine vegetation communities (snow patch Feldmark and short alpine herb-fields) and increased stress on snow-dependent plant and animal species *(high confidence)*. {11.3.1.1, 11.3.1.2}

Key risks that have potential to be severe but can be reduced substantially by rapid, large-scale and effective mitigation and adaptation

3) Transition or collapse of alpine ash, snowgum woodland, pencil pine and northern jarrah forests in southern Australia due to hotter and drier conditions with more fires. For example declining rainfall in southern Australia over the past 30 years, has led to drought-induced canopy dieback across a range of forest and woodland types and death of fire-sensitive tree species due to unprecedented wildfires *(high confidence)*. {11.3.1.1, 11.3.1.2}
4) Loss of kelp forests in southern Australia and southeast New Zealand due to ocean warming, marine heatwaves and overgrazing by climate-driven range extensions of herbivore fish and urchins. For example less than 10% of giant kelp in Tasmania was remaining by 2011 due to ocean warming *(high confidence)*. {11.3.2.1, 11.3.2.2}
5) Loss of natural and human systems in low-lying coastal areas due to sea level rise (SLR). For example for 0.5 m sea level rise (SLR), the value of buildings in New Zealand exposed to 1-in-100-year coastal inundation could increase by NZ$12.75 billion and the current 1-in-100-year flood in Australia could occur several times a year *(high confidence)*. {11.3.5; Box 11.6}
6) Disruption and decline in agricultural production and increased stress in rural communities in southwestern, southern and eastern mainland Australia due to hotter and drier conditions. For example by 2050, a decline in median wheat yields of up to 30% in southwestern Australia and up to 15% in South Australia and increased heat stress in livestock by 31–42 days per year *(high confidence)*. {11.3.4; 11.3.5; Box 11.3}
7) Increase in heat-related mortality and morbidity for people and wildlife in Australia due to heatwaves. For example heat-related excess deaths in Melbourne, Sydney and Brisbane are projected to increase by about 300/year (low emission pathway) to 600/year (high emission pathway) during the 2031–2080 period relative to 142/year in the period 1971–2020 *(high confidence)*. {11.3.1, 11.3.5.1, 11.3.5.2, 11.3.6.1, 11.3.6.2}

Key cross-sectoral and system-wide risk

8) Cascading, compounding and aggregate impacts on cities, settlements, infrastructure, supply chains and services due to wildfires, floods, droughts, heatwaves, storms and sea level rise (SLR). For example in New Zealand, extreme snow, heavy rainfall and wind events have combined to impact road networks, power and water supply, interdependent wastewater and stormwater services and business activities *(high confidence)* {11.3.3, 11.5.1, 11.8.1}.

Key implementation risk

9) Inability of institutions and governance systems to manage climate risks. For example the scale and scope of projected climate impacts overwhelm the capacity of institutions, organisations and systems to provide necessary policies, services, resources and coordination to address socioeconomic impacts *(high confidence)* {11.5.1.2, 11.5.1.3, 11.5.2.3, 11.7.1, 11.7.2, 11.7.3}.

There are important interactions between mitigation and adaptation policies and their implementation (*high confidence*). Integrated policies in interdependent systems across biodiversity, water quality, water availability, energy, transport, land use and forestry for mitigation can support synergies between adaptation and mitigation. These have co-benefits for the management of land use, water and associated conflicts and for the functioning of cities and settlements. For example, projected increases in fire, drought, pest incursions, storms and wind place forests at risk and affect their ongoing role in meeting New Zealand's emissions reduction goals. {11.3.4.3, 11.3.10.2, 11.3.5.3, Box 11.5}

Challenges and solutions

The ambition, scope and progress of the adaptation process have increased across governments, non-government organisations, businesses and communities (*high confidence*). This process includes vulnerability and risk assessments, identification of strategies and options, planning, implementation, monitoring, evaluation and review. Initiatives include legislated institutional frameworks for risk assessment and national adaptation planning and monitoring in New Zealand, a National Recovery and Resilience Agency and National Disaster Risk Reuction Framework in Australia, deployment of new national guidance, decision tools, collaborative governance approaches and the introduction of climate risk and disclosure regimes for the private sector. The focus, however, has been on adaptation planning, rather than on implementation. {11.5.1, 11.7.1.1, Box 11.6, Table 11.15a, Table 11.15b, Table 11.17}

Adaptation progress is uneven, due to gaps, barriers and limits to adaptation and adaptive capacity deficits (*very high confidence*). Progress in adaptation planning, implementation, monitoring and evaluation is lagging. Barriers include lack of consistent policy direction, competing objectives, divergent risk perceptions and values, knowledge constraints, inconsistent information, fear of litigation, up-front costs and lack of engagement, trust and resources. Adaptation limits are being approached for some species and ecosystems. Adaptive capacity to address the barriers and limits can be built through greater engagement with groups and communities to build trust and social legitimacy through the inclusion of diverse values, including those of Aboriginal and Torres Strait Islander Peoples and Tangata Whenua Māori. {11.4, 11.5, 11.6, 11.7, 11.8, Table 11.4, Table 11.5, Table 11.6, Table 11.16, Box 11.2}

A range of incremental and transformative adaptation options and pathways is available as long as enablers are in place to implement them (*high confidence*). Key enablers for effective adaptation include shifting from reactive to anticipatory planning, integration and coordination across levels of government and sectors, inclusive and collaborative institutional arrangements, government leadership, policy alignment, nationally consistent and accessible information and decision-support tools, along with adaptation funding and finance, and robust, consistent and strategic policy commitment. Over 75% of people in Australia and New Zealand agree that climate change is occurring and over 60% believe climate change is caused by humans, giving climate adaptation and mitigation action further social legitimacy. {11.7.3, Table 11.17}

New knowledge on system complexity, managing uncertainty and how to shift from reactive to adaptive implementation is critical for accelerating adaptation (*high confidence*). Priorities include a greater understanding of impacts on natural system dynamics; the exposure and vulnerability of different groups within society, including Indigenous Peoples; the relationship between mitigation and adaptation; the effectiveness and feasibility of different adaptation options; the social transitions needed for transformative adaptation; and the enablers for new knowledge to better inform decision-making (e.g., monitoring data repositories, risk and vulnerability assessments, robust planning approaches, sharing adaptation knowledge and practice). {11.7.3.3}

Aboriginal and Torres Strait Islander Peoples and Tangata Whenua Māori can enhance effective adaptation through the passing down of knowledge about climate change planning that promotes collective action and mutual support across the region (*high confidence*). Supporting Aboriginal and Torres Strait Islander Peoples and Tangata Whenua Māori institutions, knowledge and values enable self-determination and create opportunities to develop adaptation responses to climate change. Actively upholding the UN Declaration on the Rights of Indigenous Peoples and Māori interests under the Treaty of Waitangi at all levels of government enables intergenerational approaches for effective adaptation. {11.3, 11.4, 11.6, 11.7.3; Cross-Chapter Box INDIG in Chapter 18}

A step change in adaptation is needed to match the rising risks and to support climate resilient development (*very high confidence*). Current adaptation is largely incremental and reactive. A shift to transformative and proactive adaptation can contribute to climate resilient development. The scale and scope of cascading, compounding and aggregate impacts require new, larger-scale and timely adaptation. Monitoring and evaluation of the effectiveness of adaptation progress and continual adjustment is critical. The transition to climate resilient development pathways can generate major co-benefits, but complex interactions between objectives can create trade-offs. {11.7, 11.8.1, 11.8.2}

Delay in implementing adaptation and emission reductions will impede climate resilient development, resulting in more costly climate impacts and greater scale of adjustments (*very high confidence*). The region faces an extremely challenging future. Reducing the risks would require significant and rapid emission reductions to keep global warming to 1.5°C–2.0°C, as well as robust and timely adaptation. The projected warming under current global emissions reduction policies would leave many of the region's human and natural systems at very high risk and beyond adaptation limits. {11.8, Table 11.1, Table 11.14, Figure 11.6}

11.1 Introduction

This chapter assesses the observed impacts, projected risks, vulnerability and adaptation, and the implications for climate resilient development for the Australasia region, based on the literature published up to 1 September 2021. It should be read in conjunction with other Working Group (WG) II chapters, the climate science assessment in the WGI report and the greenhouse gas emissions and mitigation assessment in the WGIII report.

11.1.1 Context

The Australasia region is defined as the Exclusive Economic Zones (EEZs) and territories of Australia and New Zealand. In both countries, climate adaptation is largely implemented at a sub-national level through the devolution of functions constitutionally or by statute, alongside disaster risk reduction (COAG, 2011; Lawrence et al., 2015; Macintosh et al., 2015).

Australia's economy is dominated by financial and insurance services, education, mining, construction, tourism, health care and social assistance (ABS, 2018) with Australian exports accruing mostly from mining (ABS, 2018; ABS, 2019). In New Zealand, service industries, including tourism, collectively account for around two-thirds of GDP (NZ Treasury, 2016). The primary sector contributes 6% of New Zealand's GDP and over half of the country's export earnings (NZ Treasury, 2016).

Existing vulnerabilities expose and exacerbate inequalities between rural, regional and urban areas, Indigenous and non-Indigenous Peoples, those with health and disability needs, and between generations, incomes and health status, increasing the relative climate change risk faced by some groups and places (*high confidence*) (Jones et al., 2014; Bertram, 2015; Perry, 2017; Hazledine and Rashbrooke, 2018).

Previous IPCC reports (Table 11.1) have documented observed climate impacts, projected risks, adaptation challenges and opportunities. This chapter presents more evidence of observed climate impacts and adaptation, better quantification of socioeconomic risks, new information about cascading and compounding risks, greater emphasis on adaptation enablers and barriers, and links to climate resilient development.

11.1.2 Economic, Demographic and Social Trends

Economic, demographic and sociocultural trends influence the exposure, vulnerability and adaptive capacity of individuals and communities (*high confidence*) (Elrick-Barr et al., 2016; Smith et al., 2016; Hayward, 2017; B. Frame et al., 2018; Plummer et al., 2018; Smith et al., 2018; Gartin et al., 2020). In the absence of proactive adaptation, climate change impacts are projected to worsen inequalities between Indigenous and non-Indigenous peoples and other vulnerable groups (Green et al., 2009; Manning et al., 2014; Ambrey et al., 2017) (*high confidence*). Socioeconomic inequality, low incomes and high levels of debt, poor health and disabilities increase vulnerability and limit adaptation (Hayward, 2012) (11.7.2). A lack of services, such as schools and medical services, in poorer and rural areas and decision-making processes that privilege some voices over others exacerbate inequalities (Kearns et al., 2009; Hinkson and Vincent, 2018).

Changes to the composition and location of different demographic groups in the region contribute to increased exposure or vulnerability to climate change (*medium confidence*). Australia's population reached 25 million in 2018 and is projected to grow to 37.4–49.2 million by 2066, with most growth in major cities (accounting for 81% of Australia's population growth from 2016 to 2017) (ABS, 2018), although COVID-19 is expected to slow the growth rate (CoA, 2020c). The highest growth rates outside of major cities occurred mostly in coastal regions (ABS, 2017), which have built assets exposed to sea level rise (SLR). New Zealand's population was 5.1 million at the end of 2020 and is projected to increase to 6.0–6.5 million by 2068, assuming no marked changes in migration patterns (Stats NZ, 2016; Stats NZ, 2021). Although the population densities of both countries are much lower than other OECD countries, they are highly urbanised with over 86% living in urban areas in both countries (Productivity Commission, 2017; World Bank, 2018). This proportion is projected to increase to over 90% by 2050 (UN DESA, 2019) mostly in coastal areas (Rouse et al., 2017). Consideration of climate change impacts when planning and managing such growth and associated infrastructure could help avoid new vulnerabilities being created, particularly from wildfires, sea level rise (SLR), heat stress and flooding.

The region has an increasingly diverse population through the arrival of migrants, including those from the Pacific, whose innovations, skills and transnational networks enhance their and others' adaptive capacity (De et al., 2016; Fatorić et al., 2017; Barnett and McMichael, 2018), although language barriers and socioeconomic disadvantage can create vulnerabilities for some (11.7.2).

Climate change inaction exacerbates intergenerational inequity, including prospects for the current younger population (Hayward, 2012). Increasing transient worker populations (ABS, 2018) may diminish social networks and adaptive capacity (Jiang et al., 2017). The region has an ageing population and increasing numbers of people living on their own who are highly vulnerable to extreme events, including heat stress and flooding (Zhang et al., 2013).

Socioeconomic trends are affected by global mega trends (KPMG, 2021), which are expected to influence the region's ability to implement climate change adaptation strategies (World Economic Forum, 2014). Digital technological advances have potential benefits for building adaptive capacity (Deloitte, 2017a).

11.2 Observed and Projected Climate Change

11.2.1 Observed Climate Change

Regional climate change has continued since AR5 was released in 2014, with trends exacerbating many extreme events (*very high confidence*). The following changes are quantified with references in Tables 11.2a and 11.2b. The region has continued to warm (Figure 11.1), with more

Table 11.1 | Summary of key conclusions from the IPCC 5th Assessment Report (AR5) Australasia chapter (Reisinger et al., 2014) and relevant conclusions from the IPCC Special Reports on Global Warming of 1.5°C (IPCC, 2018), Climate Change and Land (IPCC, 2019a) and Oceans and Cryosphere (IPCC, 2019b).

Conclusions	Report
Our regional climate is changing (*very high confidence*) and warming will continue through the 21st century (*virtually certain*) with more hot days, fewer cold days, less snow, less rainfall in southern Australia and the northeast of both of New Zealand's islands, more rainfall in western New Zealand, more extreme rainfall, SLR, increased fire weather in southern Australia and across New Zealand and fewer cyclones but a greater proportion of intense cyclones.	(Reisinger et al., 2014)
Key risks include changes in the structure and composition of Australian coral reefs, loss of montane ecosystems, increased flood damage, reduced water resources in southern Australia, more deaths and infrastructure damage during heatwaves, more fire-related impacts on ecosystems and settlements in southern Australia and across New Zealand, greater risk to coastal infrastructure and ecosystems and reduced water availability in the Murray-Darling Basin (MDB) and southern Australia (*high confidence*). Benefits are projected for some sectors and locations (*high confidence*), including reduced winter mortality and energy demand for heating, increased forest growth and enhanced pasture productivity.	
Adaptation is occurring and becoming mainstreamed in some planning processes (*high confidence*). Adaptive capacity is considered generally high in many human systems, but adaptation implementation faces major barriers, especially for transformational responses (*high confidence*). Some synergies and trade-offs exist between different adaptation responses and between mitigation and adaptation, with interactions occurring both within and outside the region (*very high confidence*).	
Vulnerability remains uncertain due to incomplete consideration of socioeconomic dimensions (*very high confidence*), including governance, institutions, patterns of wealth and ageing, access to technology and information, labour force participation and societal values.	
Emissions reductions under Nationally Determined Contributions from signatories to the Paris Agreement are consistent with a global warming of 2.5°C–3.0°C above pre-industrial temperatures by 2100. Much deeper emission reductions are needed prior to 2030 to limit warming to 1.5°C. There are limits to adaptation and adaptive capacity for some human and natural systems at global warming of 1.5°C, with associated losses.	(IPCC, 2018)
Climate impacts will disproportionately affect the welfare of impoverished and vulnerable people because they lack adaptation resources. Strengthening the climate-action capacities of national and sub-national authorities, civil society, the private sector, Indigenous People and local communities can support implementation of actions.	
Land-related responses that contribute to climate change adaptation and mitigation can also combat desertification and land degradation and enhance food security.	(IPCC, 2019a)
Appropriate design of policies, institutions and governance systems at all scales can contribute to land-related adaptation and mitigation while facilitating the pursuit of climate-adaptive development pathways.	
Mutually supportive climate and land policies have the potential to save resources, amplify social resilience, support ecological restoration and foster collaboration between stakeholders.	
Near-term action to address climate change adaptation and mitigation, desertification, land degradation and food security can bring social, ecological, economic and development co-benefits. Delaying action (both mitigation and adaptation) will be more costly.	
The rate of global mean SLR of 3.6 mm yr^{-1} for 2006–2015 is unprecedented over the last century. Extreme wave heights, coastal erosion and flooding have increased in the Southern Ocean by around 1.0 cm yr^{-1} over the period 1985–2018.	(IPCC, 2019b)
Some species of plants and animals have increased in abundance, shifted their range and established in new areas as glaciers receded and the snow-free season lengthened. Some cold-adapted or snow-dependent species have declined in abundance, increasing their risk of extinction, notably on mountain summits.	
Many marine species have shifted their range and seasonal activities. Altered interactions between species have caused cascading impacts on ecosystem structure and functioning.	
Mean SLR projections are higher by 0.1 m compared to AR5 under RCP8.5 in 2100. Extreme sea level events that are historically rare (once per century) are projected to occur frequently (at least once yr^{-1}) at many locations by 2050.	
Projected ecosystem responses include losses of species habitat and diversity and degradation of ecosystem functions. Warm water corals are at high risk already and are projected to transition to very high risk even if global warming is limited to 1.5°C.	
Governance arrangements (e.g., marine protected areas, spatial plans and water management systems) are too fragmented across administrative boundaries and sectors to provide integrated responses to the increasing and cascading risks. Financial, technological, institutional and other barriers exist for implementing responses.	
Enabling climate resilience and sustainable development depends critically on urgent and ambitious emissions reductions coupled with coordinated, sustained and increasingly ambitious adaptation actions. This includes better cooperation and coordination among governing authorities, education and climate literacy, sharing of information and knowledge, finance, addressing social vulnerability and equity, and institutional support.	

extremely high temperatures and fewer extremely low temperatures. Snow depths and glacier volumes have declined. Sea level rise and ocean acidification have continued. Northern Australia has become wetter, while April–October rainfall has decreased in south-western and south-eastern Australia. In New Zealand, most of the south has become wetter, while most of the north has become drier (Figure 11.2). The frequency, severity and duration of extreme fire weather conditions have increased in southern and eastern Australia and eastern New Zealand. Changes in extreme rainfall are mixed. There has been a decline in tropical cyclone frequency near Australia.

Reliable measurements are limited for some types of storms, particularly thunderstorms, lightning, tornadoes and hail (Walsh et al., 2016). Many high-impact events are a combination of interacting physical processes across multiple spatial and temporal scales (e.g., fires, heatwaves and droughts), and better understanding of these extreme and compound events is needed (Zscheischler et al., 2018).

Some of the observed trends and events can be partly attributed to anthropogenic climate change, as documented in Chapter 16. Examples include regional warming trends and sea level rise (SLR), terrestrial and marine heatwaves, declining rainfall and increasing fire weather

Observed temperature changes in Australia and New Zealand

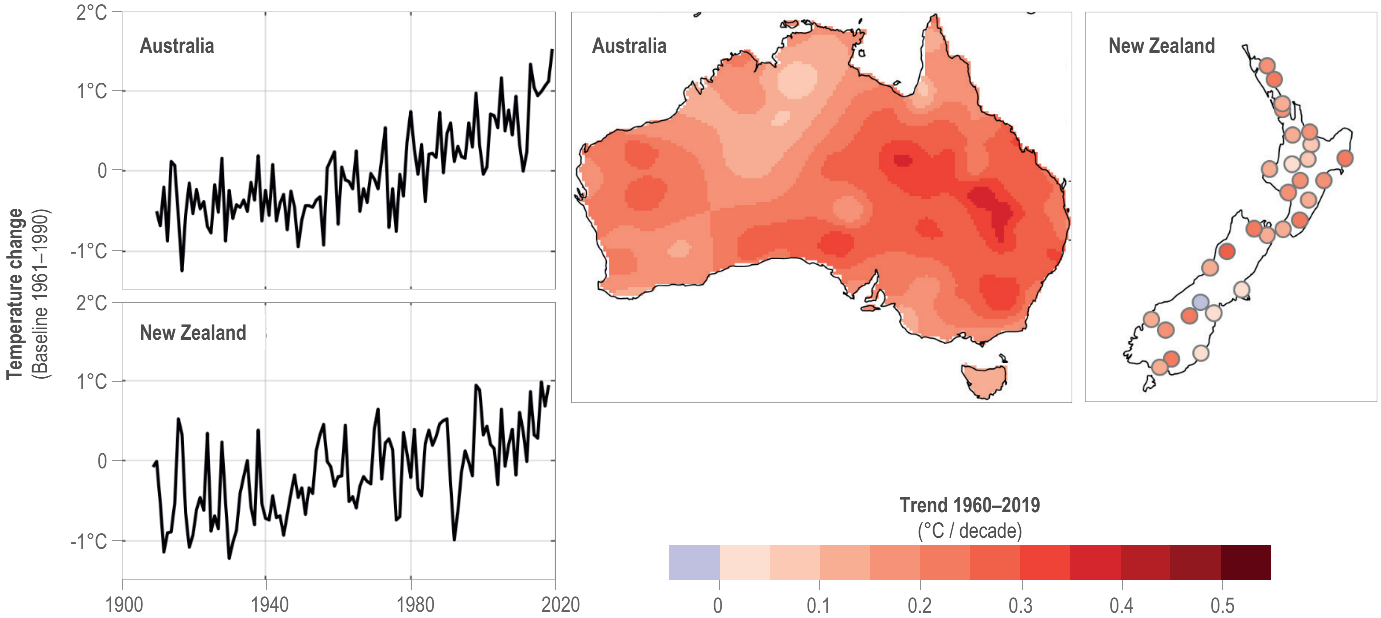

Figure 11.1 | Observed temperature changes in Australia and New Zealand. Annual temperature change time series are shown for 1910–2019. Mean annual temperature trend maps are shown for 1960–2019 using contours for Australia and individual sites for New Zealand. Data courtesy of BOM and NIWA.

Observed rainfall changes in Australia and New Zealand

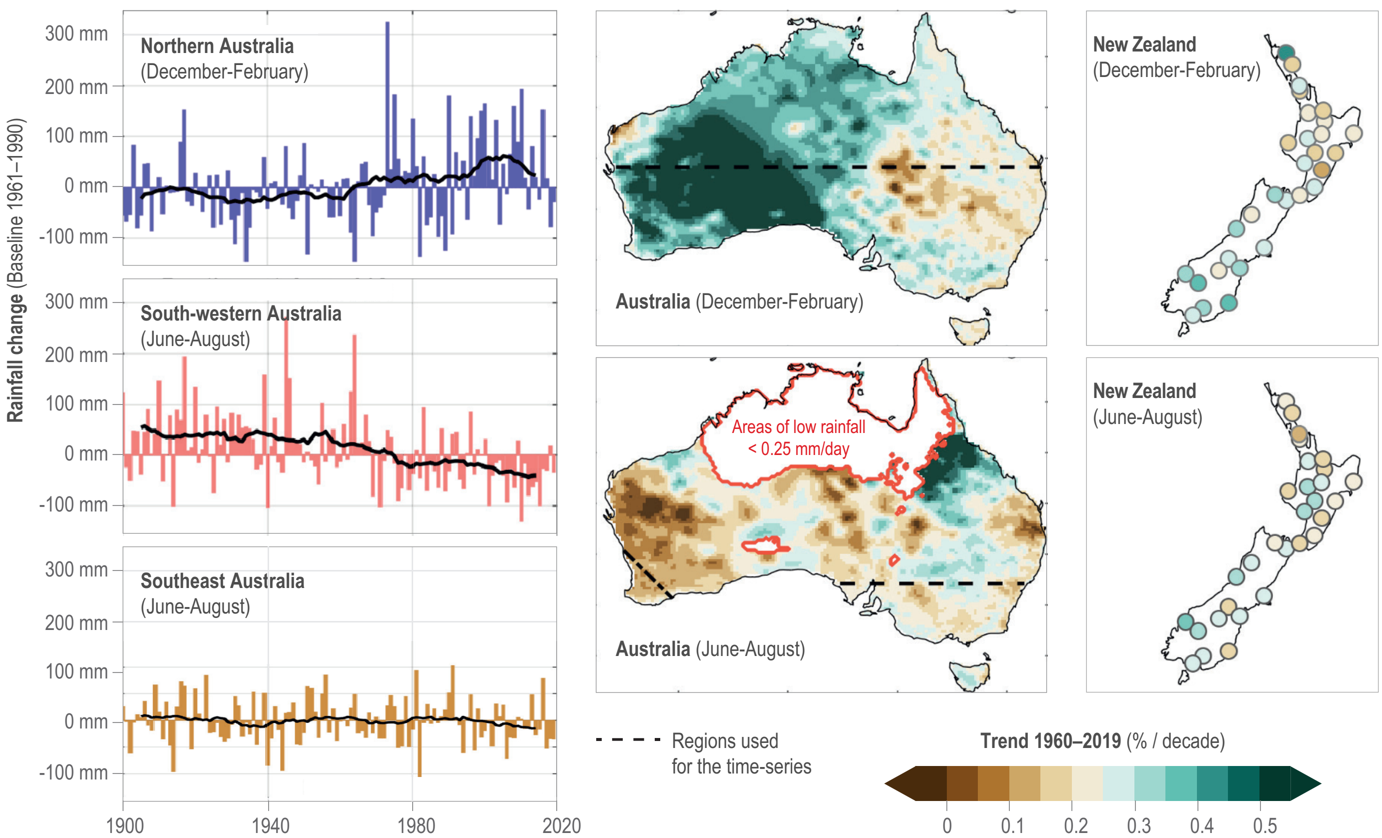

Figure 11.2 | Observed rainfall changes in Australia and New Zealand. Rainfall change time series for 1900–2019 are shown for Northern Australia (December–February: DJF), southwest Australia (June–August: JJA) and southeast Australia (JJA). Dashed lines on the maps for Australia show regions used for the time series. Rainfall trend maps are shown for 1960–2019 (DJF and JJA) using contours for Australia and individual sites for New Zealand. Areas of low Australian rainfall (less than 0.25 mm/day) are shaded white in JJA. Data courtesy of BOM and NIWA.

Table 11.2a | Observed climate change for Australia.

Climate variable	Observed change	References
Air temperature over land	Increased by 1.4°C from 1910 to 2019, with 2019 being the warmest year; 9 of the 10 warmest on record have occurred since 2005; clear anthropogenic attribution.	(BoM and CSIRO, 2020; Trewin et al., 2020; BoM, 2021a; Gutiérrez et al., 2021)
Sea surface temperature	Increased by 1.0°C from 1900 to 2019 (0.09°C/decade), with an increase of 0.16°C–0.20°C/decade since 1950 in the southeast. Eight of the 10 warmest years on record have occurred since 2010.	(BoM and CSIRO, 2020)
Air temperature extremes over land	More extremely hot days and fewer extremely cold days in most regions. Weaker warming trends in minimum temperatures in southeast Australia compared to elsewhere during 1960–2016. Frost frequency in southeast and southwest Australia has been relatively unchanged since the 1980s. Very high monthly maximum or minimum temperatures that occurred around 2% of the time in the past (1960–1989) now occur 11–12% of the time (2005–2019). Multi-day heatwave events have increased in frequency and duration across many regions since 1950. In 2019, the national average maximum temperature exceeded the 99th percentile on 43 days (more than triple the number in any of the years prior to 2000) and exceeded 39°C on 33 days (more than the number observed from 1960 to 2018 combined).	(Perkins-Kirkpatrick et al., 2016; Alexander and Arblaster, 2017; Pepler et al., 2018; BoM and CSIRO, 2020; Perkins-Kirkpatrick and Lewis, 2020; Trancoso et al., 2020)
Sea temperature extremes	Intense marine heatwave in 2011 near western Australia (peak intensity 4°C, duration 100 days). The likelihood of an event of this duration is estimated to be about five times higher than under pre-industrial conditions. Marine heatwave over northern Australia in 2016 (peak intensity 1.5°C, duration 200 days). Marine heatwave in the Tasman Sea and around southeast mainland Australia and Tasmania from September 2015 to May 2016 (peak intensity 2.5°C, duration 250 days)—likelihood of an event of this intensity and duration has increased about 50-fold. Marine heatwave in the Tasman Sea from November 2017 to March 2018 (peak intensity 3°C, duration 100 days). Marine heatwave on the GBR in 2020 (peak intensity 1.2°C, duration 90 days)	(BoM and CSIRO, 2018; BoM, 2020; Laufkötter et al., 2020; Oliver et al., 2021)
Rainfall	Northern Australian rainfall has increased since the 1970s, with an attributable human influence. April to October rainfall has decreased 16% since the 1970s in southwestern Australia (partly due to human influence) and 12% from 2000–2019 in south-eastern Australia. The lowest recorded average rainfall in Australia occurred in 2019.	(Delworth and Zeng, 2014; Knutson and Zeng, 2018; Dey et al., 2019; BoM and CSIRO, 2020; BoM, 2021a)
Rainfall extremes	Hourly extreme rainfall intensities increased by 10–20% in many locations between 1966 to1989 and 1990 to 2013. Daily rainfall associated with thunderstorms increased 13–24% from 1979 to 2016, particularly in northern Australia. Daily rainfall intensity increased in the northwest from 1950 to 2005 and in the east from 1911 to 2014 and decreased in the southwest and Tasmania from 1911 to 2010.	(Donat et al., 2016; Alexander and Arblaster, 2017; Evans et al., 2017; Guerreiro et al., 2018; Dey et al., 2019; BoM and CSIRO, 2020; Bruyère et al., 2020; Dowdy, 2020; Dunn et al., 2020; Gutiérrez et al., 2021)
Drought	Major Australian droughts occurred in 1895–1902, 1914–1915, 1937–1945, 1965–1968, 1982–1983, 1997–2009 and 2017–2019. Fewer droughts have occurred across most of northern and central Australia since the 1970s, and more droughts have occurred in the southwest since the 1970s; drought trends in the southeast have been mixed since the late 1990s.	(Gallant et al., 2013; Delworth and Zeng, 2014; Alexander and Arblaster, 2017; Dai and Zhao, 2017; Knutson and Zeng, 2018; Dey et al., 2019; Spinoni et al., 2019; Dunn et al., 2020; Rauniyar and Power, 2020; BoM, 2021b; Seneviratne et al., 2021)
Wind speed	Wind speed decreased 0.067 m/s/decade over land in the period 1941–2016, with a decrease of 0.062 m/s/decade over land from 1979 to 2015, and a decrease of 0.05–0.10 m/s/decade over land from 1988 to 2019. Wind speed increased 0.02 m/s/year across the Southern Ocean during 1985–2018.	(Troccoli et al., 2012; Young and Ribal, 2019; Blunden and Arndt, 2020; Azorin-Molina et al., 2021)
Sea level rise	Relative SLR was 3.4 mm/year from 1993 to 2019, which includes the influence of internal variability (e.g., ENSO) and anthropogenic greenhouse gases.	(Watson, 2020)
Fire	An increase in the number of extreme fire weather days from July 1950 to June 1985 compared to July 1985 to June 2020, especially in the south and east, partly attributed to climate change. More dangerous conditions for extreme pyro convection events since 1979, particularly in south-eastern Australia. Extreme fire weather in 2019–2020 was at least 30% more likely due to climate change.	(Dowdy and Pepler, 2018; BoM and CSIRO, 2020; van Oldenborgh et al., 2021)
Tropical cyclones and other storms	Fewer tropical cyclones since 1982, with a 22% reduction in translation speed over Australian land areas in the period1949–2016. No significant trend in the number of East Coast Lows. From 1979 to 2016, thunderstorms and dry lightning decreased in spring and summer in northern and central Australia, decreased in the north in autumn, and increased in the southeast in all seasons. Convective rainfall intensity per thunderstorm increased by about 20% in the north and 10% in the south. An increase in the frequency of large to giant hail events across southeastern Queensland and northeastern and eastern New South Wales in the most recent decade. Seven major hail storms over eastern Australia from 2014 to 2020 and three major floods over eastern Australia from 2019 to 2021.	(Pepler et al., 2015b; Ji et al., 2018; Kossin, 2018; BoM and CSIRO, 2020; Dowdy, 2020; ICA, 2021; Bruyère et al., 2020)
Snow	At Spencers Creek (1830 m elevation) in NSW, annual maximum snow depth decreased 10% and length of snow season decreased 5% during 2000–2013 relative to 1954–1999. At Rocky Valley Dam (1650 m elevation) in Victoria, annual maximum snow depth decreased 5.7 cm/decade from 1954 to 2011. At Mt Hotham, Mt Buller and Falls Creek (1638–1760 m elevation), annual maximum snow depth decreased 15%/decade from 1988 to 2013.	(Bhend et al., 2012; Fiddes et al., 2015; Pepler et al., 2015a; BoM and CSIRO, 2020)
Ocean acidification	Average pH of surface waters has decreased since the 1880s by about 0.1 (over 30% increase in acidity).	(BoM and CSIRO, 2020)

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Table 11.2b | Observed climate change for New Zealand.

Climate variable	Observed change	References
Air temperature	Increased by 1.1°C in the period 1909–2019. Warmest year on record was 2016, followed by 2018 and 1998, which tied for second warmest. The six years between 2013 and 2020 were among New Zealand's warmest on record.	(MfE, 2020a; NIWA, 2020)
Sea surface temperature	Increased by 0.2°C/decade from 1981 to 2018.	(MfE, 2020a)
Air temperature extremes	Number of frost days (below 0°C) decreased at 12 of 30 sites, the number of warm days (over 25°C) increased at 19 of 30 sites, and the number of heatwave days increased at 18 of 30 sites during 1972–2019. Increase in the frequency of hot February days exceeding the 90th percentile between 1980–1989 and 2010–2019, with some regions showing more than a five-fold increase.	(Harrington, 2020; MfE, 2020a)
Sea temperature extremes	The eastern Tasman Sea experienced a marine heatwave in 2017/2018 lasting 138 days with a maximum intensity of 4.1°C, and another marine heatwave in 2018/2019 lasting 137 days with a maximum intensity of 2.8°C.	(NIWA, 2019; Salinger et al., 2019b; Salinger et al., 2020; Oliver et al., 2021)
Rainfall	From 1960 to 2019, almost half of the 30 sites had an increase in annual rainfall (mostly in the south) and 10 sites (mostly in the north) had a decrease, but few of the trends are statistically significant. Rainfall increased by 2.8% per decade in Whanganui, 2.1% per decade in Milford Sound and 1.3% per decade in Hokitika. Rainfall decreased by 4.3% per decade in Whangarei and 3.2% per decade in Tauranga.	(MfE, 2020a)
Rainfall extremes	The number of days with extreme rainfall increased at 14 of 30 sites and decreased at 11 sites during 1960–2019. Most sites with increasing annual rainfall had more extreme rainfall, and most sites with decreasing annual rainfall had less extreme rainfall.	(MfE, 2020a)
Drought	Drought frequency increased at 13 of 30 sites from 1972 to 2019 and decreased at 9 sites. Drought intensity increased at 14 sites, 11 of which are in the north, and decreased at 9 sites, 7 of which are in the south.	(MfE, 2020a)
Wind speed	Since 1970, the wind belt has often shifted to the south of New Zealand, bringing an overall decrease in wind speed over the country. For 1980–2019, the annual maximum wind gust decreased at 11 of the 14 sites that had enough data to calculate a trend and increased at 2 of the 14 sites.	(MfE, 2020a)
Sea level rise	Increased 1.8 mm/year during 1900–2018 and 2.4 mm/year during 1961–2018, mostly due to climate change.	(Bell and Hannah, 2019)
Fire	Of the 28 sites, 6 sites (Napier, Lake Tekapo, Queenstown, Gisborne, Masterton, and Gore) had an increase in days with very high or extreme fire danger during 1997–2019 and 6 sites (Blenheim, Christchurch, Nelson, Tara Hills, Timaru, and Wellington) had a decrease. An increase in fire impacts during 1988–2018 included homes lost, damaged, threatened and evacuated.	(Pearce, 2018; MfE, 2020a)
Tropical cyclones and other storms	No significant change in storminess. Three major floods and two major hail storms during 2019–2021.	(MfE, 2020a; ICNZ, 2021)
Snow and ice	From 1978 to 2019, the snowline rose 3.7 m/year. From 1977 to 2018, glacier ice volume decreased from 26.6 to 17.9 km^3 (a loss of 33%). From 1978 to 2016, the area of 14 glaciers in the southern Alps declined 21%. The end-of-summer snowline elevation for 50 glaciers rose 300 m from 1949 to 2019. In the southern Alps, extreme glacier mass loss was at least 6 times more likely in 2011 and 10 times more likely in 2018 due to climate change.	(Salinger et al., 2019a; Baumann et al., 2020; Chinn and Chinn, 2020; MfE, 2020a; Salinger et al., 2021; Vargo et al., 2020)
Ocean acidification	The Sub-Antarctic ocean off the Otago coast became 7% more acidic from 1998–2017.	(MfE, 2020a)

in southern Australia and extreme rainfall and severe droughts in New Zealand.

11.2.2 Projected Climate Change

There are three main sources of uncertainty in climate projections: emission scenarios, regional climate responses and internal climate variability (CSIRO and BOM, 2015). Emission scenario uncertainty is captured in Representative Concentration Pathways (RCPs) for greenhouse gases and aerosols. RCP2.6 represents low emissions, RCP4.5 medium emissions and RCP8.5 high emissions. Regional climate response uncertainty and internal climate variability uncertainty are captured in climate model simulations driven by the RCPs.

Further climate change is inevitable, with the rate and magnitude largely dependent on the emission pathway (*very high confidence*) (IPCC, 2021). Preliminary projections based on Climate Model Intercomparison Project Phase 6 (CMIP6) models are described in the IPCC Working Group I Atlas. For Australia, the CMIP6 projections broadly agree with CMIP5 projections except for a group of CMIP6 models with greater warming and a narrower range of summer rainfall change in the north and winter rainfall change in the south (Grose et al., 2020). For New Zealand, the CMIP6 projections are similar to CMIP5, but the CMIP6 models indicate greater warming, a smaller increase in summer precipitation and a larger increase in winter precipitation (Gutiérrez et al., 2021).

Dynamical and statistical downscaling offer the prospect of improved representation of regional climate features and extreme weather events (IPCC 2021: Working Group I Chapter 10 (Doblas-Reyes et al., 2021)), but the added value of downscaling is complex to evaluate (Ekström et al., 2015; Rummukainen, 2015; Virgilio et al., 2021). Downscaled simulations are available for New Zealand (MfE, 2018) and various Australian regions (Gutiérrez et al., 2021). Further downscaling was recommended by the Royal Commission into National Natural Disaster Arrangements (CoA, 2020e). Projections for rainfall, thunderstorms, hail, lightning and tornadoes have large uncertainties (Walsh et al., 2016; MfE, 2018).

Future changes in climate variability are affected by the El Niño Southern Oscillation (ENSO), Southern Annular Mode (SAM), Indian Ocean Dipole (IOD) and Interdecadal Pacific Oscillation (IPO). An increase in strong El Niño and La Niña events is projected (Cai, 2015), along with more extreme positive phases of the IOD (Cai et al., 2018) and a positive trend in SAM (Lim et al., 2016), but potential changes in the IPO are unknown (NESP ESCC, 2020). There is uncertainty about regional climate responses to projected changes in ENSO (King et al., 2015; Perry et al., 2020; Virgilio et al., 2021).

Australian climate projections are quantified with references in Table 11.3a. Further warming is projected, with more hot days, fewer cold days, reduced snow cover, ongoing sea level rise (SLR) and ocean acidification (*very high confidence*). Winter and spring rainfall and soil moisture are projected to decrease, with higher evaporation rates, decreased wind over southern mainland Australia, increased wind over Tasmania, and more extreme fire weather in southern and eastern Australia (*high confidence*). Heavy rainfall intensity is projected to increase, with more droughts over southern and eastern Australia (*medium confidence*). Increased winter rainfall is projected over Tasmania, with decreased rainfall in southwestern Victoria in autumn and in western Tasmania in summer, fewer tropical cyclones with a greater proportion of severe cyclones and decreased soil moisture in the north (*medium confidence*). Hailstorm frequency may increase (*low confidence*).

New Zealand climate projections are quantified with references in Table 11.3b. Further warming is projected, with more hot days, fewer cold days, less snow and glacial ice, ongoing sea level rise (SLR) and ocean acidification (*very high confidence*). Increases in winter and spring rainfall are projected in the west of the North and South Islands, with drier conditions in the east and north, caused by stronger westerly winds (*medium confidence*). In summer, wetter conditions are projected in the east of both islands, with drier conditions in the west and central North Island (*medium confidence*). Fire weather indices are projected to increase over northern and eastern New Zealand (*medium confidence*). Heavy rainfall intensity is projected to increase over most regions, with increased extreme wind speeds in eastern regions, especially in Marlborough and Canterbury, and reduced relative humidity almost everywhere, except for the west coast in winter (*medium confidence*). Drought frequency may increase in the north (*medium confidence*).

11.3 Observed Impacts, Projected Impacts and Adaptation

This section assesses observed impacts, projected risks and adaptation for 10 sectors and systems. Boxes provide more details on specific issues. Risk is considered in terms of vulnerability, hazards (impact driver), exposure, reasons for concern and complex and cascading risks (Chapter 1; Figure 1.2).

11.3.1 Terrestrial and Freshwater Ecosystems

11.3.1.1 Observed Impacts

Widespread and severe impacts on ecosystems and species are now evident across the region (*very high confidence*) (Table 11.4). Climate impacts reflect both ongoing change and discrete extreme weather events (Harris et al., 2018), and the climatic change signal is emerging despite confounding influences (Hoffmann et al., 2019). Fundamental shifts are observed in the structure and composition of some ecosystems and associated services (Table 11.4). Impacts documented for species include global and local extinctions, severe regional population declines and phenotypic responses (Table 11.4). In terrestrial and freshwater ecosystems, land use impacts are interacting with climate, resulting in significant changes to ecosystem structure, composition and function (Bergstrom et al., 2021), with some landscapes experiencing catastrophic impacts (Table 11.4). Some of the observed changes may be irreversible where projected impacts on ecosystems and species persist (Table 11.5). Of note is the global extinction of an endemic mammal species, the Bramble Cay melomys (*Melomys rubicola*), from the loss of habitat attributable in part to sea level rise (SLR) and storm surges in the Torres Strait (Table 11.4).

Natural forest and woodland ecosystem processes are experiencing differing impacts and responses depending on the climate zone (*high confidence*). In Australia, an overall increase in the forest fire danger index, associated with warming and drying trends (Table 11.2a), has been observed particularly for southern and eastern Australia in recent decades (Box 11.1). The 2019–2020 mega wildfires of south eastern Australia burnt between 5.8 and 8.1 million hectares of mainly temperate broadleaf forest and woodland, but with substantial areas of rainforest also impacted, and were unprecedented in their geographic location, spatial extent and forest types burnt (Boer et al., 2020; Nolan et al., 2020; Abram et al., 2021; Collins et al., 2021; Godfree et al., 2021). The human influence on these events is evident (Abram et al., 2021; van Oldenborgh et al., 2021) (Box 11.1). The fires had significant consequences for wildlife (Hyman et al., 2020; Nolan et al., 2020; Ward et al., 2020) (Box 11.1) and flow-on impacts for aquatic fauna (Silva et al., 2020). In southern Australia, deeply rooted native tree species can access soil and groundwater resources during drought, providing a level of natural resilience (Bell and Nikolaus Callow, 2020; Liu et al., 2020). However, the Northern Jarrah forests of south western Australia have experienced tree mortality and dieback from long-term precipitation decline and acute heatwave-compounded drought (Wardell-Johnson et al., 2015; Matusick et al., 2018). While there is limited information on observed impacts for New Zealand, increased mast seeding events in beech forest ecosystems that stimulate invasive population irruptions have been recorded (Schauber et al., 2002; Tompkins et al., 2013).

11.3.1.2 Projected Impacts

In the near term (2030–2060), climate change is projected to become an increasingly dominant stress on the region's biodiversity, with some ecosystems experiencing irreversible changes in composition and structure and some threatened species becoming extinct (*high confidence*). Climate change will interact with current ecological conditions, threats and pressures, with cascading ecological impacts,

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Table 11.3a | Projected climate change for Australia. Projections are given for different RCPs (RCP2.6 is low, RCP4.5 is medium, RCP8.5 is high) and years (e.g., 20-year period centred on 2090). Uncertainty ranges are generally 10th–90th percentile, and median projections are given in square brackets where possible. The four Australian regions are shown in Chapter 2 of (CSIRO and BOM, 2015). Preliminary projections based on CMIP6 models are included for some climate variables from the IPCC (2021) WGI report.

Climate variable	Projected change (year, RCP) relative to 1986–2005	References
Air temperature	Annual mean temperature – +0.5–1.5°C (2050, RCP2.6), +1.5–2.5°C (2050, RCP8.5), +0.5–1.5°C (2090, RCP2.6), +2.5–5.0°C (2090, RCP8.5) – Weaker increase in the south, stronger increase in the centre – Preliminary CMIP6 projections: +0.6°C–1.3°C (2050, SSP1-RCP2.6), +1.2°C–2.0°C (2050, SSP5-RCP8.5), +0.6°C–1.5°C (2090, SSP1-RCP2.6), +2.8°C–4.9°C (2090, SSP5-RCP8.5) relative to 1995–2014	(NESP ESCC, 2020; IPCC, 2021)
Sea surface temperature	– + 0.4–1.0°C (2030, RCP8.5) – +2–4°C (2090, RCP8.5)	(CSIRO and BOM, 2015)
Air temperature extremes	– Annual frequency of days over 35°C may increase 20–70% by 2030 (RCP4.5) and 25–85% (RCP2.6) to 80–350% (RCP8.5) by 2090 – Heatwave frequency may rise by 85% if global warming increases from 1.5°C to 2.0°C, and it may rise by four times for xxxx 3°C warming – Annual frequency of frost days may decrease by 10–40% (2030, RCP4.5), 10–40% (2090, RCP2.6) and 50–100% (2090, RCP8.5)	(CSIRO and BOM, 2015; Trancoso et al., 2020)
Rainfall	Annual mean rainfall – South: –15 to +2% (2050, RCP2.6), –14 to +3% (2050, RCP8.5), –15 to +3% (2090, RCP2.6), –26 to +4% (2090, RCP8.5) – East: –13 to +7% (2050, RCP2.6), –17 to +8% (2050, RCP8.5), –19 to +6% (2090, RCP2.6), –25 to +12% (2090, RCP8.5) – North: –12 to +5% (2050, RCP2.6), –8 to +11% (2050, RCP8.5), –12 to +3% (2090, RCP2.6), –26 to +23% (2090, RCP8.5) – Rangelands: –18 to +3% (2050, RCP2.6), –15 to +8% (2050, RCP8.5), –21 to +3% (2090, RCP2.6), –32 to +18% (2090, RCP8.5)	(Liu et al., 2018; NESP ESCC, 2020)
Rainfall extremes	Intensity of daily total rain with 20-year recurrence interval – +4 to +10% (2050, RCP2.6) – +8 to +20% (2050, RCP8.5) – +4 to +10% (2090, RCP2.6) – +15 to +35% (2090, RCP8.5)	(NESP ESCC, 2020)
Drought	Time in drought (Standardised Precipitation Index below –1) – Southern Australia: 32–46% [39%] (1995), 38–68% [54%] (2050, RCP8.5), 41–81% [60%] (2090, RCP8.5) – Eastern Australia: 25–46% [37%] (1995), 24–67% [47%] (2050, RCP8.5), 19–76% [56%] (2090, RCP8.5) – Northern Australia: 26–44% [34%] (1995), 18–54% [40%] (2050, RCP8.5), 9–81% [39%] (2090, RCP8.5) – Australian Rangelands: 29–43% [34%] (1995), 26–58% [42%] (2050, RCP8.5), 23–70% [46%] (2090, RCP8.5)	(Kirono et al., 2020)
Wind speed	0–5% decrease over southern mainland Australia and 0–5% increase over Tasmania (2090, RCP8.5)	(CSIRO and BOM, 2015)
Sea level rise	– South (Port Adelaide): 13–29 cm [21 cm] (2050, RCP2.6), 16–33 cm [25 cm] (2050, RCP8.5), 23–55 cm [39 cm] (2090, RCP2.6), 40–84 cm [61 cm] (2090, RCP8.5) – East (Newcastle): 14–30 cm [22 cm] (2050, RCP2.6), 19–36 cm [27 cm] (2050, RCP8.5), 22–54 cm [38 cm] (2090, RCP2.6), 46–88 cm [66 cm] (2090, RCP8.5) – North (Darwin City Council, 2011): 13–28 cm [21 cm] (2050, RCP2.6), 17–33 cm [25 cm] (2050, RCP8.5), 22–55 cm [38 cm] (2090, RCP2.6), 41–85 cm [62 cm] (2090, RCP8.5) – West (Port Hedland): 13–28 cm [20 cm] (2050, RCP2.6), 16–33 cm [24 cm] (2050, RCP8.5), 22–55 cm [38 cm] (2090, RCP2.6), 40–84 cm [61 cm] (2090, RCP8.5) These projections have not been updated to include an Antarctic dynamic ice sheet factor which increased global sea level projections for RCP8.5 by approx. 10 cm. Preliminary CMIP6 projections indicate +40–50 cm (2090, SSP1-RCP2.6) and +70–90 cm (2090, SSP5-RCP8.5)	(McInnes et al., 2015; Zhang et al., 2017; IPCC, 2019b) (IPCC, 2021)
Sea level extremes	Increase in the allowance for a storm tide event with 1% annual exceedance probability (100-year return period) – South (Port Adelaide): 21 cm (2050, RCP2.6), 25 cm (2050, RCP8.5), 41 cm (2090, RCP2.6), 66 cm (2090, RCP8.5) – East (Newcastle): 24 cm (2050, RCP2.6), 30 cm (2050, RCP8.5), 49 cm (2090, RCP2.6), 86 cm (2090, RCP8.5) – North (Darwin): 21 cm (2050, RCP2.6), 26 cm (2050, RCP8.5), 43 cm (2090, RCP2.6), 71 cm (2090, RCP8.5) – West (Port Hedland): 21 cm (2050, RCP2.6), 26 cm (2050, RCP8.5), 43 cm (2090, RCP2.6), 70 cm (2090, RCP8.5)	(McInnes et al., 2015)
Fire	– East: annual number of severe fire weather days 0 to +30% (2050, RCP2.6), 0 to +60% (2050, RCP8.5), 0 to +30% (2090, RCP2.6), 0 to +110% (2090, RCP8.5) – Elsewhere: number of severe fire weather days +5 to +35% (2050, RCP2.6), +10 to +70% (2050, RCP8.5), +5 to +35% (2090, RCP2.6) +20 to +130% (2090, RCP8.5)	(Clarke and Evans, 2019; Dowdy et al., 2019; Virgilio et al., 2019; Clarke et al., 2020; NESP ESCC, 2020; Clark et al., 2021)
Tropical cyclones and other storms	– Eastern region tropical cyclones: –8 to +1% (2050, RCP2.6), –15 to +2% (2050, RCP8.5), –8 to +1% (2090, RCP2.6), –25 to +5% (2090, RCP8.5) – Western region tropical cyclones: –10 to –2% (2050, RCP2.6), –20 to –4% (2050, RCP8.5), –10 to –2% (2090, RCP2.6), –30 to –10% (2090, RCP8.5) – East coast lows: –15 to –5% (2050, RCP2.6), –30 to –10% (2050, RCP8.5), –15 to –5% (2090, RCP2.6), –50 to –20% (2090, RCP8.5) – Hailstorm frequency may increase, but there are large uncertainties	(NESP ESCC, 2020; Raupach et al., 2021)

Climate variable	Projected change (year, RCP) relative to 1986–2005	References
Snow and ice	– Maximum snow depth at Falls Creek and Mt Hotham may decline 30–70% (2050, B1) and 45–90% (2050, A1FI) relative to 1990 – Maximum snow depth at Mt Buller and Mt Buffalo may decline 40–80% (2050, B1) and 50–100% (2050, A1FI) relative to 1990 – Length of Victorian ski season may contract 65–90% and mean annual snowfall may decline 60–85% (2070–2099, RCP8.5) relative to 2000–2010. – The snowpack may decrease by about 15% (2030, A2) to 60% (2070, A2)	(Bhend et al., 2012; Harris et al., 2016; Di Luca et al., 2018)
Ocean acidification	pH is projected to drop by about 0.1 (2090, RCP2.6) to 0.3 (2090, RCP8.5)	(CSIRO and BOM, 2015; Hurd et al., 2018)

Table 11.3b | Projected climate change for New Zealand. Projections are given for different RCPs (RCP2.6 is low, RCP4.5 is medium, RCP8.5 is high) and years (e.g., 20-year period centred on 2090). Uncertainty ranges are 5th–95th percentiles, and median projections are given in square brackets where possible. Preliminary projections (10th–90th percentiles) based on CMIP6 models are included for some climate variables from the IPCC (2021) WGI report.

Climate variable	Projected change (year, RCP) relative to 1986–2005	References
Air temperature	Annual mean temperature – +0.2–1.3°C [0.7°C] (2040, RCP2.6), +0.5–1.7°C [1.0°C] (2040, RCP8.5), +0.1–1.4°C [0.7°C] (2090, RCP2.6), +2.0–4.6°C [3.0°C] (2090, RCP8.5) – More warming in summer and autumn, less in winter and spring – More warming in the north than the south – Preliminary CMIP6 projections: +0.4°C–1.1°C (2050, SSP1-RCP2.6), +0.9°C–1.7°C (2050, SSP5-RCP8.5), +0.5°C–1.5°C (2090, SSP1-RCP2.6), +2.2°C–4.1°C (2090, SSP5-RCP8.5) relative to 1995–2014	(MfE, 2018); (IPCC, 2021)
Sea surface temperature	– +1.0°C (2045, RCP8.5), – +2.5°C (2090, RCP8.5).	(Law et al., 2018b)
Air temperature extremes	– Annual frequency of days over 25°C may increase 20–60% (2040, RCP2.6) to 50–100% (2040, RCP8.5), and 20–60% (2090, RCP2.6) to 130–350% (2090, RCP8.5) – Annual frost frequency may decrease 20–60% (2040, RCP2.6) to 30–70% (2040, RCP8.5), and 20–60% (2090, RCP2.6) to 70–95% (2090, RCP8.5).	(MfE, 2018)
Rainfall	Annual mean rainfall – Waikato, Auckland and Northland: –7 to +7% (2040, RCP2.6), –8 to +5% (2040, RCP8.5), –5 to +11% [+2%] (2090, RCP2.6), –15 to +12% [–2%] (2090, RCP8.5) – Hawke's Bay and Gisborne: –8 to +8% [–1%] (2040, RCP2.6), –12 to +7% [–2%] (2040, RCP8.5), –9 to +4% [–2%] (2090, RCP2.6), –15 to +15% [–3%] (2090, RCP8.5) – Taranaki, Manawatū and Wellington: –4 to +9% [+1%] (2040, RCP2.6), –6 to +10% [+1%] (2040, RCP8.5), –6 to +15% [+3%] (2090, RCP2.6), –14 to +14% [+2%] (2090, RCP8.5) – Tasman-Nelson and Marlborough: –3 to +5% [+1%] (2040, RCP2.6), –3 to +8% [+1%] (2040, RCP8.5), –4 to +8% [+2%] (2090, RCP2.6), –3 to +15% [+5%] (2090, RCP8.5) – West coast and Southland: –4 to +12% [+3%] (2040, RCP2.6), –4 to +12% [+4%] (2040, RCP8.5), –2 to +18% [+5%] (2090, RCP2.6), –8 to +23% (2090, RCP8.5) – Canterbury and Otago: –7 to +15% [+3%] (2040, RCP2.6), –7 to +19% [+3%] (2040, RCP8.5), –6 to +18% (2090, RCP2.6), –9 to +28% [+8%] (2090, RCP8.5)	(Liu et al., 2018; MfE, 2018)
Rainfall extremes	Intensity of daily rain with 20-year recurrence interval – +2.8 to 7.2% [5%] (2040, RCP2.6) – +4.2 to 10.4% [7%] (2040, RCP8.5) – +2.8 to 7.2% [5%] (2090, RCP2.6) – +12.6 to 31.5% [2%] (2090, RCP8.5)	(MfE, 2018)
Drought	Increase in potential evapotranspiration deficit – Northern and eastern North Island: 100–200 mm (2090, RCP8.5) – Western North Island: 50–100 mm (2090, RCP8.5) – Eastern South Island: 50–200 mm (2090, RCP8.5) – Western South Island: 0–50 mm (2090, RCP8.5)	(MfE, 2018)
Wind speed	99th percentile of daily mean wind speed – Northern North Island: 0 to –5% (2090, RCP8.5) – Southern North Island: 0 to +5% (2090, RCP8.5) – South Island: 0 to +10% (2090, RCP8.5)	(MfE, 2018)
Sea level rise	– 23 cm (2050, RCP2.6) – 28 cm (2050, RCP8.5) – 42 cm (2090 RCP2.6) – 67 cm (2090 RCP8.5) These projections have not been updated to include an Antarctic dynamic ice sheet factor which increased global sea level projections for RCP 8.5 by approx. 10 cm. Preliminary CMIP6 projections indicate 40–50 cm (2090, SSP1-RCP2.6) and 70–90 cm (2090, SSP5-RCP8.5).	(MfE, 2017a; IPCC, 2019b)

Climate variable	Projected change (year, RCP) relative to 1986–2005	References
Sea level extremes	For a rise in sea level of 30 cm, the 1-in-100-year high water levels may occur about – Every 4 years at the port of Auckland – Every 2 years at the port of Dunedin – Once a year at the port of Wellington – Once a year at the port of Christchurch	(PCE, 2015)
Fire	– Seasonal Severity Rating (SSR) increases 50–100% in coastal Marlborough and Otago, 40–50% in Wellington and 30–40% in Taranaki and Whanganui, 0–30% elsewhere (2050, A1B). – Number of days with very high or extreme fire weather increase >100% in coastal Otago, Marlborough and the lower North Island, 50–100% in Taupō and Rotorua, 20–50% in the rest of the North Island, and little change in the rest of the South Island (2050, A1B).	(Pearce et al., 2011)
Tropical cyclones and other storms	Poleward shift of mid-latitude cyclones and potential for a small reduction in frequency	(MfE, 2018)
Snow and ice	– Maximum snow depth on 31 August may decline by 0–10% (2040, A1B) and 26–54% (2090, A1B). – Annual snow days may be reduced by 5–15 days (2040, RCP2.6), 10–25 days (2040, RCP8.5), 5–15 days (2090, RCP2.6) and 15–45 days (2090 RCP8.5). – Relative to 2015, New Zealand glaciers are projected to lose 36%, 53% and 77% of their mass by the end of the century under RCP2.6, RCP4.5 and RCP8.5, respectively. – Over the period 2006–2099, New Zealand glaciers are projected to lose 50 to 92% of their ice volume for RCP2.6 to RCP8.5.	(Hendrikx et al., 2013; MfE, 2018; Marzeion et al., 2020; Anderson et al., 2021)
Ocean acidification	pH is projected to drop by about 0.1 (2090, RCP2.6) to 0.3 (2090 RCP8.5).	(CSIRO and BOM, 2015; Hurd et al., 2018; Law et al., 2018b)

including population declines, heat-related mortalities, extinctions and disruptions for many species and ecosystems (*high confidence*) (Table 11.5). These include inadequate allocation of environmental flows for freshwater fish (Vertessy et al., 2019), native forest logging for old-growth-forest-dependent fauna (Lindenmayer et al., 2015; Lindenmayer and Taylor, 2020a; Lindenmayer and Taylor, 2020b), and invasive species (Scott et al., 2018). Climate change has synergistic and compounding impacts, particularly in bioregions already experiencing ecosystem degradation, threatened endemics and collapse of keystone species, including those of value to Indigenous Peoples, and high extinction rates as a consequence of human activities (Table 11.4) (Gordon, 2009; Australia SoE, 2016; Weeks et al., 2016; Cresswell and Murphy, 2017; Hare et al., 2019; MfE, 2019; Lindenmayer and Taylor, 2020a; Lindenmayer and Taylor, 2020b; Bergstrom et al., 2021). Some native species are projected to have potentially greater geographic range if they can colonise new areas, while other species may be resilient to projected climate change impacts (Bulgarella et al., 2014; K.E. Lawrence et al., 2017; Conroy et al., 2019; Rizvanovic et al., 2019).

In southern Australia, some forest ecosystems (alpine ash, snow gum woodland, pencil pine, northern jarrah) are projected to transition to a new state or collapse due to hotter and drier conditions with more fires (*high confidence*) (Table 11.5). In Australia, most native eucalyptus forest plants have a range of traits that enable them to persist with recurrent fire through recovery buds (sprouters) or regenerate through seeding (Collins, 2020), affording them a high level of resilience. For high-end projected 2060–2080 fire weather conditions in southeast Australia (Clarke and Evans, 2019), stand-killing wildfires could occur at a severity and frequency greater than the regenerative capacity of seeders (Enright et al., 2015; Clarke and Evans, 2019). Most New Zealand native plants are not fire resistant and are projected to be replaced by fire-resistant introduced species following climate-change-related fires (Perry et al., 2014).

A loss of alpine biodiversity in the southeast Australian Alps bioregion is projected in the near-term as a result of less snow on snow patch feldmark and short alpine herb fields as well as increased stress on snow-dependent plant and animal species (*high confidence*) (Table 11.3, Table 11.5). In Australia, invasive plants' and weeds' response rates are expected to be faster than for native species, and climate change could foster the appearance of a new set of weed species, with many bioregions facing increased impacts from non-native plants (*medium confidence*) (Gallagher et al., 2013; Scott et al., 2014; March-Salas and Pertierra, 2020) (Table 11.5), along with declines in some listed weeds (Duursma et al., 2013; Gallagher et al., 2013). In New Zealand, climate change is projected to enable invasive species to expand to higher elevations and southwards (*medium confidence*) (Table 11.5) (Giejsztowt et al., 2020; MfE, 2020a).

Projected responses of ecosystem processes are uncertain in part due to complex interactions of climate change with soil respiration, plant nutrient availability (Hasegawa et al., 2015; Orwin et al., 2015; Ochoa-Hueso et al., 2017) and changing fire regimes (Table 11.5) (Scheiter et al., 2015; Dowdy et al., 2019). For aquatic biota, responses will reflect seasonal differences in water temperature (Wallace et al., 2015) and changes in rainfall intensity, productivity and biodiversity (Jardine et al., 2015). Extreme floods may have negative impacts on New Zealand river biota, by mobilising nutrients, sediments and toxic chemicals and aiding the dispersal of invasive species. These effects are compounded by homogenisation of rivers through channelisation (Death et al., 2015).

Improved coastal modelling, experiments and *in situ* studies are reducing uncertainties at a local scale about the impact of future sea level rise (SLR) on coastal freshwater terrestrial wetlands (*medium confidence*) (Shoo et al., 2014; Bayliss et al., 2018; Grieger et al., 2019). Low-lying coastal wetlands are susceptible to saltwater intrusion from sea level rise (SLR) (Shoo et al., 2014; Kettles and Bell, 2015; Finlayson et al., 2017) with consequences for species dependent on freshwater habitats (Houston et al., 2020). Saline habitat conditions will move

Table 11.4 | Observed impacts on terrestrial and freshwater ecosystems and species in the region where there is documented evidence that these are directly (e.g., a species thermal tolerances are exceeded) or indirectly (e.g., through changed fire regimes) the result of climate change pressures.

Ecosystem	Climate-related pressure	Impact	Source
Australia			
Forest and woodlands of southern and southwestern Australia	30-year declining rainfall	Drought-induced canopy dieback across a range of forest and woodland types (e.g., northern jarrah)	(Matusick et al., 2018; Hoffmann et al., 2019)
	Multiple wildfires in short succession resulting from increased fire risk conditions, including declining winter rainfall and increasing hot days	Local extirpations and replacement of dominant canopy tree species and replacement by woody shrubs due to seeders having insufficient time to reach reproductive age (alpine ash) or vegetative regeneration capacity is exhausted (snow gum woodlands)	(Slatyer, 2010; Bowman et al., 2014; Fairman et al., 2016; Harris et al., 2018; Zylstra, 2018)
	Background warming and drying created soil and vegetation conditions that are conducive to fires being ignited by lightning storms in regions that have rarely experienced fire over the last few millennia	Death of fire-sensitive trees species from unprecedented fire events (Palaeo-endemic pencil pine forest growing in sphagnum, Tasmania, killed by lightning-ignited fires in 2016)	(Hoffmann et al., 2019)
Australian Alps Bioregion and Tasmanian alpine zones	Severe winter drought; warming and climate-induced biotic interactions	Shifts in dominant vegetation with a decline in grasses and other graminoids and an increase in forb and shrub cover in Bogong High Plains, Victoria, Australia	(Bhend et al., 2012; Hoffmann et al., 2019)
	Snow loss, fire, drought and temperature changes	Changing interactions within and among three key alpine taxa related to food supply and vegetation habitat resources: The mountain pygmy-possum (*Burramys parvus*), the mountain plum pine (*Podocarpus lawrencei*) and the bogong moth (*Agrostis infusia*)	(Hoffmann et al., 2019)
	Retreat of snow line	Increased species diversity in alpine zone	(Slatyer, 2010)
	Reduced snow cover	Loss of snow-related habitat for alpine zone endemic and obligate species	(ACE CRC, 2010; Pepler et al., 2015a; Thompson, 2016; Mitchell et al., 2019)
Wet Tropics World Heritage Area	Warming and increasing length of dry season	Some vertebrate species have already declined in both distribution area and population size, both earlier and more severely than originally predicted	(Moran et al., 2014; Hoffmann et al., 2019)
Sub-Antarctic Macquarie island	Reduced summer water availability for 17 consecutive summers, and increases in mean wind speed, sunshine hours and evapotranspiration over four decades	Dieback in critically endangered habitat-forming cushion plant *Azorella macquariensis* in the fellfield and herb field communities	(Bergstrom et al., 2015; Hoffmann et al., 2019)
Mass mortality of wildlife species (flying foxes, freshwater fish)	Extreme heat events; rising water temperatures, temperature fluctuations, altered rainfall regimes including droughts and reduced in-flows	Flying foxes—thermal tolerances of species exceeded; fish—amplified extreme temperature fluctuations, increasing annual water basin temperatures, extreme droughts and reduced runoff after rainfall	(AAS, 2019; Ratnayake et al., 2019; Vertessy et al., 2019)
Bramble Cay melomys (mammal) *Melomys rubicola*	SLR and storm surges in Torres Strait	Loss of habitat and global extinction	(Lunney et al., 2014; Gynther et al., 2016; Waller et al., 2017; CSIRO, 2018)
Koala, *Phascolarctos cinereus*	Increasing drought and rising temperatures, compounding impacts of habitat loss, fire and increasing human population	Population declines and enhanced risk of local extinctions	(Lunney et al., 2014)
Tawny dragon lizard, *Ctenophorus decresii*	Desiccation stress driven by higher body temperatures and declining rainfall	Population decline and potential local extinction in Flinders Ranges, south Australia	(Walker et al., 2015)
Birds	Changing thermal regimes including increasing thermal stress and changes in plant productivity are identified as being causal	Changes in body size, mass and condition and other traits linked to heat exchange	(Gardner et al., 2014a; Gardner et al., 2014b; Campbell-Tennant et al., 2015; Gardner et al., 2018; Hoffmann et al., 2019)

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Ecosystem	Climate-related pressure	Impact	Source
New Zealand			
Forest birds	Warming	Increasing invasive predation pressure on endemic forest birds surviving in cool forest refugia, particularly larger-bodied bird species that nest in tree cavities and are poor dispersers	(Walker et al., 2019)
Coastal ecosystems	More severe storms and rising sea levels	Erosion of coastal habitats, including dunes and cliffs, is reducing habitat	(Rouse et al., 2017)
Beech forest ecosystems	Increasing mean temperatures and indirectly through effects of events like ENSO	Increased beech mast seeding events that stimulate population irruptions for invasive rodents and mustelids, which then prey on native species	(Schauber et al., 2002; Tompkins et al., 2013)

inland and new coastal ecosystem states may emerge, including the World Heritage listed Kakadu's freshwater wetland (Bayliss et al., 2018) (Table 11.5). Increasingly, sea level rise (SLR) will shrink the intertidal zone, having implications for wading birds which use this zone (Tait and Pearce, 2019) (Box 11.6). The ecology of freshwater wetlands in New Zealand are projected to be impacted by the intersection of warming, drought and heavy rainfall (Pingram et al., 2021) (Table 11.5).

The impacts on species from projected global warming depend on their physiological and ecological responses for which knowledge is limited (Table 11.5) (Bulgarella et al., 2014; Carter et al., 2018; Green et al., 2021). Knowledge of projected impacts is constrained by uncertainties about the influence of physiological limits, barriers to dispersal, competition, the availability of habitat resources (Worth et al., 2014) and disruptions to ecological interactions (Lakeman-Fraser and Ewers, 2013; Parida et al., 2015; Porfirio et al., 2016). Gaps in ecological modelling of future climate impacts include consideration of long-term rainfall and temperature changes (Grimm-Seyfarth et al., 2017; Grimm-Seyfarth et al., 2018), species dispersal rates, evolutionary capacity and phenotypic plasticity and the thresholds at which they are considered adequate to counter the impacts of climate change (Ofori et al., 2017b), as well as indirect effects including sea level rise (SLR) and altered fire regimes (Shoo et al., 2014; Cadenhead et al., 2016; He et al., 2016).

11.3.1.3 Adaptation

Managing climate change risks to ecosystems is primarily based on reducing the impact of other anthropogenic pressures, including invasive species, and facilitating natural adaptation (*high confidence*). This approach is most feasible within protected areas on public, private and Indigenous land and sea (Bellard et al., 2014; Liu et al., 2020) but is also applicable elsewhere (Barnes et al., 2015). Effective strategies promote ecosystem resilience by changing unsustainable land uses and management practices, increasing habitat connectivity, controlling introduced species, restoring habitats, implementing appropriate fire management, integrated risk assessment and adaptation planning (B. Frame et al., 2018; Lindenmayer et al., 2020; Macinnis-Ng et al., 2021). Complementary approaches include *ex situ* seed banks (Morrison and Pickering, 2013; Christie et al., 2020).

Best practice conservation adaptation planning is informed by data on key habitats, including refugia, and restoration that facilitates species movements and employs adaptive pathways (*very high confidence*) (Guerin and Lowe, 2013; Reside et al., 2014; Shoo et al., 2014; Keppel et al., 2015; Andrew and Warrener, 2017; Baumgartner et al., 2018; Harris et al., 2018; Jacobs et al., 2018a; Das et al., 2019; Walker et al., 2019; Molloy et al., 2020). Landscape planning (Bond et al., 2014; McCormack, 2018) helps reduce habitat loss, facilitates species dispersal and gene flow (McLean et al., 2014; Shoo et al., 2014; Lowe et al., 2015; Harris et al., 2018; McCormack, 2018) and allows for new ecological opportunities (Norman and Christidis, 2016). Coastal squeeze is a threat to freshwater wetlands and requires planning for the potential inland shift (Grieger et al., 2019). Adaptations that maintain critical volumes and periodicity of environmental flows will help protect freshwater biodiversity (Box 11.3) (Yen et al., 2013; Barnett et al., 2015; Wang et al., 2018b).

Adaptation planning for ecosystems and species requires monitoring and evaluation to identify trigger points and thresholds for new actions to be implemented (*high confidence*) (Tanner-McAllister et al., 2017; Williams et al., 2020). Best planning practice includes keeping options open (Barnett et al., 2015; Dunlop et al., 2016; Finlayson et al., 2017) and updating management plans in light of new information. New insights are emerging into how species' natural adaptive capacities can inform adaptation planning (Llewelyn et al., 2016; Steane et al., 2017; Hoeppner and Hughes, 2019). Physiological limits to adaptation in some species are being identified (Barnett et al., 2015; Sorensen et al., 2016), and where natural responses are not feasible, human-assisted translocations may be warranted (Becker et al., 2013; Chauvenet et al., 2013; Innes et al., 2019) for some species (Ofori et al., 2017a; Ofori et al., 2017b). Legal reform may be needed to better enable climate adaptation for biodiversity conservation that recognises species' natural adjustments to their distributions and the difficulties encountered in predicting the consequences for ecological interactions and ecosystem services (McCormack, 2018; McDonald et al., 2019).

Adaptation research priorities include understanding of the interactions and cumulative impacts of existing stressors and climate change and the implications for managing ecosystems and natural resources (Williams et al., 2020). For Australia, research on implementation strategies for conservation and managing threats, stress and natural assets is a priority (Williams et al., 2020). For New Zealand, understanding how terrestrial ecosystems and species respond to climate change is a priority, and where existing stressors are affecting freshwater quantity and quality, *in situ* monitoring to detect and evaluate projections of climate change impacts on

Table 11.5 | An indicative selection of projected climate-change impacts on terrestrial and freshwater ecosystems and species in Australia and New Zealand respectively.

Ecosystem, species	Climate-related pressure	Projected Impact	Source
Australia			
Floristic composition of vegetation communities	Increases in temperature and reductions in annual precipitation by 2070. Many plant species based on median projection from five global climate models (ACCESS1.0, CNRM-CM5, HADGEM2-CC, MIROC5, NorESM1-M) centred on the decade 2070 under RCP8.5	47% of vegetation types have characteristic plant species at risk of their climatic tolerances being exceeded from increasing mean annual temperature by 2070 with only 2% at risk from reductions in annual precipitation by 2070	(Gallagher et al., 2019)
Some south east Australian temperate forests	Reduction in winter rainfall and rising spring temperatures resulting in an increase in the frequency of very high fire weather conditions and increased risk of catastrophic wildfires; based on output from 15 CMIP5 GCMs using RCP8.5 for years for 2060–2079 as compared to 1990–2009	Increase in fire frequency prevents recruitment of obligate seeder resulting in changing dominant species and vegetation structure including long lasting or irreversible shift in formation from tall wet temperate eucalypt forests dominated by obligate seeder trees (e.g., alpine ash) to open forest or in worst case to shrubland Declining rainfall and regolith drying, more unplanned, intense fires and declining productivity place stress on tree growth and compromise biodiversity in northern jarrah forest	(Doherty et al., 2017; Zylstra, 2018; Bowman et al., 2019; Dowdy et al., 2019; Naccarella et al., 2020) (Wardell-Johnson et al., 2015)
		Tree line stasis or regression (snow gum)	(Doherty et al., 2017); (Bowman et al., 2019; Naccarella et al., 2020)
	Increase in lightning-ignited landscape fires along with contracting palaeo-endemic refugia due to warmer and drier climates	Population collapse and severe range contraction of slow-growing, fire-sensitive palaeo-endemic temperate rainforest species (e.g., pencil pine)	(Doherty et al., 2017); (Bowman et al., 2019)
	Rhizosphere responses or accelerated rates of soil organic matter decomposition	Plant nutrient availability may be enhanced	(Hasegawa et al., 2015; Ochoa-Hueso et al., 2017)
Alpine ecosystems	Increasing global warming and rising temperatures, ongoing reduction in snow cover and winter rain and increasing frequency and magnitude of wildfires	Loss of alpine vegetation communities (snow patch feldmark and short alpine herb fields) and increased stress on snow-dependent plant and animal species; changing suitability for invasive species	(Slatyer, 2010; Morrison and Pickering, 2013; Pepler et al., 2015a; Williams et al., 2015; Harris et al., 2017)
Northern tropical savannahs	Rainfall and CO_2 effects	Potentially resulting in an increase in ecosystem carbon storage	(Scheiter et al., 2015)
Murray-Darling River Basin	Drought	Reduced river flow; mass fish kills	(Grafton et al., 2014; AAS, 2019)
Unimpaired river basins	Elevated CO_2 levels	Increase plant water use reduces stream flow	(Ukkola et al., 2016)
Bearded dragons (lizards), *Pogona* spp.	Changes in precipitation	*P. henrylawsoni* and *P. microlepidota* to gain suitable habitat, *P. nullarbor* and *P. vitticeps* showing the most potential loss	(Wilson and Swan, 2017; Silva et al., 2018)
Xeric bees	Broad temperate tolerances, arid climate adapted	Climate-resilient, only small response	(Silva et al., 2018)
Great desert skink Liopholis kintorei	Buffering capacity of underground microclimates, for nocturnal and crepuscular ectotherms	Warming impacts projected to be indirect	(Moore et al., 2018)
22 narrow-range fish species in imminent risk of extinction	Projected changes in rainfall, run-off, air temperatures and the frequency of extreme events (drought, fire, flood) compound risk from other key threats especially invasive species	Extinction projected within next 20 years	(Lintermans et al., 2020)
Freshwater taxa (freshwater fish, crayfish, turtles and frogs)	Changed hydrological regimes	Substantial changes to the composition of faunal assemblages in Australian rivers well before the end of this century, with gains/ losses balanced for fish but suitable habitat area predicted to decrease for many crayfish and turtle species and nearly all frog species	(James et al., 2017)

Ecosystem, species	Climate-related pressure	Projected Impact	Source
New Zealand			
Modified lowland wetlands	Intersection of warming, drought and heavy rainfall (ex-tropical cyclones)	Prolonged anoxic conditions in waterways (blackwater events) leading to mortality of fish (e.g., shortfin eels) and invertebrates, while botulism outbreaks can lead to impacts on waterfowl	(Pingram et al., 2021)
Native forests and lands	Elevated CO_2 levels, warming, increased precipitation.	Short-term beneficial effects on carbon storage; droughts in eastern areas would decrease productivity and rates of carbon storage in the medium term	(Ausseil et al., 2019b)
	Increased fire intensity and frequency in hot and dry parts of New Zealand	Much of the native vegetation has no fire adaptations, causing vulnerability to local extinction due to 'interval squeeze'	(Perry et al., 2014)
Freshwater rivers	Rainfall variation	Cascading effects of warming, drought, floods and algal blooms compounded by water abstraction	(Macinnis-Ng et al., 2021)
Three species of naturalised woody weeds	Warming and increased CO_2 levels	Increased geographic range	(Sheppard and Stanley, 2014)
Kauri tree, *Agathis australis*	Lower than average rainfall stimulates a drought-deciduous response in this evergreen species	Increased litter fall	(Macinnis-Ng and Schwendenmann, 2015)
Windmill palm	Warming	Increased geographic range	(Aguilar et al., 2017)
New Zealand tussock grasslands	Warming	Enhanced respiration	(Graham et al., 2014)
Invasive species	Warming	Increased invasive species abundance and increased predation on native species	(Tompkins et al., 2013; Macinnis-Ng et al., 2021)
	Warming	Expanded ranges of invasive species in higher/cooler areas	(Sheppard and Stanley, 2014; Walker et al., 2019)
	Warming	Change in flowering phenology and pollination competition	(Giejsztowt et al., 2020)
	Warming	Increase in invasive plants, insects and pathogens from sub-tropical/tropical climates	(Macinnis-Ng et al., 2021)
Tuatara (reptile), *Sphenodon punctatus*	Warming	Temperature-dependent sex determination with more male hatches threatening small, isolated populations	(Grayson et al., 2014)
	Warming	Increased geographic range	(Carter et al., 2018)
Cattle tick	Warming	Increased geographic range and risk of tick-spread anaemia in cattle	(K.E. Lawrence et al., 2017)
Brown mudfish, *Neochanna apoda*	Drought	Reduced flow regimes associated with drought interact with reduced habitat due to land use change, leading to population declines and potential local extinction	(White et al., 2016b; White et al., 2017)
Suter's skink (lizard) *Oligosoma suteri*	Warming	Increased suitable range but unclear if dispersal is possible because habitats are isolated	(Stenhouse et al., 2018)
Threatened endemic passerine bird, *Notiomystis cincta*	Fluctuations in total precipitation, particularly increased and more variable rainfall	Heavy rainfall can flood nests and kill fledglings while droughts can cause population-wide reproductive failure	(Correia et al., 2015)
Feral cats	Warming	Increased geographic range	(Aguilar et al., 2015b)

biodiversity and a national data repository are lacking (MfE, 2020a). The projected increase in invasive species indicates the importance of a step-up in pest management efforts to ensure native species persistence as invasive species spread from climate change (Firn et al., 2015). There remains a gap between the knowledge generated, potential adaptation strategies and their incorporation into conservation instruments (*medium confidence*) (Graham et al., 2019; Hoeppner and Hughes, 2019), though there is increasing recognition of the need to improve governance and management structures for their implementation (Christie et al., 2020).

11.3.2 Coastal and Ocean Ecosystems

Australia's EEZ covers over 8.1 million km[2] of marine territory, including 50,000 km of coastline (Dhanjal-Adams et al., 2016), spanning sub-Antarctic islands in the south to tropical waters in the north. New Zealand's marine territory extends from the sub-tropics to sub-

Box 11.1 | Escalating Impacts and Risks of Wildfire

Fire activity depends on weather, ignition sources, land management practices and fuel flammability, availability and continuity (Bradstock et al., 2014). Increased fire activity in southeast Australia associated with climate change has been observed since 1950 (Abram et al., 2021), though trends vary regionally (*medium confidence*) (Bradstock et al., 2014). In New Zealand, there has been an increased frequency of major wildfires in plantations (FENZ, 2018) and at the rural–urban interface (*medium confidence*) (Pearce, 2018). In northern Australia, increased wet season rainfall (Gallego et al., 2017) has increased dry season fuel loads (Harris et al., 2008).

In Australia, the frequency and severity of dangerous fire weather conditions is increasing, with partial attribution to climate change (*very high confidence*) (Dowdy and Pepler, 2018; Abram et al., 2021) (11.2.1, Figure Box 11.1.1), especially in southern and eastern Australia during spring and summer (Harris and Lucas, 2019). Although Australia's eucalyptus forests and woodlands are fire adapted (Collins, 2020), increasing intensity and frequency of fires may exceed their resilience because of the shorter intervals between high-severity fires (Bowman et al., 2014; Etchells et al., 2020; Lindenmayer and Taylor, 2020a). Recent fires have severely impacted eastern rainforests, including significant Gondwana refugia (Abram et al., 2021). In New Zealand, the trends in very high and extreme fire weather (1997–2019) have not yet been attributed to climate change (MfE, 2020a).

Fire weather is projected to increase in frequency, severity and duration for southern and eastern Australia (*high confidence*) and most of New Zealand (*medium confidence*) (11.2.2), with projected increases in pyro-convection risk for parts of southern Australia (Dowdy et al., 2019) and increased dry-lightning and fire ignition for southeast Australia (Mariani et al., 2019; Dowdy, 2020). Increased fire risk in spring may reduce opportunities for prescribed fuel-reduction burning in some regions (Harris and Lucas, 2019; Di Virgilio et al., 2020). Fuel dryness is a key constraint on wildfire occurrence (Ruthrof et al., 2016). Vegetation change will affect fuel load and fire risk in different areas in complex ways (Watt et al., 2019; Alexandra and Max Finlayson, 2020; Clarke et al., 2020; Sanderson and Fisher, 2020).

Direct effects of wildfire include death and injury to people and animals and damage to ecosystems, property, agriculture, water supplies and other infrastructure (Brodison, 2013; Pearce, 2018; de Jesus et al., 2020; Johnston et al., 2020; Maybery et al., 2020). Indirect effects include electricity and communication blackouts leading to cascading impacts on services, infrastructure and communities (Bowman, 2012; Schavemaker and van der Sluis, 2017).

For New Zealand, there has been recent increased frequency and magnitude of property losses due to wildfire (Pearce, 2018). The 1660-hectare Port Hills fire in 2017 resulted in the greatest house losses (9) in almost 100 years (Langer et al., 2018), but the subsequent 5540-hectare Lake Ohau fire destroyed 53 houses in 2020 (Waitaki District Council, 2020).

In Australia, between 1987 and 2016, there were 218 deaths, 1000 injuries, 2600 people left homeless and 69,000 people affected by wildfire (Deloitte, 2017b). Wildfires cost about AUD$1.1 billion per year on average (11.5.2).

The Australian wildfires of 2019–2020 resulted in 33 deaths, over 3000 houses destroyed, AUD$2.3 billion in insured losses and AUD$3.6 billion in losses for tourism, hospitality, agriculture and forestry (CoA, 2020e; Filkov et al., 2020) (Figure Box 11.1.2). Smoke caused a further 429 deaths and 3230 hospitalisations as a result of respiratory distress and illness, with health costs totalling AUD$1.95 billion (Johnston et al., 2020). These fires burnt about 5.8 to 8.1 million hectares of forest in eastern Australia (Ward et al., 2020; Godfree et al., 2021), resulting in the loss or displacement of nearly 3 billion vertebrate animals (CoA, 2020e; Wintle et al., 2020). Further, 114 listed threatened species lost at least 50% of their habitat, and 49 lost 80% (Wintle et al., 2020), among other severe ecological impacts (Hyman et al., 2020). Smoke carried over 4000 km to New Zealand, where it increased snow/glacier melt through darkening surfaces and produced a detectable odour (Pu et al. 2021;(Filkov et al., 2020). The fire season of 2019–2020 was at least 30% more likely than a century ago due to the influence of climate change (van Oldenborgh et al., 2021). Following the fires, a Royal Commission into National Natural Disaster Arrangements made 80 recommendations, most of which were accepted by government, including establishing a disaster advisory body and a resilience and recovery agency (11.5.2.3) (CoA, 2020e).

In the face of climate change and the increased cost of fire damage and suppression, there has been considerable investment in fire risk reduction (Table Box 11.1.1). Recent analysis of 8800 fires in Australia shows resource constraints in response capacity are a barrier to effectively containing fires (Collins et al., 2018b), compounded by lengthened and more extreme fire seasons.

https://doi.org/10.1017/9781009325844.013

Box 11.1 (continued)

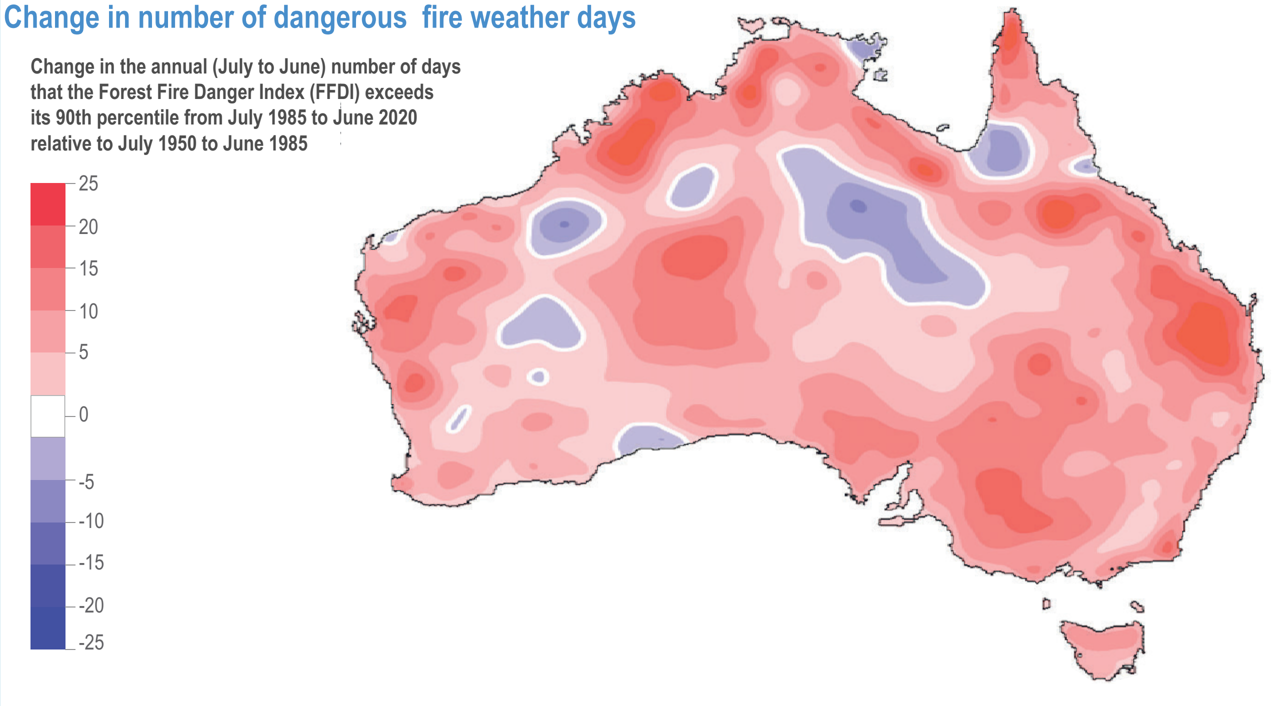

Figure Box 11.1.1 | Change in the annual (July to June) number of days that the Forest Fire Danger Index (FFDI) exceeds its 90th percentile from July 1985 to June 2020 relative to July 1950 to June 1985 (BoM and CSIRO, 2020; Abram et al., 2021).

Table Box 11.1.1 | Examples of adaptation options and enablers to reduce wildfire risk (Hart and Langer, 2011; Mitchell, 2013; Price et al., 2015; Tolhurst and McCarthy, 2016; Deloitte, 2017b; Miller et al., 2017; Steffen et al., 2017; Kornakova and Glavovic, 2018; Newton et al., 2018; Pearce, 2018; CoA, 2020e; McKemey et al., 2020).

Land management	Communications	Infrastructure
Prescribed burning to reduce fuel load close to built assets.	Clearer communication of existing exposure and vulnerability to enable informed decisions about risk tolerance and management, including sites of key biodiversity that are sensitive or susceptible to fire.	Enhanced training and support for firefighters and aerial firefighting assets, including sharing of resources nationally and internationally to address the increasing overlap of fire seasons, which are lengthening across the world.
Engagement with Australia's Aboriginal and Torres Strait Islander Peoples to utilise and learn from their fire management knowledge and skills to assist in landscape management and greenhouse gas mitigation.	Increased research to understand interactions between fire, fuel, weather, climate and human factors to enhance projections of fire occurrence and behaviour.	Nationally consistent response to exceedance of air quality standards.
Locating power lines appropriately or underground and decentralising power supply to reduce ignitions.	Community education and engagement, encouraging house and property maintenance, improving early-warning systems, more targeted messaging and increased emergency evacuation planning and sheltering options.	Improved governance arrangements to ensure greater accountability and coordination between agencies, sharing of data and resources for emergency planning and greater understanding of risks to critical infrastructure and supply chains.
Preventive, community-based interventions to reduce ignitions from arson and accidental fires.		Development of new systems to augment capability of fire services and technological advances to detect and respond to fires.
Reduced exposure of new assets through statutory spatial planning and land use regulations, building codes and building design standards.		

Box 11.1 (continued)

Fires in southern and eastern Australia from Sep 2019 to Feb 2020

Key

- **A** Extreme air pollution
- **B** 5.8 to 8.1 million hectares burned with net emissions of up to 830 million tonnes of CO_2-eq
- **C** Respiratory illness and disruption of outdoor activities and transport
- **D** Massive fire-fighting effort, saving many lives and at least 16,000 buildings
- **E** Building and facility closures, sporting events cancelled, holidays cancelled, workplace closures
- **F** Degraded and destroyed: Wineries, fruit, livestock, dairy, plantations
- **G** Loss of or displacement of 3 billion animals, with possible extinctions
- **H** Change in framework vegetation species and depletion of vegetation habitat resources
- **I** Smoke and ash transported to New Zealand, affecting air quality and glaciers
- **J** Destroyed and damaged utilities and infrastructure, e.g. roads closed for weeks, power and communication outages, fuel shortages, back-up generators without diesel, phone batteries run flat
- **K** Emergency evacuations of thousands of people by road, sea and air involving State Emergency Services and National Defence Force
- **L** Contamination of rivers and water supply with ash and sediment
- **M** Economic impacts: Estimates of the national financial impacts are over $8 billion
- **N** Social impacts: 33 people killed by fires, 429 killed by smoke, 3,103 houses destroyed, social disruption, injuries, exhaustion and mental health issues
- **O** Environmental impacts: Loss of ecosystem service benefits

Figure Box 11.1.2 | Cascading impacts on people, economic activity, built assets, ecosystems and species arising from the Black Summer fires of 2019–2020 in eastern and southern Australia (Boer et al., 2020; CoA, 2020e; CoA, 2020b; CoA, 2020a; CSIRO, 2020; Filkov et al., 2020; Johnston et al., 2020; Ward et al., 2020; Wintle et al., 2020; Abram et al., 2021; Godfree et al., 2021).

Antarctic waters, encompassing an EEZ of 4 million km^2, 18,000 km of coastline and 700 smaller islands and islets, in addition to the two main islands (Costello et al., 2010a; MfE, 2016).

The marine environment is important to the culture, health and well-being of the region's diverse Indigenous Peoples, including those who had sovereign ownership, governance, resource rights, and stewardship over 'Sea Country' for many thousands of years before the current sea level stabilised approximately 6000 years ago and before current coastal ecosystems were established (Rist et al., 2019). Marine environments contribute AUD$69 billion per year to Australia's economy (Eadie et al., 2011), and NZD$4 billion per year to New Zealand's economy (MfE, 2016). They have a high proportion of rare and endemic species (Croxall et al., 2012) and provide ecosystem services including food production, coastal protection, tourism and carbon sequestration (Croxall et al., 2012; Kelleway et al., 2017). Half of the species within New Zealand's seas are endemic (Costello et al., 2010b).

11.3.2.1 Observed Impacts

Climate change is having major impacts on the region's oceans (*very high confidence*) (Table 11.6) (Law et al., 2016; Sutton and Bowen, 2019). Rising sea surface temperatures (SSTs) have exacerbated marine heatwaves, notably near western Australia in 2011, the GBR in 2016, 2017 and 2020 and the Tasman Sea in 2015/2016, 2017/2018 and 2018/2019 (Table 11.2) (BoM and CSIRO, 2018; AMS, 2019; NIWA, 2019; Salinger et al., 2019b; Sutton and Bowen, 2019; BoM, 2020; Salinger et al., 2020; Oliver et al., 2021). Temperature anomalies ranged from 1.2°C to 4.0°C and durations ranged from 90–250 days (Table 11.2).

Ocean carbon storage and acidification has led to decreased surface pH in the region (Table 11.2), including the sub-Antarctic waters off the East Coast of New Zealand's South Island (*very high confidence*) (Law et al., 2016). The depth of the Aragonite Saturation Horizon has shallowed by 50–100 m over much of New Zealand, which may limit and/or increase the energetic costs of growth of calcifying species (*low confidence*) (Anderson et al., 2015; Bostock et al., 2015; Mikaloff-Fletcher et al., 2017).

In the estuaries of southwestern Australia, sustained warming and drying trends have caused dramatic declines in freshwater flows of up to 70% since the 1970s and increased frequency and severity of hypersaline conditions, enhanced water column stratification and hypoxia and reduced flushing and greater retention of nutrients (Hallett et al., 2017).

Extensive changes in the life history and distribution of species have been observed in Australia's (*very high confidence*) (Gervais et al., 2021) and New Zealand's marine systems (*medium confidence*) (Table 11.6) (Cross-Chapter box MOVING SPECIES in Chapter 5). New occurrences or increased prevalence of disease, toxins and viruses are evident (de Kantzow et al., 2017; Condie et al., 2019), along with heat stress mortalities and changes in community composition (Wernberg et al., 2016; Zarco-Perello et al., 2017; Thomsen et al., 2019). Extreme climatic events in Australia from 2011 to 2017 led to abrupt and extensive mortality of key habitat-forming organisms—corals, kelps, seagrasses and mangroves—along over 45% of the continental coastline of Australia (*high confidence*) (Babcock et al., 2019).

In 2016 and 2017, the GBR experienced consecutive occurrences of the most severe coral bleaching in recorded history (*very high confidence*) (Box 11.2), with shallow-water reef in the top two-thirds of the GBR affected and the severity of bleaching on individual reefs tightly correlated with the level of local heat exposure (Hughes et al., 2018b; Hughes et al., 2019c). Mass mortality of corals from these two unprecedented events resulted in larval recruitment in 2018 declining by 89% compared to historical levels (Hughes et al., 2019b). southern reefs were also affected by warming, although significantly less than in the north (Kennedy et al., 2018). Coral reefs in Australia are at very high risk of continued negative effects on ecosystem structure and function (*very high confidence*) (Hughes et al., 2019b), cultural well-being (*very high confidence*) (Goldberg et al., 2016; Lyons et al., 2019), food provision (*medium confidence*) (Hoegh-Guldberg et al., 2017), coastal protection (*high confidence*) (Ferrario et al., 2014) and tourism (*high confidence*) (Deloitte Access Economics, 2017; Prideaux and Pabel, 2018; GBRMPA, 2019). If bleaching persists, an estimated 10,000 jobs and AUD$1 billion in revenue would be lost per year from declines in tourism alone (Swann and Campbell, 2016).

11.3.2.2 Projected Impacts

Future ocean warming, coupled with periodic extreme heat events, is projected to lead to the continued loss of ecosystem services and ecological functions (*high confidence*) (Smale et al., 2019) as species further shift their distributions and/or decline in abundance (Day et al., 2018). Compounding climate-driven changes in the distribution of habitat-forming species, invasive macroalgae are predicted to exhibit higher growth under all higher pCO_2 and lower pH conditions (Roth-Schulze et al., 2018). Corals and mangroves around northern Australia and kelp and seagrass around southern Australia are of critical importance for ecosystem structure and function, fishery productivity, coastal protection and carbon sequestration; these ecosystem services are therefore *extremely likely*[2] to decline with continued warming. Equally, many species provide important ecosystem structure and function in New Zealand's seas including in the deep sea (Tracey and Hjorvarsdottir, 2019). The future level of sustainable exploitation of fisheries is dependent on how climate change impacts these ecosystems. Native kelp is projected to further decline in southeastern New Zealand with warming seas (Table 11.6). Climate change could affect New Zealand fisheries' productivity (Cummings et al., 2021), and both ocean warming and acidification may directly affect shellfish culture (Cunningham et al., 2016; Cummings et al., 2019) and indirectly through changes in phytoplankton production (Pinkerton, 2017).

Climate-change-related temperature and acidification may affect species sex ratios and, thus, population viability (*medium confidence*)

2 In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

(Table 11.3) (Law et al., 2016; Tait et al., 2016; Mikaloff-Fletcher et al., 2017). Acidification may alter sex determination (e.g., in the oyster *Saccostrea glomerate*), resulting in changes in sex ratios (Parker et al., 2018), and may thus affect reproductive success (*low confidence*). Decreasing river flows (Chiew et al., 2017) are projected to cause periodically open estuaries across southwest Australia to remain closed for longer periods, inhibiting the extent to which marine taxa can access these systems (Hallett et al., 2017) and with warming predicted to constrain activity in some large fish (Scott et al., 2019b). Major knowledge gaps include environmental tolerances of key life stages, sources of recruitment, population linkages, critical ecological (e.g., predator–prey interactions) or phenological relationships and projected responses to lowered pH (Fleming et al., 2014; Fogarty et al., 2019).

Black-browed albatrosses breeding on Macquarie Island may be more vulnerable to future climate-driven changes to weather patterns in the Southern Ocean and potential latitudinal shifts in the sub-Antarctic Front (Cleeland et al., 2019). New Zealand coastal ecosystems face risks from sea level rise (SLR) and extreme weather events (MfE, 2020a).

Table 11.6 | Observed climate-change-related changes in the marine ecosystems of Australia and New Zealand. Climate-related impacts have been documented at a range of scales from single-species or region-specific studies to multi-species or community-level changes.

Type of change	Examples	Climate-related Pressure	Source
Australia			
Reduced activity and increased energetic demands	Coral trout (*Plectropomus leopardus*), one of Australia's most important commercial and recreational tropical finfish species	Increased temperature (experimental laboratory study) and ocean warming	(Johansen et al., 2014; Scott et al., 2017)
Estuaries warming and freshening	Australian lagoons and rivers warming and decreasing pH at a faster rate than predicted by climate models	Warming and reduction in rainfall (leading to reduced flows and therefore being less frequently open to the sea)	(Scanes et al., 2020)
Changes in life-history traits, behaviour or recruitment	Reduced size of Sydney rock oysters (for commercial sale)	Limited capacity to bio mineralise under acidification conditions	(Fitzer et al., 2018)
	Reduced growth in tiger flathead fish in equatorward range	Ocean warming	(Morrongiello and Thresher, 2015)
	55% of 335 fish species became smaller and 45% became larger as seas warmed around Australia	Ocean warming (over three decades)	(Audzijonyte et al., 2020)
	Rock lobster display reduced avoidance of predators at 23°C compared to 20°C	Increased temperature (experimental laboratory study)	(Briceño et al., 2020)
	Analysis of stress rings in cores of corals from the GBR dating back to 1815 found that following bleaching events, the coral was less affected by subsequent marine heatwaves	Heat events	(DeCarlo et al., 2019)
	Mortality and reductions in spawning stocks of fishery important abalone, prawns, rock lobsters	2011 marine heatwave	(Caputi et al., 2019)
	Recruitment of coral on GBR reduced to 11% of long-term average	Warming-driven back-to-back global bleaching events	(Hughes et al., 2019b)
	Green turtle hatchlings from southern GBR 65–69% female and hatchlings from northern GBR 100% female for last two decades	Increased sand temperatures	(Jensen et al., 2018)
New diseases, toxins	First occurrence of virulent virus causing Pacific Oyster Mortality Syndrome (POMS), up to 90% of all farmed oysters died in impacted areas	Detected during heatwave	(de Kantzow et al., 2017)
	Mussels, scallops, oysters, clams, abalone and rock lobsters on east coast of Tasmania found to have high levels of Paralytic Shellfish toxins, originating from a bloom of harmful *Alexandrium tamarense*	Warming and extension of the East Australian Current	(Hallegraeff and Bolch, 2016)
	Range expansion of phytoplankton *Noctiluca*, which can be toxic	Warming and extension of the East Australian Current	(Hallegraeff et al., 2020)
	Mortality of fish following algal blooms in South Australia	2013 marine heatwave	(Roberts et al., 2019)
Changes in species distributions	Range extensions at the poleward range limit have been detected in: fish, cephalopods, crustaceans, nudibranchs, urchins, corals	Ocean warming	(Baird et al., 2012; Robinson et al., 2015; Sunday et al., 2015; Ling et al., 2018; Nimbs and Smith, 2018; Ramos et al., 2018; Smith et al., 2019; Caswell et al., 2020)
	Contractions in range at the equatorward range edge have been detected in anemones, asteroids, gastropods, mussels, algae	Ocean warming	(Pitt et al., 2010; Poloczanska et al., 2011; Smale et al., 2019)

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Type of change	Examples	Climate-related Pressure	Source
	Australia's most southern dominant reef building coral, *Plesiastrea versipora*, in eastern Bass Strait, increasing in abundance at the poleward edge of the species' range and in western Australia	Ocean warming	(Tuckett et al., 2017; Ling et al., 2018)
	Southwestern Australia fish assemblages—warm-water fish increasing in density at poleward edge of distributions and cool-water species decreasing in density at equatorward edge of distributions; increase in warm-water habitat forming species leading to reduced habitat for invertebrate assemblages	Combination of increased temperatures and changes in habitat-forming algal species	(Shalders et al., 2018; Teagle et al., 2018)
	Predicted reduction range of rare W*ilsonia humilis* herb in Tasmanian saltmarsh but no change in rest of community	Wetter and drier climate	(Prahalad and Kirkpatrick, 2019)
Changes in abundance	Shift towards a zooplankton community dominated by warm-water small copepods in southeast Australia	Ocean warming	(Kelly et al., 2016)
	Diebacks of tidal wetland mangroves	2015–2016 heatwaves combined with moisture stress	(Duke et al., 2017)
	Decline in giant kelp in Tasmania, Australia, less than 10% remaining; loss of kelp Australia-wide totalling at least 140,187 hectares	Ocean warming and change in East Australian Current (lower nutrients)	(Wahl et al., 2015; Butler et al., 2020; Filbee-Dexter and Wernberg, 2020)
	Regional loss of seagrass in Shark Bay World Heritage Area, western Australia	High air and water temperatures during 2011 heatwave	(Strydom et al., 2020)
	Increased annual dugong and inshore dolphin mortality across Queensland	Sustained low air temperature and increased freshwater discharge during high Southern Oscillation Index (SOI) (ENSO) index	(Meager and Limpus, 2014)
	Predicted equatorward decline and poleward shift of sea urchin in eastern Australia	Ocean warming	(Castro et al., 2020)
	Increasing mortality of Australian fur seal pups in low-lying colonies	Storm surges and high tides amplified by ongoing SLR	(McLean et al., 2018) (Box 11.6)
Rapid shifts in community composition, structure and integrity	Community-wide tropicalisation in Australian temperate reef communities; temperate species replaced by seaweeds, invertebrates, corals, and fishes characteristic of sub-tropical and tropical waters	Extreme marine heatwaves led to 100-km range contraction of extensive kelp forests	(Vergés et al., 2016; Wernberg et al., 2016)
	Ongoing declines in habitat-forming seaweeds	Climate-driven shift of tropical herbivores	(Thomson et al., 2015; Nowicki et al., 2017; Zarco-Perello et al., 2017; Wernberg et al., 2016)
	Dieback of temperate seagrass in Shark Bay, Australia, subsequently replaced by tropical early successional seagrass with seagrass-associated megafauna (sea turtles) declining in health status	2011 marine heatwave	(Strydom et al., 2020)
	Increased herbivory by fish on tropicalised reefs of western Australia	Change in species composition due to ocean warming	(Zarco-Perello et al., 2019)
	No recovery 2 years after coral bleaching and macroalgae mortality in western Australia	2011 marine heatwave	(Bridge et al., 2014)
	Mass mortality of particular coral species on affected reefs during heatwaves on GBR (Eastern Australia) led to altered coral reef structure and species composition 8 months later.	2016 marine heatwave	(Hughes et al., 2018c)
	Community-wide restructuring along GBR 1 year after the 2016 mass bleaching event	2016 marine heatwave	(Stuart-Smith et al., 2018)
New Zealand			
Changes in life-history	Alteration of shell of pāua (black footed abalone, *Haliotis iris*) under lowered pH (calcite layer thinner, greater etching of external shell surface)	Lowered pH (experimental laboratory study)	(Cummings et al., 2019)
	Decline in maximum swimming performance of kingfish and snapper	Elevated CO_2 (experimental laboratory study)	(Watson et al., 2018; McMahon et al., 2020)
	Increased mortality and faster growth in juvenile kingfish	Increased temperature	(Watson et al., 2018)
	Earlier spawning of snapper in South Island	2017–2018 heatwave	(Salinger et al., 2019b)
Increase in mortality	Heat stress mortality in salmon farms off Marlborough, New Zealand, where 20% of salmon stocks died	2017–2018 marine heatwave	(Salinger et al., 2019b)

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Type of change	Examples	Climate-related Pressure	Source
Changes in species distributions	Species increasingly caught further south (e.g., snapper and kingfish)	Ocean warming and 2017–2018 marine heatwave	(Salinger et al., 2019b)
	Non-breeding distribution of New Zealand nesting seabird (Antarctic prion) shifting south with long-term climate inferred from stable isotopes	Climate warming	(Grecian et al., 2016)
	Less phytoplankton production in Tasman Sea but more on sub-tropical front	Ocean warming	(Chiswell and Sutton, 2020)
	Loss of bull kelp (*Durvillaea*) populations in southern New Zealand subsequently replaced by introduced kelp *Undaria*	2017–2018 heatwave when sea and air temperatures exceeded 23°C and 30°C respectively	(Salinger et al., 2019b; Thomsen et al., 2019; Salinger et al., 2020)

Box 11.2 | The Great Barrier Reef in Crisis

The GBR is the world's largest coral reef system, comprising 3863 reefs over an area of 348,700 km^2, stretching for 2300 km. The GBR is a central cornerstone of the beliefs, knowledges, lores, languages and ways of living for over 70 geographically and culturally diverse Traditional Owner groups spanning the length of the GBR (Dale et al., 2018), and it contributes an estimated AUD$6.4 billion per year (pre-COVID) to the Australian economy, mainly via tourism. As the world's most extensive coral reef ecosystem, the GBR is a globally outstanding and significant entity, with practically the entire ecosystem inscribed as a World Heritage Site in 1981 (UNESCO, 1981).

The GBR is already severely impacted by climate change, particularly ocean warming, through more frequent and severe coral bleaching (*very high confidence*) (Hughes et al., 2018b; Hughes et al., 2019c). The worst coral bleaching event on record affected over 90% of reefs in 2016 (Hughes et al., 2018b). In the most northern 700-km-long section of the GBR in which the heat exposure was the most extreme, 50% of the coral cover on reef crests was lost within 8 months (Hughes et al., 2018c). Throughout the entire GBR, including the southern third where heat exposure was minimal, the cover of corals declined by 30% between March and November 2016 (Hughes et al., 2018b). In 2017, the central third of the reef was the most severely affected and the back-to-back regional-scale bleaching events has led to an unprecedented shift in the composition of GBR coral assemblages, transforming the northern and middle sections of the reef system (Hughes et al., 2018c) to a highly degraded state (*very high confidence*). Coral recruitment to the GBR in 2018 was reduced to only 11% of the long-term average (Hughes et al., 2019b). A mass bleaching event also occurred in 2020, making it the third event in 5 years (BoM, 2020) (Figure Boxes 11.2.1 and 11.2.2).

Increased heat exposure also affects the abundance and distribution of associated fish, invertebrates and algae (*high confidence*) (Stuart-Smith et al., 2018). Thus, coral bleaching is an indicator of thermal effects on coral habitat, fauna and flora. Bleaching is expected to continue for the GBR and Australia's other coral reef systems (*virtually certain*). Bleaching conditions are projected to occur twice each decade from 2035, annually after 2044 under RCP8.5 and annually after 2051 under RCP4.5 (Heron et al., 2017). Global warming of 3°C would result in over six times the 2016 level of thermal stress (Lough et al., 2018).

Increases in cyclone intensity projected for this century, and other extreme weather events, will greatly accelerate coral reef degradation (Osborne et al., 2017). Additionally, through interactions between elevated ocean temperature and coastal runoff (nutrient and sediment), extreme weather events may contribute to an increased frequency and/or amplitude of crown-of-thorns starfish outbreaks (Uthicke et al., 2015), further reducing the spatial distribution of coral.

Recovery of coral reefs following repeated disturbance events is slow (Hughes et al., 2019b; IPCC, 2019b), and it takes at least a decade after each bleaching event for the very fastest growing corals to recover (*high confidence*) (Gilmour et al., 2013; Osborne et al., 2017). Estimates of future levels of thermal stress, measured as degree heating months, which incorporates both the magnitude and duration of warm season SST anomalies, suggest that achieving the 1.5°C Paris Agreement target would be insufficient to prevent more frequent mass bleaching events (*very high confidence*) (Lough et al., 2018), although it may reduce their occurrence (Heron et al., 2017), and occurrences of warming events similar to 2016 bleaching could be reduced by 25% (King et al., 2017).

Tourist motivations for visiting the GBR are changing, with a recent survey finding that two-thirds of tourists were visiting 'before it was gone' and a similar number were reporting damage to the reef—an example of 'last chance tourism' (Piggott-McKellar and McNamara, 2016). The Australian government is investing AUD$1.9 billion to support the GBR through science and practical environmental outcomes, including reducing other anthropogenic pressures, which can suppress natural adaptive capacity (CoA, 2019b; GBRMPA, 2019). However, adaptation efforts on the GBR aimed specifically at climate impacts, for example coral restoration following marine heatwave impacts (Boström-Einarsson et al., 2020), may slow the impacts of climate change in small discrete regions of the reef or reduce short-term socioeconomic ramifications, but they will not prevent widespread bleaching (Condie et al. 2021).

11

Box 11.2 (continued)

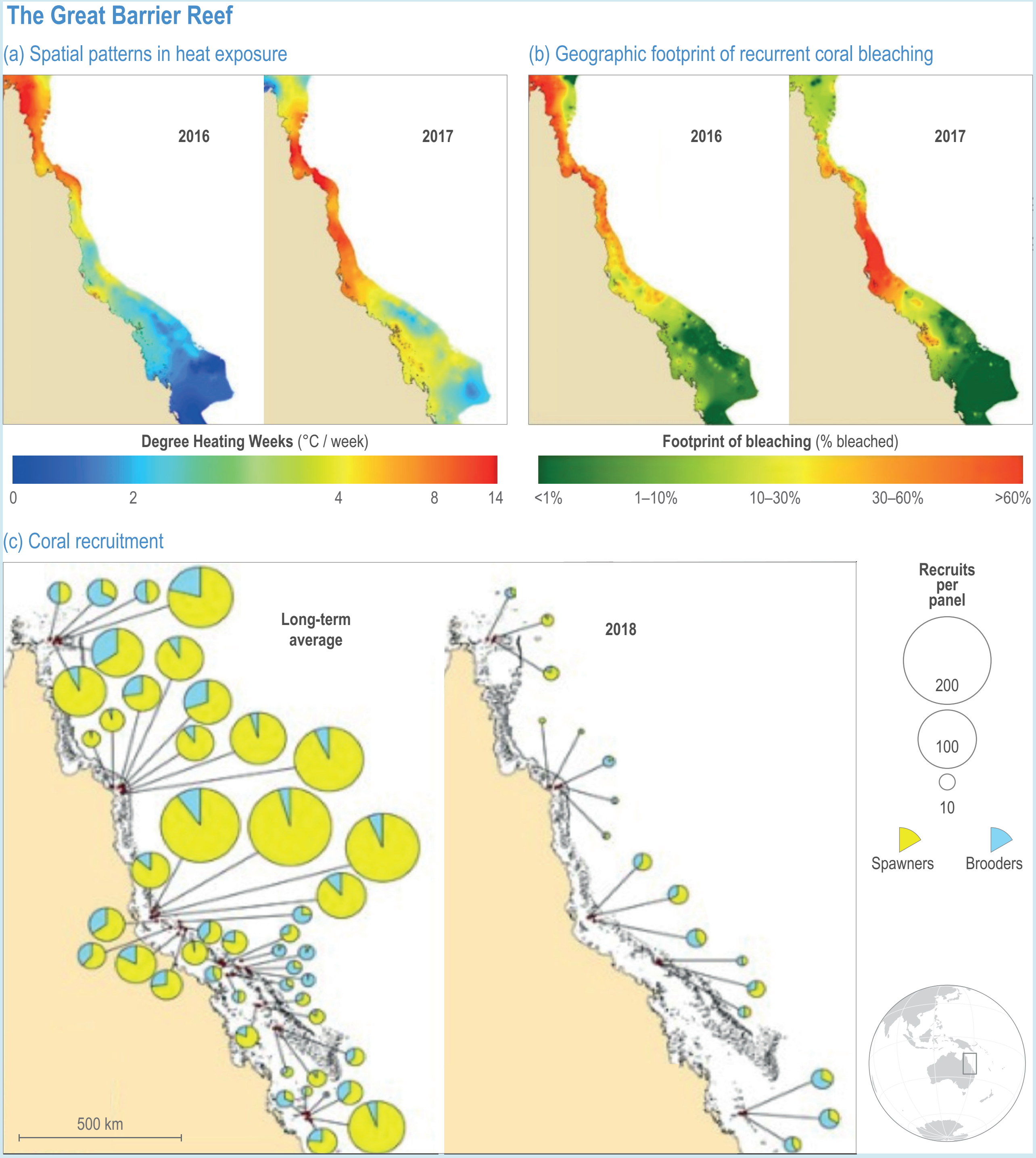

Figure Box 11.2.1 | Top panels: spatial patterns in heat exposure along the GBR in 2016 (left pair) and 2017 (right pair), measured from satellites as Degree Heating Weeks (DHW, °C-weeks). Middle panels: geographic footprint of recurrent coral bleaching in 2016 (left) and again in 2017 (right), measured by aerial assessments of individual reefs (adapted from (Hughes et al., 2019c)]). Bottom panels: density of coral recruits (mean per recruitment panel on each reef), measured over three decades, from 1996 to 2016 (*n* = 47 reefs, 1784 panels) (left), compared to the density of coral recruits in 2018 after the mass mortality of corals in 2016 and 2017 due to the back-to-back bleaching events (*n* = 17 reefs, 977 panels) (right). The area of each circle is scaled to the overall recruit density of spawners and brooders combined. Yellow and blue indicate the proportion of spawners and brooders respectively (from (Hughes et al., 2019b)]).

Box 11.2 (continued)

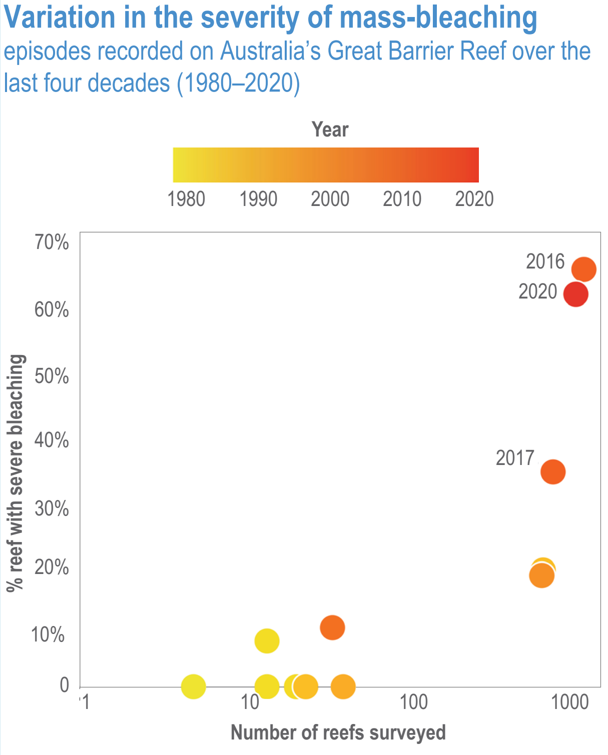

Figure Box 11.2.2 | Variation in the severity of mass-bleaching episodes recorded on Australia's GBR over the last four decades (1980–2020). The overall number of reefs surveyed was substantially higher in 1998, 2002, 2016, 2017 and 2020 when aerial surveys were undertaken, whereas the severity of other more localised bleaching episodes was documented with in-water surveys (adapted from (Pratchett et al., 2021). Extent of bleaching in 2020 was similar in severity to that of 2016 but more geographically widespread and included southern reefs.

Nutrient availability and productivity in the sub-tropical waters of New Zealand are projected to decline due to increased SST and strengthening of the thermocline, but they may increase in sub-Antarctic waters, potentially bringing some benefit to fish and other species (*low confidence*) (Law et al., 2018b). For New Zealand waters as a whole, declines in net primary productivity of 1.2% and 4.5% are projected under RCP4.5 and RCP8.5 respectively by 2100, and declines in the primary production of surface waters by an average 6% from the present day under RCP8.5, with sub-tropical waters experiencing the largest decline (Tait et al., 2016).

The pH of surface waters around New Zealand is projected to decline by 0.33 under RCP 8.5 by 2090 (Tait et al., 2016), and the depth at which carbonate dissolves is projected to be significantly shallower (Mikaloff-Fletcher et al., 2017), affecting the distribution of some species of calcifying cold water corals (*medium confidence*) (Law et al., 2016). However, model projections suggest that the top of the Chatham Rise may provide temporary refugia for scleractinian stony corals from ocean acidification because the Chatham Rise sits above the aragonite saturation horizon (Anderson et al., 2015; Bostock et al., 2015). For sub-tropical corals, skeletal formation will be vulnerable to the changes in ocean pH, with implications for their longer-term growth and resilience (Foster et al., 2015).

11.3.2.3 Adaptation

Climate change adaptation opportunities and pathways have been identified across aquaculture, fisheries, conservation and tourism sectors in the region (MacDiarmid et al., 2013; Fleming et al., 2014; MPI, 2015; Jennings et al., 2016; MfE, 2016; Royal Society Te Apārangi, 2017; Ling and Hobday, 2019), and some stakeholders are already autonomously adapting (Pecl et al., 2019). Some fishing and aquaculture industries use seasonal forecasts of environmental conditions to improve decision-making, risk management and business planning (Hobday et al., 2016), with the potential to use 5-yearly forecasts similarly (Champion et al., 2019). Shifts in the distribution and availability of target species (e.g., oceanic tuna) would impact the ability of domestic fishing vessels to continue current fishing practices, with potential social and economic adjustment costs (Dell et al., 2015), including disruption to supply chains (Fleming et al., 2014; Plagányi et al., 2014) (Cross-Chapter Box MOVING SPECIES in Chapter 5). Species abundance data are insufficient to enable projections of climate impacts on fishery productivity. However, fishery and aquaculture industries are considering adaptation strategies, such as changing harvests and relocating farms (Pinkerton, 2017). Thus, while climate change is *extremely likely* to affect the abundance and distribution of marine species around New Zealand, insufficient monitoring means there is *limited evidence* of ecosystem level change in biodiversity to date and no quantitative projections of which species may win and lose to climate change (Table 11.6) (Law et al., 2018a; Law et al., 2018b).

11.3.3 Freshwater Resources

Climate change impacts on freshwater resources cascade across people, agriculture, industries and ecosystems (Boxes 11.3 and 11.5). The challenge of satisfying multiple demands with a finite resource is exacerbated by high interannual and inter-decadal variability of river flows, particularly in Australia (Chiew and McMahon, 2002; Peel et al., 2004; McKerchar et al., 2010).

11.3.3.1 Observed Impacts

Streamflow has generally increased in northern Australia and decreased in southern Australia since the mid-1970s (*high confidence*) (Zhang et al., 2016). Declining river flows since the mid-1970s in southwest Australia have led to changed water management (WA Government, 2012; WA Government, 2016). The large decline in river flows during the so-called 1997–2009 Millennium drought in southeast Australia resulted in low irrigation water allocations, severe water restrictions and major environmental impacts (Potter et al., 2010; Chiew and Prosser, 2011; Leblanc et al., 2012; van Dijk et al., 2013). The drying in southern Australia highlighted the need for hydrological models that adequately account for climate change (Vaze et al., 2010; Chiew et al., 2014; Saft et al., 2016; Fowler et al., 2018). The decline in streamflow was largely due to the decline in cool-season rainfall (which has been partly attributed to climate change) (Figure 11.2) (Timbal and Hendon, 2011; Post et al., 2014; Hope et al., 2017; DELWP, 2020), when most of the runoff in southern Australia occurs.

In New Zealand, precipitation has generally decreased in the north and increased in the southwest (Figure 11.2) (Harrington et al., 2014), but it is difficult to ascertain trends in the relatively short streamflow records. Glaciers in New Zealand's southern alps have lost one third of their mass since 1977 (Mackintosh et al., 2017; Salinger et al., 2019b), and glacier mass loss in 2018 was at least 10 times more likely to occur with anthropogenic forcing than without (Vargo et al., 2020).

11.3.3.2 Projected Impacts

Projections indicate that future runoff in southeast and southwest Australia are *likely* to decline (median estimates of 20% and 50% respectively under 2.2°C global average warming) (Figure 11.3) (Chiew et al., 2017; Zheng et al., 2019). These projections are broadly similar to those reported previously and in AR5 (Teng et al., 2012; Reisinger et al., 2014). The range of estimates arises mainly from the uncertainty in projected future precipitation (Table 11.2a).

The runoff decline in southern Australia is projected to be further accentuated by higher temperature and potential evapotranspiration (Potter and Chiew, 2011; Chiew et al., 2014), transpiration from tree regrowth following more frequent and severe wildfires (Brookhouse et al., 2013) (Box 11.1), interceptions from farm dams (Fowler et al., 2015) and reduced surface–groundwater connectivity (limiting groundwater discharge to rivers) in long dry spells (*high confidence*) (Petrone et al., 2010; Hughes et al., 2012; Chiew et al., 2014). In the longer term, runoff will also be affected by changes in vegetation and surface–atmosphere feedback in a warmer and higher CO_2 environment, but the impact is uncertain because of the complex interactions, including changes in climate inputs, fire patterns (Box 11.1) and nutrient availability (Raupach et al., 2013; Ukkola et al., 2016; Cheng et al., 2017).

Climate change is projected to affect groundwater recharge and the relationship between surface waters and aquifers and through rising sea levels where groundwater has a tidal signature (PCE, 2015; MfE, 2017a). Groundwater recharge across southern Australia has decreased in recent decades (Fu et al., 2019), and this trend is expected to continue (*high confidence*) (Barron et al., 2011; Crosbie et al., 2013). Climate change is also projected to impact water quality in rivers and water bodies, particularly through higher temperature and low flows (Jöhnk et al., 2008) (Box 11.5) and increased sediment and nutrient load following wildfires (*high confidence*) (Biswas et al., 2021) (Box 11.1) and floods (Box 11.4).

The projected changes in river flows in New Zealand are consistent with the precipitation projections (Table 11.2), with increases in the west and south of the South Island and decreases in the east and north of the North Island (Figure 11.4). In the South Island, the runoff increase occurs mainly in winter due to increasing moisture-bearing westerly airflow, with more precipitation falling as rain and snow melting earlier. In the North Island, the runoff decrease occurs in spring and summer (Caruso et al., 2017; Collins et al., 2018a; Jobst et al., 2018; D. Collins, 2020).

11.3.3.3 Adaptation

In Australia, prolonged droughts and projections of a drier future have accelerated policy and management change in urban and rural water systems. Adaptation initiatives and mechanisms, like significant government investment to enhance the Bureau of Meteorology online water information (Vertessy, 2013; BoM, 2016), funding to improve agricultural water use and irrigation efficiency (Koech and Langat, 2018), enhanced supply through inter-basin transfers and upgrading water infrastructure and an active water trading market (Wheeler et al., 2013; Kirby et al., 2014; Grafton et al., 2016) are helping to buffer regional systems against droughts and facilitating some adaptation to climate change (*medium confidence*). However, these measures could also be maladaptive because they may perpetuate unsustainable water and land uses under ongoing climate change (Boxes 11.3 and 11.5).

The widespread 2017–2019 drought across eastern Australia (BoM, 2021b) has led to the Australian government establishing a Future Drought Fund (Australian Government, 2019) to enhance drought resilience and a National Water Grid Authority to develop regional water infrastructure to support agriculture. Nevertheless, the ability to adapt to climate change is compounded by uncertainties in future water projections, complex interactions between science, policy, community values and political voice, and competition between different sectors dependent on water (Boxes 11.3 and 11.5). The impact of declining water resources on agricultural, ecosystems and communities in southeastern Australia would escalate with ongoing climate change (*medium confidence*) (Hart, 2016; Moyle et al., 2017), highlighting the importance of more ambitious, anticipatory, participatory and integrated adaptation responses (Bettini et al., 2015; Abel et al., 2016; Marshall and Lobry de Bruyn, 2021).

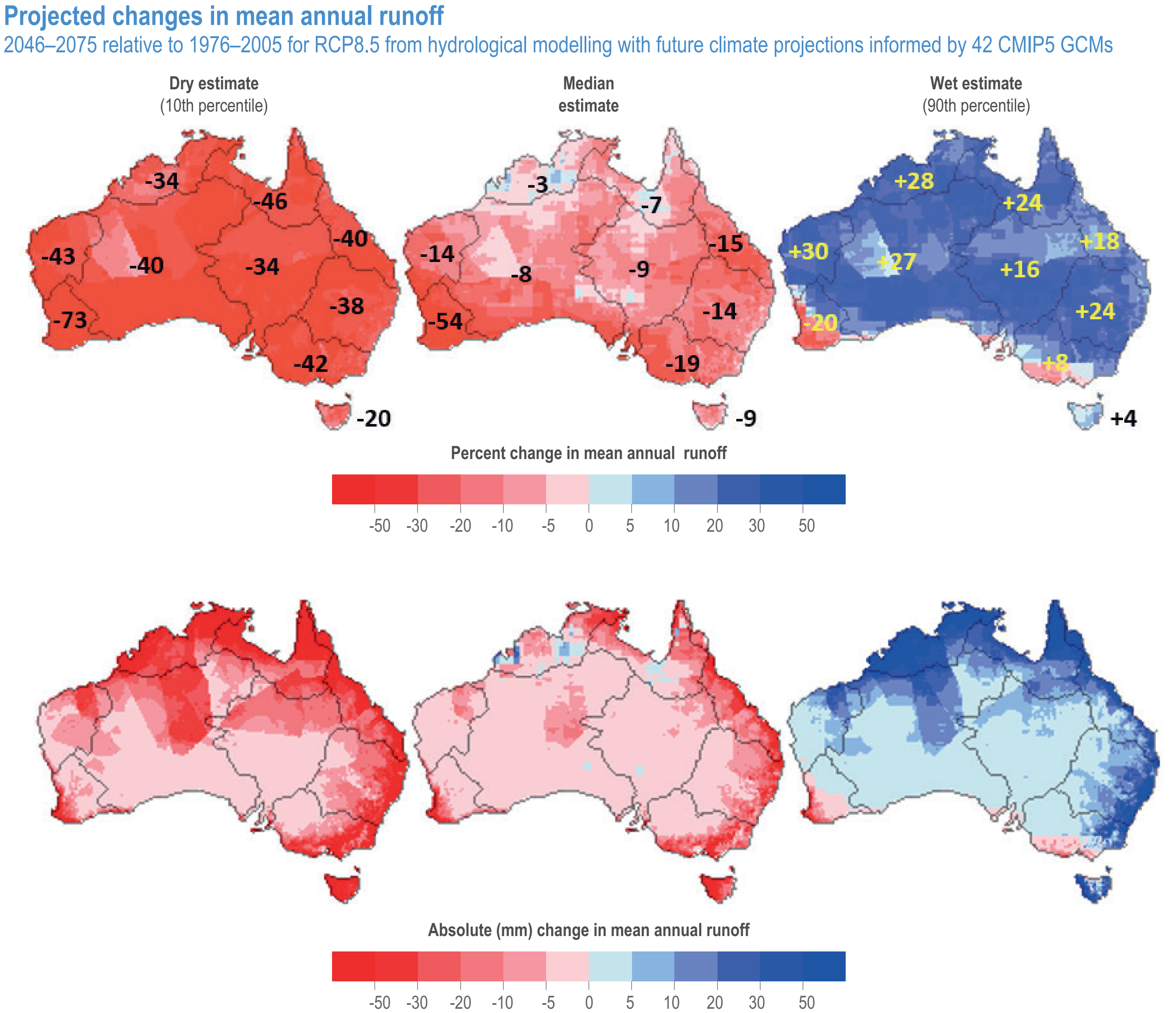

Figure 11.3 | Projected changes in mean annual runoff for 2046–2075 relative to 1976–2005 for RCP8.5 from hydrological modelling with future climate projections informed by 42 CMIP5 GCMs. Projections for RCP4.5 are about three quarters of the aforementioned projections. Plots show median projection and the 10th and 90th percentile range of estimates. The boundaries are based on hydroclimate regions and major drainage basins. Source: (Zheng et al., 2019).

Altered water regimes resulting from the combined effects of climatic conditions and water policies carry uneven and far-reaching implications for communities (*high confidence*). Acting on Indigenous Peoples' claims to cultural flows (to maintain their connections with their country) is increasingly recognised as an important water management and social justice issue (Taylor et al., 2017; Hartwig et al., 2018; Jackson, 2018; Jackson and Moggridge, 2019; Moggridge et al., 2019). Compounding stressors, such as coal and coal seam gas developments, can also severely impact local communities, water catchments and water-dependent ecosystems and assets, exacerbating their vulnerability to climate change (Navi et al., 2015; Tan et al., 2015; Chiew et al., 2018).

In Australian capital cities and regional centres, water planning has focused on securing new supplies that are resilient to climate change. This includes increasing use of stormwater and sewage recycling and managed aquifer recharge (Bekele et al., 2018; Page et al., 2018; Gonzalez et al., 2020). All major coastal Australian cities have desalination plants. Household scale adaptation, like rainwater harvesting, water-smart gardens, dual flush toilets, water-efficient showerheads and voluntary residential use targets, can help reduce water demand by up to 40% (Shearer, 2011; Rhodes et al., 2012; Moglia et al., 2018). Water utilities across Australia have established climate change adaptation guidelines (WSAA, 2016). Coordinated efforts to reduce demand, design and retrofit infrastructure to reduce flood risk and harvest water and to practice water-sensitive urban design are evident (WSAA, 2016; Kunapo et al., 2018; Rogers et al., 2020b). Transitioning centralised water systems to a more sustainable basis represents adaptation progress but is complex and faces many

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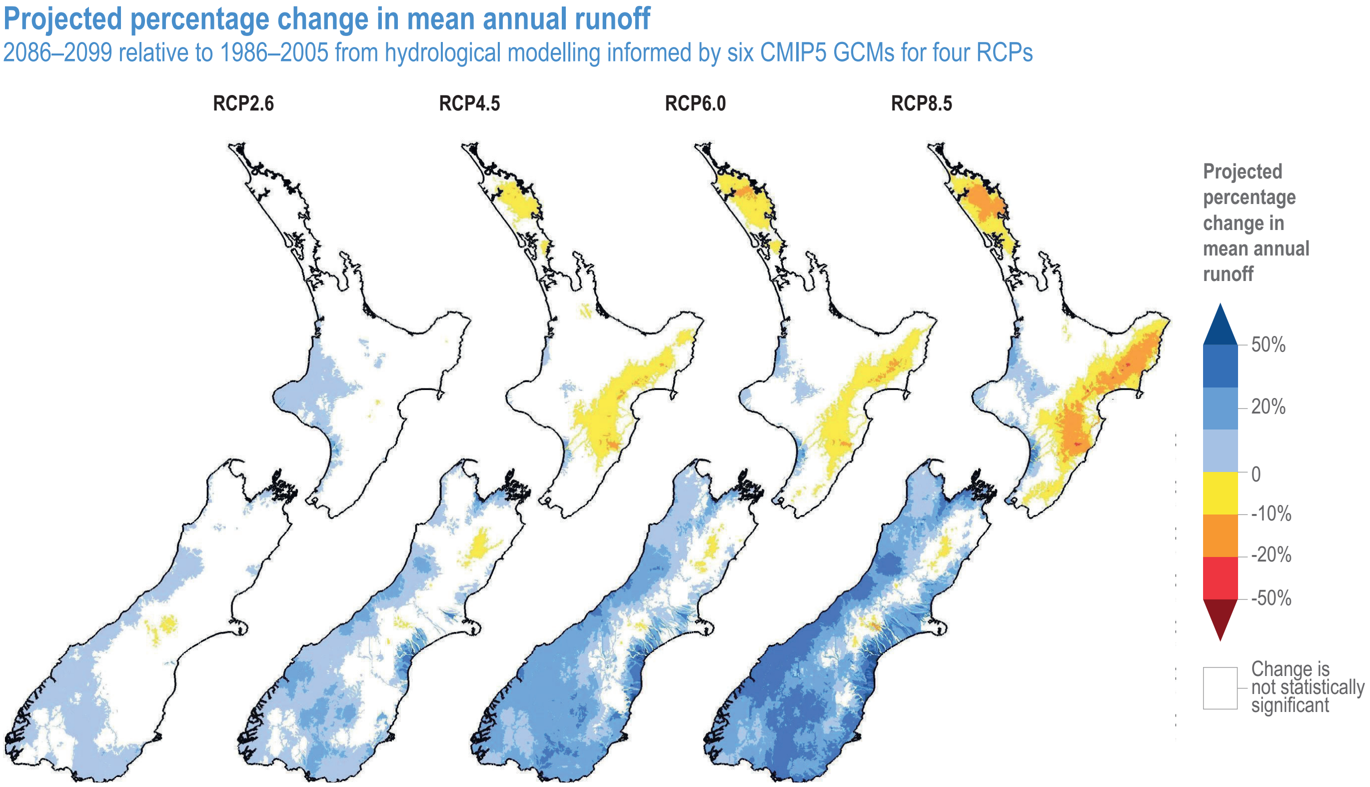

Figure 11.4 | Projected percentage change in mean annual runoff for 2086–2099 relative to 1986–2005 from hydrological modelling informed by six CMIP5 GCMs for four RCPs. Maps show median projection from the six modelling runs. White indicates that the change is not statistically significant. Source: (D. Collins, 2020).

barriers and limits (*medium confidence*) (Morgan et al., 2020). Developing multiple redundant or decentralised systems can enhance community resilience and promote autonomous adaptations that may be more sustainable and cost effective in the longer term (Mankad and Tapsuwan, 2011; WSAA, 2016; Iwanaga et al., 2020).

In New Zealand, many water supplies are at risk from drought, extreme rainfall events and sea level rise (SLR), exacerbated by underinvestment in existing water infrastructure (in part due to funding constraints) and urban densification (*high confidence*) (CCATWG, 2017; MfE and Stats NZ, 2021). Lessons can be learned from global experience (e.g., Cape Town, South Africa; Section 4.3.4). Water quality has diminished, with hotter conditions and drought causing algal blooms, combined with intensification of agricultural land uses in some areas, and heavy rainfall and sea level rise (SLR) causing flooding and sedimentation of water sources and health impacts (11.3.6; Box 11.5). Some towns are only partially metered or not metered at all, which exacerbates the adaptation challenge (Hendy et al., 2018; WaterNz, 2018; Paulik 2019a). Unregulated or absent water supplies accentuate risks to vulnerable groups of people (MfE, 2020b). Māori view water as the essence of all life, which makes any impacts on water a governance and stewardship concern, and increasingly, the subject of legal claims (MfE, 2020a; MfE, 2020b; MfE, 2020c) (11.4.2). Māori understanding of time can also open up new spaces for rethinking freshwater management in a climate change context that does not reinforce or rearticulate multiple environmental injustices (Parsons et al., 2021).

Water resource adaptation in New Zealand is variable across local government and water authorities but they all actively monitor water availability, demand and quality, and most have drought management plans. The 2019/2020 drought led to water shortages in the most populated areas of Waikato, Auckland and Northland, resulting in

Box 11.3 | Drought, Climate Change and Water Reform in the Murray-Darling Basin

The MDB is Australia's largest, most economically important and politically complex river system (Figure Box 11.3.1). The MDB supports agriculture worth AUD$24 billion/year, 2.6 million people in diverse rural communities and important environmental assets including 16 Ramsar listed wetlands (DAWE, 2012). Climate change is projected to substantially reduce water resources in the MDB (*high confidence*), with the median projection indicating a 20% decline in average annual runoff under 2.2°C average global warming (Figure 11.3) (Whetton and Chiew, 2020). This reduction, plus increased demand for water in hot and dry conditions, would increase the already intense competition for water (*high confidence*) (CSIRO, 2008; Hart, 2016).

Box 11.3 (continued)

The economic, environmental and social impacts of the 1997–2009 Millennium Drought in the MDB (Chiew and Prosser, 2011; Leblanc et al., 2012; van Dijk et al., 2013) and projections of a drier future under climate change have accelerated significant water policy reforms costing more than AUD$12 billion (Bark et al., 2014; Docker and Robinson, 2014; Hart, 2016). These reforms included the development of a Basin Plan (MDBA, 2011; MDBA, 2012) requiring consistent regional water resource plans (MDBA, 2011; MDBA, 2012; MDBA, 2013) and environmental watering strategies (MDBA, 2014) across the MDB. Despite contestation, the reforms have resulted in some substantive achievements, including returning an equivalent of about one-fifth of consumptive water to the environment through the purchase of irrigation water entitlements and infrastructure projects (*medium confidence*) (Hart, 2016; Gawne et al., 2020; MDBA, 2020). However, the overall impacts of these water management initiatives are difficult to measure due to hydroclimatic variability, time lags and environmental, social and institutional complexity (Crase, 2011; Bark et al., 2014; Docker and Robinson, 2014; MDBA, 2020).

Reform initiatives such as water markets, improving agriculture water use efficiency (Koech and Langat, 2018), and increasing environmental water are helping buffer the system against droughts (*medium confidence*) (Moyle et al., 2017), but they can also be maladaptive by perpetuating unsustainable water and land use under ongoing climate change. While water markets can allow users to adapt and shift water to higher value uses, they can also have adverse impacts unless supported by wider policy goals and planning processes (Wheeler et al., 2013; Kirby et al., 2014; Grafton et al., 2016; Qureshi et al., 2018).

Adapting MDB management to climate risks is an escalating challenge, with the projected decline in runoff being potentially greater than the water recovered for the environment (Chiew et al., 2017). While the Basin Plan includes mechanisms for climate risk management (Neave et al., 2015), it does not require altering pre-existing rules that distribute the impacts of anticipated reductions in water resources between users (Hart, 2016; Capon and Capon, 2017; Alexandra, 2020). The intense drought conditions in 2017–2019 (BoM, 2021b), the South Australian Royal Commission investigation into the MDB reforms (SA Government, 2019b) and major fish kills in the lower Darling River in the summer of 2018/2019 (AAS, 2019; Vertessy et al., 2019) have increased concerns about the Basin Plan's climate adaptation deficit (*medium confidence*). Consequently, the MDB Authority (MDBA) is undertaking an assessment of climate change risks and developing adaptation mechanisms (MDBA, 2019) that can feed into the revisions to the Basin Plan scheduled for 2026. The MDB reforms to date illustrate the difficulties in integrating climate change science and projections into management (Alexandra, 2018; Alexandra, 2020). Anticipatory and participatory governance and adaptive management approaches supported by structural and institutional reforms would support the effectiveness of the reforms (Abel et al., 2016; Alexandra, 2019; Hassenforder and Barone, 2019; Marshall and Lobry de Bruyn, 2021).

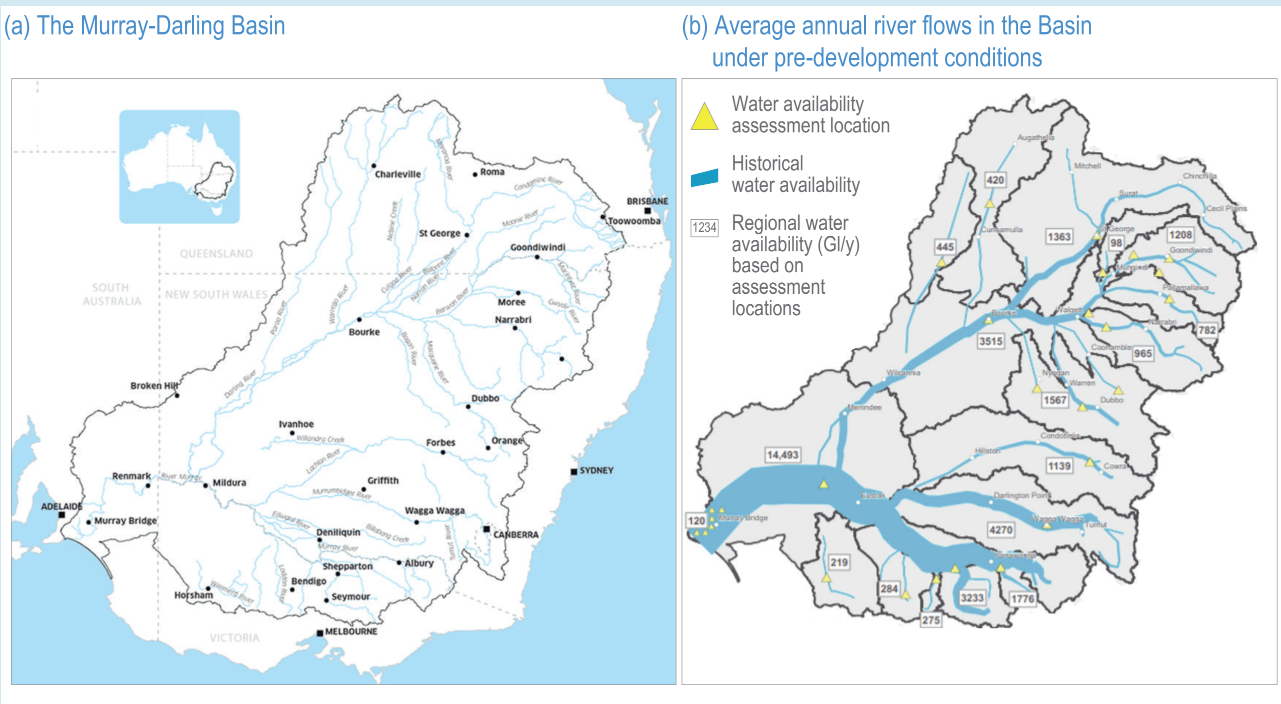

Figure Box 11.3.1 | (A) The Murray-Darling Basin, and (B) average annual river flows in the basin under pre-development conditions (from (CSIRO, 2008) showing that most of the runoff comes from the southeastern highlands. The borders show key drainage basins.

water reduction advisories and 5 to 8 weeks' waiting time for water tank refills and water rationing. The Havelock North water supply contamination, which arose after an extreme rainfall event (DIA, 2017a; DIA, 2017b), was exacerbated by fragmented governance and led to passage of the Taumata Arawai-Water Services Regulator Act of 2020 and the Water Services Bill of 2020 aimed at the protection of source water. The 2017 update to the National Policy Statement for Freshwater Management contains guidelines for implementation at the regional level (MfE, 2017b), including consideration of climate change, which creates opportunities for adaptation. However, there remain tensions between land, water and people which are exacerbated by climate changes and have yet to be addressed (Box 11.5). The first National Adaptation Plan and the Resource Management law reform have the potential to help resolve these tensions (11.7.1) (CCATWG, 2017; MfE, 2020a).

Box 11.4 | Changing Flood Risk

Pluvial (flash flood from high intensity rainfall) and fluvial (river) flooding are the most costly natural disasters in Australia, averaging AUD$8.8 billion per year (Deloitte, 2017b). In New Zealand, insured damages for the 12 costliest flood events from 2007 to 2017 exceeded NZD$472 million, of which NZD$140 million has been attributed to anthropogenic climate change (Frame et al., 2020). Extreme rainfall intensity in northern Australia and New Zealand has been increasing, particularly for shorter (sub-daily) duration and more extreme high rainfall (*high confidence*) (Westra and Sisson, 2011; Griffiths, 2013; Laz et al., 2014; Rosier et al., 2015) (Table 11.2b). Changes are also occurring in spatial and temporal patterns and seasonality (Wasko and Sharma, 2015; Zheng et al., 2015; Wasko et al., 2016).

Extreme rainfall is projected to become more intense (*high confidence*), but the magnitude of change is uncertain (Evans and McCabe, 2013; Bao et al., 2017) (Table 11.3). The insured damage in New Zealand from more intense extreme rainfall under RCP8.5 is projected to increase 25% by 2080–2100 (Pastor-Paz et al., 2020). In urban areas, extreme rainfall intensity is projected to increase pluvial flood risk (*high confidence*). In New Zealand, 20,000 km^2 of land, 675,000 people, and 411,000 buildings with a NZD$135 billion replacement value are exposed to flood risk (Paulik et al., 2019a).

In non-urban areas, where the flood response is also dependent on antecedent catchment conditions (Johnson et al., 2016; Sharma et al., 2018), there is no evidence of increasing flood magnitudes in Australia (Ishak et al., 2013; Zhang et al., 2016; Bennett et al., 2018), except for the most extreme events (Sharma et al., 2018; Wasko and Nathan, 2019). Modelling studies project increases in flood magnitudes in northern and eastern Australia and in western and northern New Zealand (*high confidence*) (Hirabayashi et al., 2013; Collins et al., 2018a; Do et al., 2020). The change in flood magnitude in southern Australia is uncertain because of the compensating effect of more intense extreme rainfall versus projected drier antecedent conditions (Johnson et al., 2016; Pedruco et al., 2018; Wasko and Nathan, 2019). Higher rainfall intensity and peak flows also increase erosion and sediment and nutrient loads in waterways (Lough et al., 2015) and exacerbate problems from ageing stormwater and wastewater infrastructure (Jollands et al., 2007; WSAA, 2016; Hughes et al., 2021).

There is some recognition of the need for flood management and planning to adapt to climate change (*medium confidence*) (COAG, 2011; CCATWG, 2018; CoA, 2020d). Australian flood estimation guidelines recommend a 5% increase in design rainfall intensity per degree global average warming (Bates et al., 2015). In New Zealand, the recommended increase ranges from 5% to more than 10% for shorter-duration and longer-return-period storms (MfE, 2010; Carey-Smith et al., 2018). Both guidelines also indicate the potential for higher increases in extreme rainfall intensity.

Adaptation to reduce flooding and its impacts have included improved flood forecasting (Vertessy, 2013; BoM, 2016) and risk management (AIDR, 2017), accommodating risk through raising floor levels and sealing external doors (Queensland Government, 2011; Wang et al., 2015), deploying temporary levee structures and reducing risk through spatial planning and relocation. Adaptation options in urban areas include improved stormwater management (Hettiarachchi et al., 2019; Matteo et al., 2019), ecosystem-based approaches such as maintaining floodplains, restoring wetlands and retrofitting existing flood control systems to attenuate flows, and water-sensitive urban design (WSAA, 2016; Radcliffe et al., 2017; Radhakrishnan et al., 2017; Rogers et al., 2020b).

Adaptation to changing flood risks is currently mostly reactive and incremental in response to flood and heavy rainfall events (*high confidence*). For example, the 2010–2011 flooding in eastern Australia resulted in changes to reservoir operations to mitigate floods (QFCI, 2012) and insurance practice to cover flood damages (Phelan, 2011; Phelan et al., 2011; QFCI, 2012; Schuster, 2013). Nevertheless, adaptation planning that is pre-emptive and incorporates uncertainties into flood projections is emerging (*medium confidence*) (Schumacher, 2020). Examples from New Zealand include the use of Dynamic Adaptive Pathways Planning (DAPP) (Lawrence and Haasnoot, 2017) with Real Options assessment (Infometrics and PSConsulting, 2015) and designing decision signals and triggers to

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Box 11.4 (continued)

monitor changes before physical and coping thresholds are reached (Stephens et al., 2018). Implementing adaptive flood risk management relies upon an understanding of how such risks change in uncertain and ambiguous ways necessitating adaptive and robust decision-making processes. These can enable learning through participatory adaptive pathways approaches (Lawrence and Haasnoot, 2017; Bosomworth and Gaillard, 2019) and through coordination across different levels of government and statutory mandates, adaptation funding and individual and community adaptations (Glavovic et al., 2010; Boston and Lawrence, 2018; McNicol, 2021).

11.3.4 Food, Fibre, Ecosystem Products

The food, fibre and ecosystem product sectors are economically important in the region. Agriculture contributes around 4% of New Zealand GDP and 2% of Australian GDP and over 50% of New Zealand's and 11% of Australia's exports (NZ Treasury, 2016; Jackson et al., 2020). Forestry contributes 1% of New Zealand GDP and 0.5% Australian GDP (NZ Treasury, 2016; Whittle, 2019). With processing and indirect effects, the primary sector of New Zealand contributes 25% of GDP (Saunders et al., 2016). The region has the lowest level of agricultural subsidies across the OECD (OECD, 2017) and highly responsive producers to market drivers but limited strategic, longer-term approaches to environmental challenges and adaptation (Wreford et al., 2019). Both countries receive government financial drought assistance (Pomeroy, 2015; Downing et al., 2016).

Impacts resulting from climate change are observed across sectors and the region (*high confidence*). While more intense changes are observed in Australia, New Zealand is also experiencing impacts, including the economic impacts of drought attributable to climate change (Frame et al. 2020). Overall, modelling indicates that negative impacts will intensify with increased levels of warming in both countries, with declining crop yield and quality, and negative effects on livestock production and forestry. Although benefits are identified, particularly in the short term for New Zealand (MfE, 2020a), an absence of studies that consider the totality of climatic variables, including extremes, moderate the benefits identified from considering only selected variables and systems in isolation.

Incremental adaptation is occurring (Hochman et al., 2017; Hughes and Lawson, 2017; Hughes and Gooday, 2021). In the longer term, transformative adaptation, including land use change, will be required (Cradock-Henry et al., 2020a), both as a result of sectoral adaptations and mitigation (*medium confidence*) (Grundy et al., 2016). Specific changes are context specific and challenging to project (Bryan et al., 2016). Future adaptive capacity may be limited by declining institutional and community capacity resulting from high debt, unavailability of insurance, increasing regulatory requirements and funding mechanisms that lock in ongoing exposure to climate risk, creating mental health impacts (Rickards et al., 2014; Wiseman and Bardsley, 2016; McNamara and Buggy, 2017; McNamara et al., 2017; Moyle et al., 2017; Robinson et al., 2018; Ma et al., 2020; Yazd et al., 2020).

11.3.4.1 Field Crops and Horticulture

11.3.4.1.1 Observed impacts

Drought, heat and frost in recent decades have shown the vulnerability of Australian field crops and horticulture to climate change (Cai et al., 2014; Howden et al., 2014; CSIRO and BOM, 2015; Lobell et al., 2015; Hughes and Lawson, 2017; King et al., 2017; Webb et al., 2017; Harris et al., 2020) as recognised by policymakers (CoA, 2019a) (*high confidence*). Northern Australia's agricultural output losses are on average 19% each year due to drought (Thi Tran et al., 2016). In southern Australia, the frequency of frost has been relatively unchanged since the 1980s (Dittus et al., 2014; Pepler et al., 2018; BoM and CSIRO, 2020). Drier winters have increased the irrigation requirement for wine grapes (Bonada et al., 2020), while smoke from the 2019/20 fires, which occurred early in the season, caused significant taint damage (Jiang et al., 2021). In New Zealand, reduced winter chill has a compounded impact on the kiwifruit industry, resulting in early harvest and increased energy demand for refrigeration and port access problems (Cradock-Henry et al., 2019) (11.5).

Across all types of agriculture, drought and its physical flow-on effects have caused financial and emotional disruption and stress in farm households and communities (Austin et al., 2018; Bryant and Garnham, 2018; Yazd et al., 2019) (11.3.6). Severe and uncertain climate conditions are statistically associated with increases in farmer suicide (Crnek-Georgeson et al., 2017; Perceval et al., 2019). Rural women often carry extra stress and responsibilities, including increased unpaid and paid work and emotional load (Whittenbury, 2013; Hanigan et al., 2018; Rich et al., 2018).

11.3.4.1.2 Projected impacts

Australian crop yields are projected to decline due to hotter and drier conditions, including intense heat spikes (*high confidence*) (Anwar et al., 2015; Lobell et al., 2015; Prokopy et al., 2015; Dreccer et al., 2018; Nuttall et al., 2018; Wang et al., 2018a). Interactions of heat and drought could lead to even greater losses than heat alone (Sadras and Dreccer, 2015; Hunt et al., 2018). Australian wheat yields are projected to decline by 2050, with a median yield decline of up to 30% in southwest Australia and up to 15% in southern Australia, with possible increases and decreases in the east (Taylor et al., 2018; Wang et al., 2018a). In temperate fruit, accumulated winter chill for horticulture is projected to further decline (Darbyshire et al., 2016). Winegrape maturity is projected to occur earlier due to warmer temperatures (*high confidence*) (Webb et al., 2014; van Leeuwen and Darriet, 2016;

Jarvis et al., 2018; Ausseil et al., 2019b), leading to potential changes in wine style (Bonada et al., 2015). Rice is susceptible to heat stress, and average grain yield losses across rice varieties range from 83% to 53% in experimental trials when heat stress is applied during plant emergence and grain fill stages (Ali et al., 2019). In Tasmania, wheat yields are projected to increase, particularly at sites presently temperature-limited (Phelan et al., 2014).

New Zealand evidence on impacts across crops is very limited. Precipitation and temperature changes alone show minor effects on crop yield, and winter yields of some crops may increase (e.g., wheat, maize) (Ausseil et al., 2019b). For temperate fruit, loss of winter chill may reduce yields in some regions and trigger impacts across supply chains (Cradock-Henry et al., 2019) (11.5.1). Increased pathogens could damage the cut flower, guava and feijoa fruit growing and the honey and related industries (Lawrence et al., 2016). The combined effects of changes in seasonality, temperature, precipitation, water availability and extremes, such as drought, have the potential to escalate impacts, but understanding of these effects is limited.

Other climate-change-related factors complicate crop climate responses. When CO_2 was elevated from present-day levels of 400 to 550 ppm in trials, yields of rainfed wheat, field pea and lentil increased approximately 25% (0–70%). However, there was a 6% reduction in wheat protein that could not be offset by additional nitrogen fertilizer (O'Leary et al., 2015; Fitzgerald et al., 2016; Tausz et al., 2017). Elevated CO_2 will worsen some pest and disease pressures, for example, barley yellow dwarf virus impacts on wheat (Trębicki et al., 2015). Warmer temperatures are also expanding the potential range of the Queensland fruit fly, including into New Zealand (Aguilar et al., 2015a), threatening the horticulture industry (Sultana et al., 2017; Sultana et al., 2020). Some crop pests (e.g., the oat aphid) are projected to be negatively affected by climate change (Macfadyen et al., 2018), but so too are beneficial insects. There is large uncertainty in rainfall and crop projections for northern Australia (Table 11.3). For sugarcane, an impact assessment for CO_2 at 734 ppm using the A2 emission scenario at Ayr in Queensland projected modest yield increases (Singels et al., 2014). Climate change is projected to adversely impact tropical fruit crops such as mangoes through higher minimum and maximum temperatures, reducing the number of inductive days for flowering (Clonan et al., 2020).

Climate change is projected to shift agro-ecological zones (*high confidence*) (Lenoir and Svenning, 2015; Scheffers et al., 2016). This includes the climatically determined cropping strip bounded by the inner arid rangelands and the wetter coast or mountain ranges in mainland Australia (Nidumolu et al., 2012; Eagles et al., 2014; Tozer et al., 2014). A narrowing of grain-growing regions is projected with a shift of the inner margin towards the coast under drier and warmer conditions (Nidumolu et al., 2012; Fletcher et al., 2020). The economic impact of the shift depends on adaptation (Sanderson et al., 2015; Hunt et al., 2019) and how resources, support industries, infrastructure and settlements adapt. Shifts in agro-ecological zones present some opportunities, for example warming is projected to be beneficial for wine production in Tasmania (Harris et al., 2020).

11.3.4.1.3 Adaptation

Some farmers are adapting to drier and warmer conditions through more effective capture of non-growing-season rainfall (e.g., stubble retention to store soil water), improved water use efficiency and matching sowing times and cultivars to the environment (*high confidence*) (Kirkegaard and Hunt, 2011; Fitzer et al., 2019; Haensch et al., 2021). Observed adaptations include new technologies that improve resource efficiencies, professional knowledge and skills development, new farmer and community networks and diversification of business and household income (Ghahramani et al., 2015; De et al., 2016). For Australian wheat, earlier sowing and longer-season cultivars may increase yield by 2–4% by 2050, with a range of –7 to +2% by 2090 (Wang et al., 2018a). In the wheat industry, breeding for improved reproductive frost tolerance remains a priority (Lobell et al., 2015). Modelling suggests that, since 1990, farm management has held Australian wheat yields constant, but declining rainfall and increasing temperature may have contributed to a 27% decline in simulated potential Australian wheat yield (Hochman et al., 2017).

Other observed incremental adaptations include later pruning in the grape industry to spread harvest period and partially restore wine balance, with neutral effects on yield and cost (Moran et al., 2019; Ausseil et al., 2021). The cotton sector increasingly requires shifts in sowing dates to avoid financial impacts (Luo et al., 2017). During years of low water availability, rice growers have been trading water and/or shifting to dry land farming (Mushtaq, 2016).

Growers in New Zealand are changing the timing of their operations, growing crops within covered enclosures and purchasing insurance (Cradock-Henry and McKusker, 2015) Teixeira et al. 2018). Investment of capital in irrigation infrastructure has increased (Cradock-Henry et al., 2018a), although its effectiveness as an adaptation depends on water availability (Box 11.5). In industries based on long-lived plants, such as the kiwifruit and grape industries, many of the adaptations (e.g., breeding and growing heat-adapted and disease-resistant varieties) have long lead times and require greater investment than in the cropping sector (Cradock-Henry et al., 2020a). While breeding programmes for traits with enhanced resilience to future climates are beginning, there is little evidence of strategic industry planning (Cradock-Henry et al., 2018a).

For drought management, balancing near-term needs with long-term adaptation to increasing aridity is essential (Downing et al., 2016). Insufficient and maladaptive decisions can have far-reaching effects, including changes to resources, infrastructure, services and supply chains to which others must adapt (Fleming et al., 2015; Graham et al., 2018). While there is potential for a greater proportion of agriculture to be located to northern Australia, there are significant and complex agronomic, environmental, institutional, financial and social challenges for successful transformation, including the risk of disruption (*medium confidence*) (Jakku et al., 2016).

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11.3.4.2 Livestock

11.3.4.2.1 Observed impacts

Both the seasonality and annual production of pasture is changing (*high confidence*). In many regions, warming is increasing winter pasture growth (Lieffering, 2016); the effects on spring growth are more mixed, with some regions experiencing increased growth (Newton et al., 2014) and others experiencing reduced spring growth (Perera et al., 2020). Droughts are causing economic damage to livestock enterprises, with drought and market prices significantly affecting profit (Hughes et al., 2019a), in addition to the impacts on animal health and the livelihoods of pastoralists, periods of drought contribute to land degradation, particularly in the cattle regions of northern Australia (Marshall, 2015). Heat load in cattle leads to reduced growth rates and reproduction, and extreme heat waves can lead to death (Lees et al., 2019; Harrington, 2020). Temperatures over 32°C reduce ewe and ram fertility along with the birth weight of lambs (van Wettere et al., 2021).

11.3.4.2.2 Projected impacts

Some areas may experience increased pasture growth, but others may experience a decrease that cannot be fully offset by adaptation (*high confidence*) (Moore and Ghahramani, 2013; Lieffering, 2016; Kalaugher et al., 2017). Climate change may modify the seasonality of pasture growth rates more than annual yields in New Zealand (Lieffering, 2016). In eastern parts of Queensland, climate change impacts on pasture growth are equivocal, with simple empirical models suggesting a decrease in net primary productivity (Liu et al., 2017), while mechanistic models that include increases in length of the growing season and the beneficial effects of CO_2 fertilisation indicate increases in pasture growth (Cobon et al., 2020). In Tasmania, annual pasture production is projected to increase by 13–16%, even with summer growth projected to decline with increased interannual variability, resulting in a projected increase in milk yields by 3–16% per annum (Phelan et al., 2015).

Extreme climatic events (droughts, floods and heatwaves) are projected to adversely impact productivity for livestock systems (*medium confidence*). This includes reduced pasture growth rates between 3–23% by 2070 from late spring to autumn and elevated growth in winter and early spring (Cullen et al., 2009; Hennessy et al., 2016; Chang-Fung-Martel et al., 2017). Heavy rainfall and storms are projected to lead to increased erosion, particularly in extensively grazed systems on steeper land, reducing productivity for decades, reducing soil carbon (Orwin et al., 2015) and increasing sedimentation. Increased heat stress in livestock is projected to decrease milk production and livestock reproduction rates (*high confidence*) (Nidumolu et al., 2014; Ausseil et al., 2019b; Lees et al., 2019). In Australia, the average number of moderate to severe heat stress days for livestock is projected to increase 12–15 d by 2025 and 31–42 d by 2050 compared to 1970–2000 (Nidumolu et al., 2014). In New Zealand, an extra 5 (RCP2.6) to 7 (RCP8.5) moderate heat stress days per year are projected for 2046–2060 (*high confidence*) (Ausseil et al., 2019b), which would especially affect animals transported long distances (Zhang and Phillips, 2019) and strain the cold chains needed to deliver meat and dairy products safely. The distribution of existing and new pests and diseases are projected to increase, for example, new tick- and mosquito-borne diseases such as bovine ephemeral fever (Kean et al., 2015).

11.3.4.2.3 Adaptation

Adaptations in both grazing and confined beef cattle systems require enhanced decision-making skills capable of integrating biophysical, social and economic considerations (*high confidence*). Social learning networks that support integration of lessons learned from early adopters and involvement with science-based organisations can help enhance decision-making and climate adaptation planning (Derner et al., 2018). Pasture management adaptations for livestock production include deeper rooted pasture species in higher rainfall regions (Cullen et al., 2014) and drought-tolerant species (Mathew et al., 2018). Soil and land management practices are important in ensuring soils maintain their supporting and regulating services (Orwin et al., 2015). Adaptations in the primary sector in New Zealand are now positioned within the requirements of the National Policy Statement on Freshwater (MfE, 2020b). Adaptations to manage heat stress in livestock include altering the breeding calendar, providing shade and sprinklers, altering nutrition and feeding times and more heat-tolerant animal breeds (Chang-Fung-Martel et al., 2017; Lees et al., 2019; van Wettere et al., 2021).

Beef rangeland systems in Queensland are projected to have benefits in the southeast through higher CO_2 and temperatures extending the growing season and reducing frost, but a warmer and drier climate in the southwest may reduce pasture and livestock production (Cobon et al., 2020). Northern Queensland is most resilient to temperature and rainfall changes (production limited by soil fertility) while western/central west Queensland is most sensitive to rainfall changes, that is, low rainfall is associated with lower productivity (Cobon et al., 2020). The social context of climate change impacts and the processes shaping vulnerability and adaptation, especially at the scale of the individual, are critical to successful adaptation efforts (Marshall and Stokes, 2014).

11.3.4.3 Forestry

11.3.4.3.1 Observed impacts

Climate change may have increased tree mortality in Australia's commercial *Eucalyptus globulus* and *Pinus radiata* plantation forests (Crous et al., 2013; Pinkard et al., 2014). Climate warming enhanced tree water use and vulnerability to heat (Crous et al., 2013). Increases in fire frequency and intensity in forests of southern Australia are leading to diminishing resources available for timber production (Pinkard et al., 2014) (Box 11.1).

11.3.4.3.2 Projected impacts

The projected declines in rainfall in far southwest and far southeast mainland Australia are projected to reduce plantation forest yields (*high confidence*). Warmer temperatures are projected to reduce forest growth in hotter regions (between 7 and 25%), especially where species are grown at the upper range of their temperature tolerances, and increase plantation forest growth (>15%) in cooler margins like

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Tasmania and the Victorian highlands (2030, A2); emission scenario A2 creates a warming trajectory slightly higher than the RCP6.0 warming scenario, but less than RCP8.5 (Rogelj et al., 2012; Battaglia and Bruce, 2017). Elevated CO_2 is projected to increase forest growth if other biophysical factors are not limiting (*medium confidence*) (Quentin et al., 2015; Duan et al., 2018).

Forestry plantations are projected to be negatively impacted from increases in fire weather (Box 11.1), particularly in southern Australia (*high confidence*) (Pinkard et al., 2014). Increased pest damage due to temperature increases may reduce eucalyptus and pine plantation growth by as much as 40% in some Australian environments by 2050 (Pinkard et al., 2014). Increased heat and water stress may enhance insect pest defoliation for *P. radiata* in Australia (e.g., *Sirex noctilio*, *Ips grandicollis* and *Essigella californica*) (Mead, 2013; Pinkard et al., 2014).

Combined impacts from heavy rainfall, soil erosion, drought, fire and pest incursions are projected to increase risks to the permanence of carbon offset and removal strategies in New Zealand for meeting its climate change targets (PCE, 2019; Watt et al., 2019; Anderegg et al., 2020; Schenuit et al., 2021). Effective management of the interactions between mitigation and adaptation policies can be achieved through governance and institutions, including Māori tribal organisations and sectoral adaptation, to ensure effective and continued carbon sequestration and storage as the climate changes (*medium confidence*) (Lawrence et al., 2020b) (11.4.2) (Box 11.5). The productivity of radiata pine (*P. radiata D. Don*) in New Zealand due to higher CO_2 is projected to increase by 19% by 2040 and 37% by 2090, but greater wind damage to trees is expected (Watt et al., 2019). Changes in the distribution of existing weeds, pests and diseases with potential establishment of new sub-tropical pests and seasonal invasions are projected (Kean et al., 2015; Watt et al., 2019; MfE, 2020a). Increased pathogens such as pitch canker, red needle cast and North American bark beetles could damage plantations (Hauraki Gulf Forum, 2017; Lantschner, 2017; Watt et al., 2019).

11.3.4.3.3 Adaptation

Adaptation options include increased investment in monitoring forest condition and functioning; early detection and management of insect pests, diseases and invasive species; improved selection of land with appropriate growing conditions for plantation timber production under current and future conditions; trialling new species and genetic varieties; changing the timing and frequency of planned fuel reduction fires; introducing more fire-tolerant tree species where appropriate; reducing ignition sources; and maintaining access and emergency response capacity (Boulter, 2012; Pinkard et al., 2014; Keenan, 2017).

11.3.4.4 Marine Food

11.3.4.4.1 Observed impacts

The ecological impacts of climate change on fisheries species have already emerged (*high confidence*) (Morrongiello and Thresher, 2015; Gervais et al., 2021). This includes loss of habitats for fisheries species (Vergés et al., 2016; Babcock et al., 2019) and poleward shifts in the distribution of barrens-forming urchins (Ling and Keane, 2018) impacting abalone and rock lobster fisheries. The percentage of reef as barrens across eastern Tasmania grew from 3.4% to 15.2% from 2001/2002 to 2016/2017, an approx. 10.5% increase per annum over the 15-year period (Ling and Keane, 2018). Oysters farmed from wild spat (Sydney rock oysters *Saccostrea glomerata*) are most at risk from climate change, primarily due to observed increases in summer temperatures and heatwave-related mortalities (Doubleday et al., 2013). The exceptional 2017/2018 summer heatwave caused significant losses of farmed salmon in New Zealand, with farm owners seeking consent to move operations to cooler water (Salinger et al., 2019b).

11.3.4.4.2 Projected impacts

Aquaculture is projected to be more easily adapted than wild fisheries to avoid excessive exposure to the physio-chemical stresses from acidification, warming and extreme events (Richards et al., 2015). In New Zealand, wild and cultured shellfish are identified as being most at risk from climate change (Capson and Guinotte, 2014). Changes in ocean temperature and acidification and the downstream impacts on species distribution, productivity and catch are projected concerns (*medium confidence*) (Law et al., 2016) that impact Māori harvesting of traditional seafood and the social, cultural and educational elements of food gathering (mahinga kai) (MfE, 2016). Warm temperate hatchery-based finfish species (yellowtail kingfish *Seriola lalandi*) are projected to be the least at risk, because of well-controlled environmental conditions in hatcheries and temperature increases, which are expected to increase growth rates and productivity during the grow-out stage (Doubleday et al., 2013). For wild fisheries, multi-model projections suggest temperate and demersal systems, especially invertebrate shallow-water species, would be more strongly affected by climate change than tropical and pelagic systems (*medium confidence*) (Pecl et al., 2014; Fulton et al., 2018; Pethybridge et al., 2020). In New Zealand waters, available habitat for both albacore tuna and oceanic tuna (Cummings et al., 2021) is expected to widen and shift.

11.3.4.4.3 Adaptation

Selective breeding in oysters is projected to be an important global adaptation strategy for sustainable shellfish aquaculture that can withstand future climate-driven change to habitat acidification (Fitzer et al., 2019). Less than a quarter of fisheries management plans for 99 of Australia's most important fisheries considered climate change, and only to a limited degree (Fogarty et al., 2019; Fogarty et al., 2021). Implementation of management and policy responses to climate change have lagged in part because climate change has not been considered as the most pressing issue (Hobday and Cvitanovic, 2017; Fogarty et al., 2019; Fogarty et al., 2021) (Cross-Chapter Box MOVING SPECIES in Chapter 5).

11.3.5 Cities, Settlements and Infrastructure

Almost 90% of the population of Australia and New Zealand is urban (World Bank, 2019). Each country has vibrant and diverse urban, rural and remote settlements, with some highly disadvantaged areas isolated by distance and limited infrastructure and services (Argent et al., 2014; Charles-Edwards et al., 2018; Spector et al., 2019). Some

Box 11.5 | New Zealand's Land, Water and People Nexus under a changing climate

New Zealand's economy, dominated by the primary sector and the tourist industry (pre-COVID), relies upon a 'clean green' image of water, natural ecosystems and pristine landscapes (Foote et al., 2015; Roche and Argent, 2015; Hayes and Lovelock, 2017). Water is highly valued by Māori for its mauri or life force and for its intrinsic values and multiple uses (Harmsworth et al., 2016). Increasingly, these diverse values are coming into conflict (Hopkins et al., 2015) due to increasing pressures from how land is used and managed and the effects on water availability and quality. Such tensions will be further challenged as temperatures rise and extreme events intensify beyond what has been experienced, thus stressing current adaptive capacities (*high confidence*) (Hughey and Becken, 2014; Cradock-Henry and McKusker, 2015; Hopkins et al., 2015; MfE and Stats NZ, 2021) (11.2.2; 11.3.4).

Irrigation has increasingly been used to enhance primary sector productivity and regional economic development (Srinivasan et al., 2017; Fielke and Srinivasan, 2018; MfE and Stats NZ, 2021) (Srinivasan et al., 2017; Fielke and Srinivasan, 2018; MfE and Stats NZ, 2021). Pressure for long-term access to groundwater or large-scale water storage is increasing to ensure the ongoing viability of the primary sector as the climate changes. While investment in irrigation infrastructure may reduce climate change impacts in the short term, maladaptive outcomes cannot be ruled out longer term, which means that focusing attention now on adaptive and transformational measures can help increase climate resilience in areas exposed to increasing drought and climate extremes that disrupt production (*medium confidence*) (Abel et al., 2016; Cradock-Henry et al., 2019) (Yletyinen et al., 2019).

Furthermore, overallocation raises further tensions from competing uses of water such as for horticulture and urban water supplies, as well as for ecological requirements. The deterioration of water quality and loss of places of social, economic, cultural and spiritual significance creates increasing tension for Māori in particular (Harmsworth et al., 2016; Salmon, 2019; MfE and Stats NZ, 2021). Public concern has increased over the deterioration of New Zealand's waterways and the profiting of some land uses at the expense of environmental quality and human health—tensions that make adaptation to climate change more challenging (Duncan, 2014; Foote et al., 2015; Scarsbrook and Melland, 2015; McDowell et al., 2016; McKergow et al., 2016; Greenhalgh and Samarasinghe, 2018). A lack of precautionary governance of water resources linked to unsustainable land use practices degrading water quality (Scarsbrook and Melland, 2015; Salmon, 2019) highlights the role that foresight could play in managing the nexus between land, water and people in a changing climate (11.3.3). Adaptive planning holds potential for navigating these multi-dimensional challenges (Sharma-Wallace et al., 2018; Cradock-Henry and Fountain, 2019; Hurlbert et al., 2019) (11.7).

Furthermore, land and, in particular, plantation and native forests play a critical role in meeting New Zealand's emissions reduction goals. However, the persistence of land and forests as a carbon sink is uncertain, and the sequestered carbon is at risk from future loss resulting from climate change impacts, including from increased fire, drought and pest incursions, storms and wind (IPCC, 2019a; PCE, 2019; Watt et al., 2019; Anderegg et al., 2020) (11.3.4.3), underlining the importance of interactions between mitigation and adaptation policy and implementation. Integrated climate change policies across biodiversity, water quality, water availability, land use and forestry for mitigation can support the management of land use, water and people conflicts, but there is little evidence of such coordinated policies (Cradock-Henry et al., 2018b; Wreford et al., 2019). Implementation of the National Policy Statement for Freshwater Management 2020 (MfE, 2020b) and the National Adaptation Plan (due out in August 2022) present opportunities for such interconnections and diverse values to be addressed, as well as enabling sector and community benefits to be realised across New Zealand (Awatere et al., 2018; Lawrence et al., 2020b).

areas in northern Australia and New Zealand, especially those with higher proportions of Indigenous inhabitants, face severe housing, health, education, employment and services issues (Kotey, 2015), which increases their vulnerability to climate change.

Infrastructure within and between cities and settlements is critical for activity across all sectors, with interdependencies increasing exposure to climate hazards (11.5.1). Previous planning horizons for existing infrastructure are compromised by now having to accommodate ongoing sea level rise (SLR), warming and increasing frequency of extreme rainfall and storm events (Climate Institute, 2012; MfE, 2017a). There is almost no information on the costs and benefits of adapting vulnerable and exposed infrastructure in Australia or New Zealand. Given the value of that infrastructure and the rising damage costs, this represents a large knowledge gap that has led to an adaptation investment deficit.

11.3.5.1 Observed Impacts

Critical infrastructure, cities and settlements are being increasingly affected by chronic and acute climate hazards, including heat, drought, fire, pluvial and fluvial flooding and sea level rise (SLR), with consequent effects on many sectors (*high confidence*) (Instone et al., 2014; Loughnan et al., 2015; Zografos et al., 2016; Hughes et al., 2021). Risks and impacts vary with physical characteristics, location, connectivity and socioeconomic status of settlements because of the ways these influence exposure and vulnerability (*high confidence*) (Loughnan et al., 2013; MfE, 2020a).

Weather-related disasters are causing significant disruption and damage (Paulik et al., 2019a; CSIRO, 2020; Paulik et al., 2020). In Australia, during 1987–2016, natural disasters caused an estimated 971 deaths and 4370 injuries, 24,120 people were made homeless

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and about 9 million people were affected (Deloitte, 2017a). More than 50% of these deaths and injuries came from heatwaves in cities and 22% from fires. During the 2007–2016 period, Australia natural disaster costs averaged AUD$18.2 billion yr^{-1}, with the largest contributions from floods (AUD$8.8 billion), followed by cyclones (AUD$3.1 billion), hail (AUD$2.9 billion), storms (AUD$2.3 billion) and fires (AUD$1.1 billion) (Deloitte, 2017a). The Australian fires in 2019–2020 cost over AUD$8 billion, with devastating impacts on settlements and infrastructure (Box 11.1)

Sea level rise affects many interdependent systems in cities and settlements, which increases the potential for compounding and cascading impacts (11.5.1). Seaports, airports, water treatment plants, desalination plants, roads and railways are increasingly exposed to sea level rise (SLR) (*very high confidence*), impacting their longevity and levels of service and maintenance (*high confidence*) (McEvoy and Mullett, 2014; Woodroffe et al., 2014; PCE, 2015; Ranasinghe, 2016; Newton et al., 2018; Paulik et al., 2020) (Box 11.6). Compounding coastal hazards in New Zealand, such as elevated water tables associated with rising sea level and intense rainfall (Morgan and Werner, 2015; McBride et al., 2016; White et al., 2017; Hughes et al., 2021), are exerting pressure on stormwater and wastewater infrastructure and drinking water supply and quality (MfE, 2020a).

Extreme heat events exacerbate problems for vulnerable people and infrastructure in urban Australia, where urban heat is superimposed upon regional warming, and there are adverse impacts for population and vegetation health, particularly for socioeconomically disadvantaged groups (Tapper et al., 2014; Heaviside et al., 2017; Filho et al., 2018; Gebert et al., 2018; Rogers et al., 2018; Longden, 2019; Marchionni et al., 2019; Tapper, 2021) (11.3.6), energy demand, energy supply and infrastructure (*very high confidence*) (Newton et al., 2018) (11.3.10). Extreme heat is increasingly threatening liveability in some rural areas in Australia (Turton, 2017), particularly given their reliance on outside physical work and older populations. Settlement design and the level of greening interact with climate change to influence local heating levels (Tapper et al., 2014; Wong et al., 2020; Tapper, 2021).

Floods cause major damage. The floods of early 2019 in North Queensland cost AUD$5.68 billion (Deloitte, 2019), while Cyclone Yasi and the Queensland floods of 2011 cost A$6.9 billion (Deloitte, 2016). Floodplains in New Zealand have considerably higher overall national exposure of buildings and population than coasts (Paulik et al., 2019a) (Box 11.4). The insured losses from the 12 costliest floods in New Zealand from 2007 to 2017 totalled NZD$471.56 million, of which NZD$140.48 million could be attributed to climate change (Frame et al., 2020).

Climatic extremes are exacerbating existing vulnerabilities (*high confidence*). Long supply chains, poorly maintained infrastructure, social disadvantage and poor health and lack of skilled workers (Eldridge and Beecham, 2018; Mathew et al., 2018; Rolfe et al., 2020) are contributing to serious stress and disruption (Smith and Lawrence, 2014; Kiem et al., 2016). In many rural settlements, population ageing and reliance on an overstretched volunteer base for recovery from extreme events are increasing vulnerability to climate change (Astill and Miller, 2018; Davies et al., 2018). Recovery from long, intense, more frequent and compounding climatic events in rural areas has been disrupted by the erosion of natural, financial, built, human and social capital (De et al., 2016; Sheng and Xu, 2019). Delayed recovery from extreme climatic events has been compounded by long-term displacement, which in turn prolongs the impacts (Matthews et al., 2019). Severe droughts have contributed to poor health outcomes for rural communities, including extreme stress and suicide (Beautrais, 2018; Perceval et al., 2019). In Australia, competition among water users has left some rural communities experiencing extreme water shortage and insecurity with associated health impacts (Wheeler et al., 2018; Judd, 2019) (Box 11.3).

11.3.5.2 Projected Impacts

Changes in heat waves, droughts, fire weather, heavy rainfall, storms and sea level rise (SLR) are projected to increase negative impacts for cities, settlements and infrastructure (*high confidence*) (Table 11.3a, Table 11.3b; Box 11.1, Box 11.3, Box 11.4).

Increased floods, coastal inundation (assuming a sea level rise (SLR) of 1.6 m by 2100), wildfires, windstorms and heatwaves may cause property damage in Australia estimated at AUD$91 billion per year by 2050 and AUD$117 billion per year by 2100 for RCP8.5, while damage-related loss of property value is estimated at AUD$611 billion by 2050 and AUD$770 billion by 2100 for RCP8.5 (Steffen et al., 2019). For a 1.0-m sea level rise (SLR), the value of exposed assets in New Zealand would be NZD$25.5 billion (Box 11.6). For a 1.1-m sea level rise (SLR), the value of exposed assets in Australia would be AUD$164–226 billion (Box 11.6). These exposure estimates exclude impacts on personal livelihood, well-being and lifestyle.

Extreme heat risks are projected to exacerbate existing heat-related impacts on human health, vegetation and infrastructure (Tapper et al., 2014; Tapper, 2021) (11.3.6). In Australia, the annual frequency of days over 35°C is projected to increase 20–70% by 2030 (RCP4.5), and 25–85% (RCP2.6) to 80–350% (RCP8.5) by 2090 (Table 11.3a). For example, Perth may average 36 d over 35°C by 2030 (RCP4.5). In New Zealand, the annual frequency of days over 25°C may increase 20–60% (RCP2.6) to 50–100% (RCP8.5) by 2040 and 20–60% (RCP2.6) to 130–350% (RCP8.5) by 2090 (Table 11.3b). For example, Auckland may average 39 d over 25°C by 2040 (RCP8.5). Unprecedented extreme temperatures, as high as 50°C in Sydney or Melbourne, could occur with global warming of 2.0°C (Lewis et al., 2017). Heat-related costs for Melbourne during 2012–2051 are estimated at AUD$1.9 billion, of which AUD$1.6 billion is human health/mortality costs (AECOM, 2012). Extreme heat is threatening liveability in some rural areas in Australia (Turton, 2017), particularly given their reliance on outside physical work and older populations.

Key infrastructure and services face major challenges. Structural metal corrosion rates are projected to increase significantly at coastal locations but decrease inland (Trivedi et al., 2014). A drier climate may decrease the rate of deterioration of road pavements, but extreme rainfall events and heat pose a significant risk (Taylor and Philp, 2015), especially to unsealed roads in northern Australia (CoA, 2015). Critical infrastructure on coasts is at risk from sea level rise (SLR) and storm surges (Box 11.6). Facilities such as hospitals face weather-related hazards exacerbated by climate change and not originally anticipated in building and infrastructure design (Loosemore et al., 2011; Loosemore et al., 2014). By 2050, increased risks are projected for the availability and quality of potable water supplies, delivery of wastewater and stormwater services to communities, transport systems, electricity infrastructure, operating municipal landfills and contaminated sites located near rivers and the coast (Gilpin et al., 2020; MfE, 2020a; Hughes et al., 2021). These then create risks to social cohesion and community well-being from displacement of individuals, families and communities, with inequitable outcomes for vulnerable groups (Boston and Lawrence, 2018).

11.3.5.3 Adaptation

In cities and settlements, climate adaptation is under way and is being led and facilitated by state and local government leadership and facilitation, particularly in Australia (*high confidence*) (Hintz et al., 2018; Newton et al., 2018) (Table 11.7, Supplementary Material Table SM11.1a).

Effective adaptations to urban heat include spatial planning, expanding tree canopy and greenery, shading, sprays and heat-resistant and energy-efficient building design, including cool materials and reflective or green roofs (*very high confidence*) (Broadbent et al., 2018; Jacobs et al., 2018b; Haddad et al., 2019; Haddad et al., 2020a; Yenneti et al., 2020; Bartesaghi-Koc et al., 2021; Tapper, 2021). Reducing urban heat not only benefits human health but reduces the demand for, and cost of, air conditioning (Haddad et al., 2020b) and the risk of electricity blackouts (11.3.10).

Adaptation progress is being hampered by current urban redevelopment practice and statutory planning guidelines that are leading to the removal of critical urban green space (Newton and Rogers, 2020). Reform of approaches to urban redevelopment would facilitate adaptation (Newton and Rogers, 2020). Several cities in Australia and New Zealand are part of the 100 Resilient Cities global network, which helped facilitate the metropolitan Melbourne Urban Forest Strategy across councils (Fastenrath et al., 2019; Coenen et al., 2020), and in New Zealand, restoration of the urban forest in Hamilton is reducing heat stressors (Wallace and Clarkson, 2019). In peri-urban zones, adapting to fire risk is a contested issue, raising difficult trade-offs between heat management, ecological values and fuel reduction in treed landscapes (Robinson et al., 2018).

The resilience of Australia's major cities to flooding and drought has been advanced through a range of economic and physical interventions. Water-sensitive urban design irrigates vegetation with harvested storm water that improves water security, flood risk, carbon sequestration, biodiversity and air and water quality and delivers cooling that can save human lives in heatwaves (Wong et al., 2020). Stormwater harvesting is supported by some councils in New Zealand and can deliver recycled water for households (Attwater and Derry, 2017), improving climate resilience and reducing water demand (White et al., 2017). Addressing infrastructure vulnerability is essential given the long lifetime of assets, criticality of services and high costs of maintenance (Chester et al., 2020; Hughes et al., 2021).

Climate risk management is evolving, but adaptive capacity, implementation, monitoring and evaluation are uneven across all scales of cities, settlements and infrastructure (*very high confidence*) (Table 11.15a and Table 11.15b; Supplementary Material Tables SM11.1a and SM11.1b). There is increasing awareness of the need to move from incremental coping and defensive coastal strategies (Jongejan et al., 2016) to transformational adaptation, for example managed retreat (Torabi et al., 2018; Hanna, 2019), and to consider the flow-on effects (e.g., for housing and employment) (Fatorić et al., 2017; Torabi et al., 2018). Strategies limited to building household and community self-reliance (Astill and Miller, 2018) are increasingly inadequate given systemic and interconnected stressors and cascading impacts across interdependent systems (Lawrence et al., 2020b). Integrated approaches to climate change adaptation and emissions reduction have potential for addressing interdependent systems (e.g., nature-based approaches, climate-sensitive urban design, energy and transport systems) (Norman et al., 2021). Climate risk assessment and adaptation guidelines have been prepared for transport infrastructure authorities and organisations (Finlayson et al., 2017; Byett et al., 2019; Yenneti et al., 2020).

Infrastructure service vulnerability in New Zealand is supported by new institutional adaptations including the Infrastructure Commission to develop a 30-year national infrastructure strategy. The Climate Change Commission (Climate Change Commission, 2020) has issued six principles for climate-relevant infrastructure investments and is mandated to monitor the National Climate Change Adaptation Plan based on the first National Climate Change Risk Assessment (MfE, 2020a). A National Disaster Resilience Strategy addresses integrated planning for risk reduction and awareness-raising in New Zealand (Department of the Prime Minister and Cabinet, 2019).

Successive inquiries and reviews highlight potential synergies between disaster risk management and climate resilience (11.5.1) (Smith and Lawrence, 2018; Ruane, 2020). In Australia, there is a National Disaster Risk Reduction Framework (CoA, 2018b) and a National Recovery and Resilience Agency (CoA, 2021) that help underpin the development of national support systems for rural and regional emergency management and associated volunteer sectors (McLennan et al., 2016) and wildfire smoke impacts (CoA, 2020e). The National Heatwave Framework Working Group uses a Heatwave Forecast Service, and heatwave early-warning and adaptation systems that operate in Adelaide, Melbourne, Sydney and Brisbane have reduced potential death rates (Nitschke et al., 2016).

Infrastructure planning is lagging behind international standards for climate resilience evaluation and guidance for adaptation to climate risk (*high confidence*) (CSIRO, 2020; Kool et al., 2020; Hughes et al., 2021). Some companies have examined their exposure to climate risk and developed strategies to minimise their vulnerability (Climate Institute, 2012) (11.3.8). Climate risk assessments have been conducted for the electricity sector in both Australia and New Zealand (11.3.10). Climate change is considered in Australian infrastructure plans for national and regional water supply security, water for irrigated agriculture, a coastal hazards adaptation strategy and the Tanami Road upgrade (Infrastructure Australia, 2016; Infrastructure Australia, 2019; Infrastructure Australia, 2021)

Industry associations are beginning to facilitate climate adaptation for infrastructure, including the Australian Green Infrastructure

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Table 11.7 | Cities, settlements and infrastructure: key risks and adaptation options.

Sector	Key Risks	Adaptation Options	Inter-Sector Dependencies	Sources
Road	Heat, SLR, coastal surges, floods and high-intensity rainfall impacts on road foundations	Re-routing, coastal protection, improved drainage	Ports (fuel supply), rail (fuel supply), electricity	(NCCARF, 2013; CoA, 2018a; MfE, 2020a)
Rail	Extreme temperatures, flooding, SLR, high-intensity rainfall impacts on track foundations	Drainage and ventilation improvements, systematic risk assessments, overhead wire and rail/sleeper upgrades, re-routing	Electricity, telecommunications, fuel supply (transport, ports)	(CoA, 2018a; MfE, 2020a)
Urban and Rural Built Environment[1]	Extreme temperatures, floods, extreme weather events, wildfire (at urban–rural interface), SLR	Multiple options from the building-to-city scale to reduce heat impacts and improve climate resilience, behavioural change, coastal defences and managed retreat	Road, rail, electricity, air and seaports, telecommunications, water and wastewater	(CoA, 2018a; Newton et al., 2018; Haddad et al., 2019; MfE, 2020a; Paulik et al., 2020; Tapper, 2021) (Box 11.1) (Box 11.4)
Electricity	High-wind/ temperature events, wildfire, lightning, dust storms, drought (hydro)	Demand management, re-engineering and new technology, network intelligence, smart metering, improved planning for outages	Road, rail, water	(CoA, 2017; MfE, 2020a) (11.3.10.)
Ports: Air and Sea	SLR, coastal surges, wind, heat, extreme weather events	Air: improved coastal, pluvial and fluvial flood protection, on-site services; sea: widening operational limits, raising wharfs, roads and breakwaters	Electricity, road, rail, water	(McEvoy and Mullett, 2014; MfE, 2020a)
Telecommunications	Floods, wildfires, extreme wind	Protect, place underground, wireless systems	Electricity, digital connectivity, all sectors serviced, rural communities	(NCCARF, 2013)
Stormwater Wastewater and Water supply[a.]	High-intensity rainfall, increased and extreme temperatures, flooding, drought, SLR	Large investments in upgrading centralised infrastructure and capacity, increasing investment in decentralised infrastructure and capacity (e.g., water-sensitive urban design), demand management, fewer options in smaller communities, governance at scale	Electricity, telecommunications, urban and rural built environment	(White et al., 2017; CoA, 2018a; Gilpin et al., 2020; MfE, 2020a; Wong et al., 2020; Hughes et al., 2021) (Box 11.4)

Notes:

(a) Water supply safety and security and exposure of buildings have been identified as the most significant risks for New Zealand in terms of urgency and consequence (MfE, 2020a). No such ranking of risk has been done for Australia.

Council (CoA, 2015), the Green Building Council of Australia Green Star Programme (GBCA, 2020), the Water Services Association of Australia, Climate Change Adaptation Guidelines (WSAA, 2016) and the Australian Sustainable Built Environment Council Built Environment Adaptation Framework (ASBEC, 2012). The Infrastructure Sustainability Rating Scheme measures the social, environmental, governance and cultural outcomes delivered by more than AUD$160 billion worth of infrastructure, and it is projected to deliver a cost-benefit ratio of 1:1.6 to 1:2.4 during the period 2020–2040 (RPS, 2020). There is scope for engagement of industry in transitioning to a low-carbon green economy that is adapted to climate change, but less certainty on how to develop appropriate business cases (Newton and Newman, 2015).

There are tensions between settlement-scale adaptation options, such as managed retreat, that focus on the long term and people's values, place attachments, needs and capacities (Gorddard et al., 2016; Fatorić et al., 2017; Graham et al., 2018; O'Donnell, 2019; Norman et al., 2021). Tensions also exist between climate change adaptation and mitigation goals (e.g., current energy efficiency standards in Australian buildings can worsen their heat resistance and increase dependence on air-conditioning) (Hatvani-Kovacs et al., 2018). Where there is a lack of coordination between jurisdictions, there can be flow-on effects from failure to adapt, for example in coastal local government areas (Dedekorkut-Howes et al., 2020) (Box 11.6). There is limited information across the region on climate change impacts and adaptation options for telecommunications (NCCARF, 2013) (Table 11.7). There is an emerging recognition that implementing and evaluating the adaptation process (vulnerability and risk assessments, identification of options, planning, implementation, monitoring, evaluation and review) in local contexts can advance more effective adaptation (Moloney and McClaren, 2018). For example, the Victorian state government has built monitoring, evaluation and adaptation components into its adaptation plan (Table 11.15a).

Box 11.6 | Rising to the Sea Level Challenge

Many of the region's cities and settlements, cultural sites and place attachments are situated around harbours, estuaries and lowland rivers (Black, 2010; PCE, 2015; Australia SoE, 2016; Rouse et al., 2017; Hanslow et al., 2018; Birkett-Rees et al., 2020) exposed to ongoing relative sea level rise (RSLR). RSLR includes regional variability in oceanic conditions (Zhang et al., 2017) and vertical land movement along New Zealand's tectonically dynamic coasts (Levy et al., 2020) and some Australian hotspots for subsidence (Denys et al., 2020; King et al., 2020; Watson, 2020).

Table Box 11.6.1 | Observed and projected impacts from higher mean sea level

Impacts from increase in mean sea level	References
Nuisance and extreme coastal flooding have increased from higher mean sea level in New Zealand. Projected SLR will cause more frequent flooding in Australia and New Zealand before mid-century (*very high confidence*)	(Hunter, 2012; McInnes et al., 2016; Stephens et al., 2017; Stephens et al., 2020); (Steffen et al., 2014; PCE, 2015; MfE, 2017a; Hague et al., 2019; Paulik et al., 2020)
Squeeze in intertidal habitats (*high confidence*)	(Steffen et al., 2014; Peirson et al., 2015; Mills et al., 2016a; Mills et al., 2016b; Pettit et al., 2016; Rouse et al., 2017; Rayner et al., 2021)
Significant property and infrastructure exposure (*high confidence*)	(Steffen et al., 2014; PCE, 2015; Harvey, 2019; LGNZ, 2019; Paulik et al., 2020) (Table Box 11.5.2 and Table Box 11.6.2)
Loss of significant cultural and archaeological sites and projected to compound with several hazards over this century (*medium confidence*)	(Bickler et al., 2013; Birkett-Rees et al., 2020; NZ Archaeological Association, 2020)
Increasing flood risk and water insecurity with health and well-being impacts on Torres Strait Islanders (*high confidence*)	(Steffen et al., 2014; McInnes et al., 2016; McNamara et al., 2017)
Degradation and loss of freshwater wetlands (*high confidence*)	(Pettit et al., 2016; Bayliss and Ligtermoet, 2018; Tait and Pearce, 2019; Grieger et al., 2020; Swales et al., 2020)

Coastal shoreline position is driven by a complex combination of natural drivers, past and present human interventions, climate variability (Bryan et al., 2008; Helman and Tomlinson, 2018; Allis and Hicks, 2019) and variation in sediment flux (Blue and Kench, 2017; Ford and Dickson, 2018). RSLR, to date, is a secondary factor influencing shoreline stability (*medium confidence*), and in Australia no definitive SLR signature is yet observed in shoreline recession, nor is one documented in New Zealand, due to variability in shoreline position responding to storms and seasonal, annual and decadal climate drivers (Australian Government, 2009; McInnes et al., 2016; Sharples et al., 2020).

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The primary impacts of rising mean sea level (Table Box 11.6.1) are being compounded by climate-related changes in waves, storm surge, rising water tables, river flows and alterations in sediment delivery to the coast (*medium confidence*). The net effect is projected to increase erosion on sedimentary coastlines and flooding in low-lying coastal areas (McInnes et al., 2016; MfE, 2017a; Hanslow et al., 2018; Wu et al., 2018). Waves are projected to be higher in southern Australasia and lower elsewhere (Morim et al., 2019) and storm surge slightly higher in the south, slightly lower further north in New Zealand (Cagigal et al., 2019) and small robust declines in southern Australia, with potentially larger changes in the Gulf of Carpentaria (Colberg et al., 2019).

The cumulative direct and residual risk from RSLR and associated impacts are projected to continue for centuries, necessitating ongoing adaptive decisions for exposed coastal communities and assets (*high confidence*) (MfE, 2017c; Oppenheimer et al., 2019; Tonmoy et al., 2019).

Prevailing decision-making assumes shorelines can continue to be maintained and protected from extreme storms, flooding and erosion, even with RSLR (Lawrence et al., 2019a). Rapid coastal development has increased exposure of coastal communities and infrastructure (*high confidence*) (Helman and Tomlinson, 2018; Paulik et al., 2020), reinforcing perceptions of safety (Gibbs, 2015; Lawrence et al., 2015) and creating barriers to retreat and nature-based adaptations (*very high confidence*) (Schumacher, 2020). The efficacy and increasing costs of protection and accommodation risk reduction approaches and rebuilding after extreme events have been questioned and have limits (PCE, 2015; MfE, 2017a; Harvey, 2019; LGNZ, 2019; Paulik et al., 2020; Haasnoot et al., 2021). Future shoreline erosion is often signalled using defined coastal setback lines(s) and using probabilistic approaches to signal uncertainty (Ramsay et al., 2012; Ranasinghe, 2016).

Box 11.6 (continued)

Table Box 11.6.2 | Observed relative SLR (variance-weighted average) with uncertainty range (standard deviation) and projected impacts on infrastructure and population of 1.1 m in Australia and 1 m in New Zealand. SLR projections for 2050 and 2090 are given in Table 11.3a and Table 11.3b.

Country	Observed relative sea level rise	Projected impacts of SLR (1.1 m Australia, 1.0 m New Zealand)			
		Value of coastal urban infrastructure	Number of buildings exposed	Number of residents exposed	Public council assets exposed
Australia	2.2±1.8 mm/year to 2018 for four >75-year records (or an average of 0.17 m over 75 years), 3.4 mm/year from 1993–2019 (Watson, 2020)	AUD$164 to >226 billion (DCCEE, 2011; Steffen et al., 2019) 111% rise in inundation cost from 2020 to 2100 (Mallon et al., 2019)	187,000 to 274,000 residential buildings, 5800 to 8600 commercial buildings, 3700 to 6200 light industrial buildings (DCCEE, 2011)	N/A	27,000 to 35,000 km roads and 1200 to 1500 km rail lines and tramways (DCCEE, 2011)
New Zealand	1.8 mm/year from 1900–2018, 1.2 mm/year from 1900–1960 and 2.4 mm/year from 1961–2018 (Bell and Hannah, 2019)	NZD$25.5 billion (Paulik et al., 2020)	75,890 (Paulik et al., 2020)	105,580 (Paulik et al., 2020)	4000 km pipelines, 1440 km roads, 101 km rail, 72 km electricity transmission lines (Paulik et al., 2020) NZD$5 billion (2018) (reserves, buildings, utility networks, roads) (LGNZ, 2019)

Flooding from high spring ('king') tides or storm tides during extreme weather events are raising public awareness of SLR (Green Cross Australia, 2012), including through media coverage (Priestley et al., 2021). The use of adaptive decision tools (11.7.3.1; Table 11.17) is increasing the understanding of changing coastal risk (Bendall, 2018; Lawrence et al., 2019b; Palutikof et al., 2019b) and how dynamic adaptive pathways and monitoring of them can aid implementation (Stephens et al., 2018; Lawrence et al., 2020b). Collaborative governance between local governments and their communities, including with Māori tribal organisations, is emerging in New Zealand (OECD, 2019b) assisted by national direction (DoC NZ, 2010) and guidance on adaptive planning (Table 11.15b). This shift from reactive to pre-emptive planning is better suited to ongoing RSLR (Lawrence et al., 2020b).

In Australia, adaptation to SLR remains uneven across jurisdictions in the absence of clear federal or state guidance, rendering Australia unprepared for flooding from SLR (Dedekorkut-Howes et al., 2020). Risk-averse coastal governance at the local level has led to shifts in liabilities to other actors and to future generations (Jozaei et al., 2020). Managed retreat has emerged as an adaptation option in New Zealand (Rouse et al., 2017; Hanna, 2019; Kool et al., 2020; Lawrence et al., 2020c), where protective measures are transitional (DoC NZ, 2010) and where managed retreat has arisen from collaborative governance (Owen et al., 2018). Remaining adaptation barriers are social or cultural (the absence of licence and legitimacy) and institutional (the absence of regulations, policies and processes that support changes to existing property rights and the funding of retreat) (*high confidence*) (O'Donnell and Gates, 2013; Tombs et al., 2018; Grace et al., 2019; O'Donnell et al., 2019).

Legacy development, competing public and private interests, trade-offs among development and conservation objectives, policy inconsistencies, short- and long-term objectives and the timing and scale of impacts compound to create contestation over implementation of coastal adaptation (*high confidence*) (Mills et al., 2016b; McClure and Baker, 2018; Dedekorkut-Howes et al., 2020; McDonald, 2020; Schneider et al., 2020). Legal barriers to coastal adaptation remain (Schumacher, 2020) with a risk that the courts will become decision makers (Iorns Magallanes et al., 2018) due to legislative fragmentation, status quo leadership, lack of coordination between governance levels and agreement about who pays for what adaptation (*very high confidence*) (Waters et al., 2014; Boston and Lawrence, 2018; Palutikof et al., 2019a; Noy, 2020). The nexus of climate, law, place and property rights continues to expose people and assets to ongoing SLR (Johnston and France-Hudson, 2019; O'Donnell, 2019), especially where the risks of SLR are not being reflected in property valuations (Cradduck et al., 2020). Risk signalling through land use planning, flooding events and changes in insurance availability and costs is projected to increase recognition of coastal risks (*medium confidence*) (Storey and Noy, 2017; CCATWG, 2018; Lawrence et al., 2018a; Harvey and Clarke, 2019; Steffen et al., 2019; Cradduck et al., 2020; ICNZ, 2021). Proactive local-led engagement and strategy are key to effective adaptation and incentivising and supporting communities to act (Gibbs, 2020; Schneider et al., 2020). Adopting 'fit for purpose' decision tools that are flexible as sea levels rise (11.7.3) can build adaptive capacity in communities and institutions (*high confidence*).

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11.3.6 Health and Well-being

11.3.6.1 Observed Impacts

There is ample evidence of health loss due to extreme weather in Australia and New Zealand, and rising temperatures, changing rainfall patterns and increasing fire weather have been attributed to anthropogenic climate change (11.2.1). Extreme heat leads to excess deaths and increased rates of many illnesses (Hales et al., 2000; Nitschke et al., 2011; Lu et al., 2020). Between 1991 and 2011 it is estimated that 35–36% of heat-related mortality in Brisbane, Sydney and Melbourne was attributable to climate change, amounting to about 106 deaths a year on average over the study period (Vicedo-Cabrera et al., 2021). Exposure to high temperatures at work is common in Australia, and the health consequences may include more accidents, acute heat stroke and chronic disease (Kjellstrom et al., 2016). Long-term rise in temperatures is changing the balance of summer and winter mortality in Australia (Hanigan et al., 2021). The Black Summer wildfires in Australia in 2019/2020 (Box 11.1) caused 33 deaths directly (Davey and Sarre, 2020) and exposed millions of people to heavy particulate pollution (Vardoulakis et al., 2020). In the Australian states most heavily affected by the fires, 417 deaths, 3151 hospital admissions for cardiovascular or respiratory conditions and about 1300 emergency department presentations for asthma are attributed to wildfire smoke exposure (Borchers Arriagada et al., 2020). Immediate smoke-related health costs from the 2019–2020 fires are estimated at AUD$1.95 billion (Johnston et al., 2020).

Extreme heat is associated with decreased mental well-being, more marked in women than men (Ding et al., 2016). Changing climatic patterns in western Australia have undermined farmers' sense of identity and place, heightened anxiety and increased self-perceived risks of depression and suicide (Ellis and Albrecht, 2017). Following the Black Saturday wildfires in Victoria in 2009, 10–15% of the population in the most severely affected areas reported persistent fire-related post-traumatic stress disorder, depression and psychological distress (Bryant et al., 2014). Repeated exposure to the threat of wildfires in Australia, either directly (Box 11.1) or through media coverage (Looi et al., 2020), may compound effects on mental health. In March 2017, 31,000 people in New South Wales and Queensland were displaced by Tropical Cyclone Debbie. Six months post-cyclone, adverse mental health outcomes were more common among those whose access to health and social care was disrupted (King et al., 2020).

Dengue fever remains a threat in northern Australia and variations in rainfall and temperature are related to disease outbreaks and patterns of spread, although most outbreaks are sparked by travellers bringing the virus into the country (Bannister-Tyrrell et al., 2013; Hall et al., 2021). Cases of dengue fever and other arboviral diseases have been increasing among recent arrivals to New Zealand from overseas, but to date there have been no reports of local transmission (Ammar et al., 2021).

In 2016 in New Zealand, it is estimated 6000 to 8000 people became ill due to contamination of the Havelock North water supply with the bacteria *Campylobacter* (Gilpin et al., 2020). The infection was traced to sheep faeces washed into the underground aquifer that feeds the town's (untreated) water supply after an extraordinarily heavy rainfall event. This is not an isolated finding: increases in paediatric hospital admissions are seen across New Zealand two days after heavy rainfall events (Lai et al., 2020).

11.3.6.2 Projected impacts

Climate change is projected to have detrimental effects on human health due to heat stress, changing rainfall patterns including floods and drought climate-sensitive air pollution (including that caused by wildfires) (*high confidence*) and vector-borne diseases *(medium confidence)*. Vulnerability to detrimental effects of climate change will vary with socioeconomic conditions (*high confidence*).

The greatest number of people affected by compounding effects of heat, wildfires and poor air quality will be in urban and peri-urban areas of Australia. By 2100 the proportion of all deaths attributable to heat in Melbourne, Sydney and Brisbane may rise from about 0.5% to 0.8% (under RCP 2.6), or 3.2% (under RCP 8.5) (Gasparrini et al., 2017). Heatwave related excess deaths in Melbourne, Sydney and Brisbane are projected to increase to 300/year (RCP2.6) or 600/year (RCP8.5) during 2031–2080 relative to 142/year during 1971–2020, assuming no adaptation and high population growth (Guo et al., 2018). High temperatures amplify the risks due to local air pollution: without adaptation, ozone-related deaths in Sydney may increase by 50–60/year by 2070 (Physick et al., 2014).

Unless there is more effective control of nutrient runoff, bacterial contamination of drinking water supplies is projected to increase due to more intense rainfall events, exacerbating risks to human health (Gilpin et al., 2020; Lai et al., 2020), and higher temperatures will increase freshwater toxic blooms (Hamilton et al., 2016).

In general, the area of Australia suitable for the transmission of dengue is projected to increase (Zhang and Beggs, 2018; Messina et al., 2019), but estimates of local disease risk vary considerably according to climate change scenario and socioeconomic pathways (Williams et al., 2016). The spread of *Wolbachia* among *Aedes* mosquitoes in northern Australia has already reduced dengue transmission and may decrease the influence of climate in the future (Ryan et al., 2019). In New Zealand, the risk of dengue remains low for the remainder of this century (Messina et al., 2019). Higher temperatures and more intense rainfall may also increase pollen production and the risk of allergic illness throughout the region (Haberle et al., 2014).

11.3.6.3 Adaptation

Strengthening basic public health services can rapidly reduce vulnerability to death and ill-health caused by climate change; however, this opportunity is often missed (*very high confidence*). The 2020 New Zealand *Health and Disability System Review* pointed to shortcomings in leadership and governance, structures that embed health inequity, lack of transparency in planning and reporting and underinvestment in public health personnel and systems (HDSR, 2020). An Australian study found that without deliberate planning the health system 'would only be able to deal with climate change in an expensive, *ad hoc* crisis management manner' (Burton, 2014). In both Australia and New Zealand the COVID-19 epidemic has highlighted weaknesses in information systems, primary care for marginalised groups and intersectoral planning (Salvador-Carulla et al., 2020; Skegg and Hill, 2021): all these deficiencies are relevant to climate adaptation.

Underlying health and economic trends affect the vulnerability of the population to extreme weather (*high confidence*). Poor housing quality is a risk factor for climate-related health threats (Alam et al., 2016). Homeless people lack access to temperature-controlled or structurally safe housing and often are excluded from disaster preparation and responses (Every, 2016). These inequalities are reversible. For example, a government partnership with social housing providers in Australia improved the thermal performance of housing for low-income tenants (Barnett et al., 2013). A postcode-level analysis of the vulnerability of urban populations to extreme heat in Australian capital cities (Loughnan et al., 2013) led to the development of an interactive website for purposes of planning and emergency preparedness (Figure 11.5) as well as subsequent work on green urban design for cooler, more liveable cities (Tapper, 2021).

Heatwave responses, from public education to formal heat-warning systems, are the best-developed element of adaptation planning for health in Australia, but many metropolitan centres are still not covered (*high confidence*) (Nicholls et al., 2016; Nitschke et al., 2016). Air conditioning (AC) in Australian homes reduces mortality in heatwaves by up to 80% (Broome and Smith, 2012), but heavy reliance on AC carries risks. It is estimated that a power outage on the third day of extreme heatwaves would result in an additional 10–21 deaths in Adelaide, 24–47 in Melbourne and 7–13 in Brisbane (Nairn and Williams, 2019). Multiple interventions at the landscape, building and individual scale are available to reduce the negative health effects of extreme heat (Jay et al., 2021).

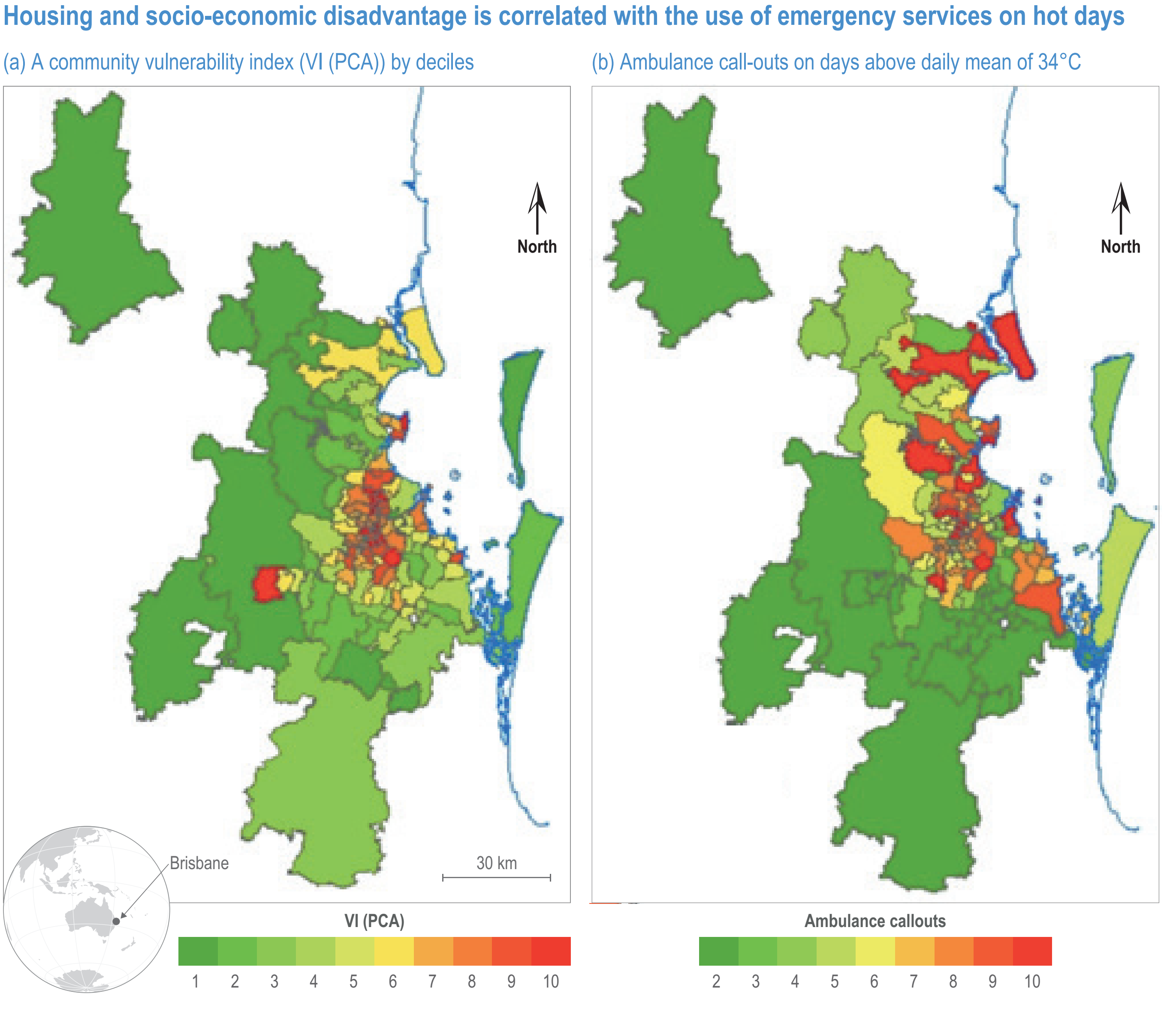

Figure 11.5 | Housing and socioeconomic disadvantage are correlated with the use of emergency services on hot days (rho = 0.55, p<0.01). The spatial distribution of (A) a community vulnerability index (VI) (PCA) by deciles and (B) ambulance call-outs on days above the daily mean of 34°C, in Brisbane, Australia. Ambulance call-out data are expressed as deciles based on per-capita calls during 2003–2011 (Loughnan et al., 2013)

Heat extremes receive most policy attention, but the numbers of deaths are less than those resulting from more frequent exposures to moderately high temperatures (Longden, 2019). Melbourne, with its Urban Forest Strategy, provides a case study in long-term planning for cooler cities (Gulsrud et al., 2018). Australian workers' perceptions of heat and responses to high temperatures show that heat policies on their own are insufficient for full protection; workers also require knowledge and agency to slow down or take breaks on their own initiative (Singh et al., 2015; Lao et al., 2016).

The first national climate change risk assessment in New Zealand (MfE, 2020a) highlighted the risk to potable water supplies. An inquiry into the Havelock North outbreak recommended that all registered drinking water supplies (which supply about 80% of the national population) in New Zealand should be disinfected and have stronger oversight by a national regulatory body (Government Inquiry into Havelock North Drinking Water, 2017). The use of local and Indigenous knowledge strengthens interventions to protect water supplies to remote settlements that may be affected by climatic changes (Henwood et al., 2019).

Adaptation requires better protection of health facilities and supply chains, but hospital managers seldom have capacity to invest in long-term improvements in infrastructure (Loosemore et al., 2014). However, health services in the region are required to prepare disaster plans: these could be expanded to explicitly cover health adaptation and local threats from climate change, including flooding events (Rychetnik et al., 2019).

11.3.7 Tourism

11.3.7.1 Observed Impacts

Tourism is a major economic driver in the region, accounting for 3% (Australia) and 6% (New Zealand) of GDP pre-COVID-19 (WTTC, 2018). Climate change is having significant impacts on tourism due to the heavy reliance of the sector on natural heritage and outdoor attractions (11.3.1; Box 11.2). Furthermore, because Australia and New Zealand are both long-haul destinations, a global increase in 'flygskam' (flight shame) will likely impact travel patterns (Becken et al., 2021).

Impacts of climate change are being observed across the tourism system (*high confidence*) (Scott et al., 2019a), most notably the GBR (Box 11.2) (Ma and Kirilenko, 2019). Australia's ski industry is very sensitive to climatic change, due to reductions in snow depth and snow season length (Table 11.2) (Steiger et al., 2019; Knowles and Scott, 2020). The 2019–2020 summer wildfires (Box 11.1) impacted tourism and travel infrastructure, affecting air quality, vineyards and wineries (CoA, 2020e; Filkov et al., 2020). Global media coverage of the wildfires, alongside Australia's climate change policy response, profoundly and negatively, affected Australia's destination image (Schweinsberg et al., 2020; Wen et al., 2020). In New Zealand's South Island, Fox and Franz Josef Glaciers have retreated approximately 700 m since 2008, with ice melt and retreat resulting in increased rock fall risks and negatively affecting the tourist experience (Purdie, 2013; Stewart et al., 2016; Wang and Zhou, 2019). The west coast of New Zealand is extremely prone to flooding events, impacting amenity values and access (Paulik et al., 2019a). Damage to tracks, huts and bridges have closed popular destinations, including the Hooker Glacier and the popular Routeburn and Heaphy Tracks during heavy rainfall events (Christie et al., 2020). Climate-driven damage is motivating 'last chance' tourism to see key natural heritage and outdoor attractions, for example, GBR (Piggott-McKellar and McNamara, 2016) and Franz Josef and Fox Glaciers (Stewart et al., 2016).

11.3.7.2 Projected Impacts

Widespread impacts from projected climate change are *very likely* across the tourism sector. The World Heritage listed Kakadu National Park in Australia is projected to experience increasing severity of cyclones (Turton, 2014), and sea level rise (SLR) is projected to affect freshwater wetlands (11.3.1.2; Table 11.5) (McInnes et al., 2015) and Indigenous rock art (Higham et al., 2016; Hughes et al., 2018a). The projected increase in the number of hot days in northern and inland Australia may impact the attractiveness of the region for tourists (Amelung and Nicholls, 2014; Webb and Hennessy, 2015). Coastal erosion and flooding of Australasian beaches due to sea level rise (SLR) and intensifying storm activity are estimated to increase by 60% on the Sunshine Coast by 2030, causing significant damage to tourist-related infrastructure (Hughes et al., 2018a). Urgent 'hard' and 'soft' adaptation strategies are projected to help reduce sea level rise (SLR) impacts (Becken and Wilson, 2016).

Glacier tourism, a multi-million-dollar industry in New Zealand, is potentially under threat because glacier volumes are projected to decrease (*very high confidence*) (Purdie, 2013). Glacier volume reductions of 50–92% by 2099 relative to the present reflect the large range of temperature projections between RCP2.6 and RCP8.5. Under RCP2.6 at 2099, the glaciers retain a similar configuration to present, although clean-ice glaciers will retreat significantly. For RCP4.5, RCP6.0 and RCP8.5, the clean-ice glaciers will retreat to become small remnants in the high mountains (Anderson et al. 2021).

Snow skiing faces significant challenges from climate change (*high confidence*). In Australia, the annual maximum snow depth is estimated to decrease from current levels by 15% (2030) and 60% by 2070 (SRES A2) (Di Luca et al., 2018). By 2070–2099, relative to 2000–2010, the length of the Victorian ski season is projected to contract by 65–90% under RCP8.5 (Harris et al., 2016). The New Zealand tourism destination of Queenstown is expected to experience declining snowfall, increased wind and more severe weather events (Becken and Wilson, 2016). Ski tourism stakeholders have been responding to longer-term climate risks with an increase in snow-making machines in New Zealand since 2013 (Hopkins, 2015) and in Australia (Harris et al., 2016).

11.3.7.3 Adaptation

Current snow-making technologies are expected to sustain the ski industry until mid-century. However, with warmer winter temperatures and declining water availability, snow-making is projected to decrease to half at most resorts by 2030 (Harris et al., 2016). New Zealand's ski industry may benefit from Australian skiers visiting New Zealand due to lower relative vulnerability (Hopkins, 2015). However, tourists may substitute destinations or ski less in the absence of snow (*medium*

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agreement, limited evidence) (Cocolas et al., 2015; Walters and Ruhanen, 2015).

With the exception of the ski industry (Becken, 2013; Hopkins, 2015), tourism stakeholders generally focus on coping with short-term weather events, rather than longer-term climate risks, but they do exhibit high adaptive capacity by diversifying their activities (Stewart et al., 2016). Post-COVID-19 pandemic economics and recovery policies challenge this sector's prospects, and the combination of COVID-19 and climate change (e.g., fires, floods) has also highlighted the need for the tourism sector to be able to respond to multiple, overlapping crises.

There is limited evidence that research into the impact of climate change on tourism in Australia and New Zealand is translating into policy or action (Moyle et al., 2017). New Zealand government tourism sector strategies acknowledge this and the need for greater understanding of climate change for the sector (TIA, 2019) but do not offer solutions (MBIE, 2019b; MfE, 2020a). The COVID-19 pandemic and the global pause of international travel offer an opportunity to potentially 'reset' tourism to account for the impacts of climate change (Prideaux et al., 2020).

11.3.8 Finance

11.3.8.1 Observed Impacts

The finance sector has significant exposure to climate variability and extreme events (*high confidence*).

Aggregated insured losses from weather-related hazard events from 2013 to 2020 were almost AUD$15 billion for Australia (1.2% of GDP) and almost NZD$1 billion for New Zealand (0.4% of GDP) (NIWA, 2020; ICA, 2021) (ICA, 2020a; NIWA, 2020). However, there is no trend in normalised losses because the rising insurance costs are being driven by more people living in vulnerable locations with more to lose (McAneney et al., 2019). In New Zealand, two major hailstorms during 2014–2020 and three major floods during 2019–2021 caused significant insurance losses (ICNZ, 2021). Insured losses exceeded NZD$472 million for the 12 costliest floods from 2007 to 2017, of which NZD$140 million could be attributed to anthropogenic climate change (Frame et al., 2020). In Australia, insured damage was almost AUD$1.0 billion for the Queensland hailstorm in 2020, AUD$1.7 billion for east coast flooding in 2020, AUD$2.3 billion for the 2019–2020 fires, AUD$2.3 billion for the Queensland hailstorm in 2019, AUD$1.2 billion for the North Queensland floods in 2019, AUD$1.4 billion for the NSW hailstorm in 2018, AUD$1.8 billion for Cyclone Debbie in 2017 and AUD$1.5 billion for the Brisbane hailstorm in 2014 (ICA, 2020b). The insured loss from the seven costliest hailstorms in Australia from 2014 to 2021 totalled AUD$7.6 billion (ICA, 2021).

Some homes in the highest-risk areas tend to be in lower socioeconomic groups that may not buy insurance (Actuaries Institute, 2020). For example, a quarter of residents that experienced loss or damage in the 2019 Townsville floods did not have insurance (ACCC, 2020). Underinsurance reduces people's capacity to recover from adverse events, while over-reliance on private insurance undermines collective disaster recovery efforts (Lucas and Booth, 2020). In Australia, those in high-risk areas minimise house and contents insurance for financial reasons (Booth and Harwood, 2016; Osbaldison et al., 2019; Actuaries Institute, 2020). Insurance premiums in northern Australia are almost double those in the rest of Australia, and rising, mainly due to cyclone damage (ACCC, 2020).

11.3.8.2 Projected Impacts

Risks for the finance sector are projected to increase (*medium confidence*). The potential impact of increased coastal and inland flooding, soil desiccation and contraction, fire and wind could lead to higher insurance costs, reduced property values and difficulties for some customers to service loans (CBA, 2018). Under a high-emissions scenario (RCP8.5), estimated annual losses to home-lending customers may increase 27% by 2060, and the proportion of properties with high credit risk may rise from 0.01% in 2020 to 1% in 2060, assuming no portfolio changes (CBA, 2018). In New Zealand, weather-related insurance claims between 2000 and 2017 totalled NZD$450 million, 40% of which was due to extreme rainfall. Using six climate model projections of extreme rainfall, the insured damage is projected to increase by 7% (RCP2.6) to 8% (RCP8.5) by 2020–2040 and 9% (RCP2.6) to 25% (RCP8.5) by 2080–2100, relative to 2000–2017 (Pastor-Paz et al., 2020). By 2050–2070, tropical cyclone risk for properties not in flood plains or storm surge zones in south-east Queensland may increase by 33% under a 2°C scenario and by 317% under a 3°C scenario for properties in flood plains and storm surge zones (IAG, 2019).

11.3.8.3 Adaptation

Banks, insurers and investors increasingly recognise the risks posed by climate change to their businesses (*high confidence*) (Paddam and Wong, 2017). Collaborations between banks, insurers and superannuation funds in Australia and New Zealand are driving efforts aimed at achieving the Paris Agreement goals, including the New Zealand Centre for Sustainable Finance and Australian Sustainable Finance Initiative (AFSI, 2020; TAO, 2020; NZCFSF, 2021). Company directors, including superannuation fund directors, have legal obligations to disclose and appropriately manage material financial risks (Barker et al., 2016; Hutley and Davis, 2019). Financial regulators are aware of climate risks for financial stability and financial institutions (RBNZ, 2018; RBA, 2019) and are closely supervising climate risk disclosure practices (TCFD, 2017; RBNZ, 2018; APRA, 2019; CMSI, 2020; IGCC, 2021b). In Australia, regulatory action (APRA, 2021) includes issuing prudential guidelines for financial institutions on managing climate risk, aligned with guidelines developed by the Climate Measurement Standards Initiative (NESP ESCC, 2020). In New Zealand, the financial sector (climate-related disclosure and other matters) amendment bill aims to ensure that the effects of climate change are routinely considered in business, investment, lending and insurance underwriting decisions (NZ Government, 2021).

Banks and insurers are beginning to undertake climate risk analyses (CRO Forum, 2019; Bruyère et al., 2020) and disclose their risks (Paddam and Wong, 2017; ANZ, 2018; CBA, 2018). For example, the agricultural banking sector has analysed climate risk and embedded climate adaptation financing into its risk scoring and lending practices

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(CBA, 2019). However, the overall number of disclosures continues to lag expectations, suggesting the need for mandatory climate risk disclosure in Australia (IGCC, 2021a).

Climate adaptation finance is not evident (*medium confidence*). There is an adaptation finance gap (Mortimer et al. 2020). Private sector initiatives are beginning to emerge through large scale projects or public–private partnerships, such as the Queensland Betterment Fund (Banhalmi-Zakar et al., 2016; Ware and Banhalmi-Zakar, 2020). Addressing investor pressure (IGCC, 2017) could increase investment in adaptation. However, ongoing policy uncertainty in Australia continues to be the key barrier to allocating additional capital to invest in climate solutions for 70% of investors (IGCC, 2021a).

Current and future insurance affordability pressures could be addressed by increased mitigation, revisions to building codes and standards and better land use planning (ACCC, 2020; Actuaries Institute, 2020). In New Zealand, insurance signals are motivating the government to address adaptation funding mechanisms (Boston and Lawrence, 2018; CCATWG, 2018). Some insurers offer premium discounts to customers with reduced risk (Drill et al., 2016), with increasing premiums reflecting known risk and no cover for some hazards in risky locations (CCATWG, 2017). Special excess payments are available for flood hazard so customers take responsibility for part of the claim, with increasing premiums to reflect known and foreseeable risk and downgrading cover from replacement value to market value (Bruyère et al., 2020). Retreat by private insurers from risky locations could increase the unfunded fiscal risk to the government (Storey and Noy, 2017), creating moral hazard (Boston and Lawrence, 2018). The litigation risk from failing to take adaptation action (Hodder, 2019) could affect financial markets and government policy settings, creating cascading impacts across society (Lawrence et al., 2020b) CRO Forum, 2019). For some climate risks, national governments act as 'last resort' insurers (CCATWG, 2017), but this could become unsustainable (CRO Forum, 2019).

11.3.9 Mining

Many mines are exposed and sensitive to climate extremes (*high confidence*), but there is little available research on climate change impacts on them (Odell et al., 2018). Most Australian mines face higher temperatures, cyclones, erosion and landslides and hazards such as sea level rise (SLR) and storms across their supply chains, including ports (Cahoon et al., 2016). Impacts include operational disruptions such as acute drainage problems (Loechel and Hodgkinson, 2014) and heat-induced illness, irritation and absenteeism among workers (McTernan et al., 2016), lost revenue and increased costs (Pizarro et al., 2017).

Damage and disruption from climate impacts can cost operators billions of dollars (Cahoon et al., 2016). Climatic extremes increase the risk and impact of spillages along transportation routes (Grech et al., 2016), exacerbate mining's effects on hydrology, ecosystems and air quality (Phillips, 2016; Ali et al., 2018), increase contamination risks (Metcalfe and Bui, 2016) and disrupt and slow mine site rehabilitation (Wardell-Johnson et al., 2015; Hancock et al., 2017). Adaptations such as improved water management are emerging slowly (Gasbarro et al., 2016; Becker et al., 2018). Some companies are spatially diversifying and relocating (Hodgkinson et al., 2014). Others are replacing workers with automation and remote operations (Halteh et al., 2018; Keenan et al., 2019).

11.3.10 Energy

Australia's energy generation is a mix of coal (56%), gas (23%) and renewables (21%) (DISER, 2020), with ageing coal-fired infrastructure being replaced by a growing proportion of renewable and distributed energy resources (AEMO, 2018). In New Zealand, 60% of energy generation comes from hydro-electricity and 15% from geothermal (MBIE, 2021), with coal (2%) and gas (13%) generation capacity to be retired, and total renewable energy to increase from 82% in 2017 to around 95% by 2050, mostly through wind generation (MBIE, 2019a).

11.3.10.1 Observed Impacts

The energy sector is highly vulnerable to climate change (*high confidence*). Oil and gas systems are vulnerable to storms, fires, drought, floods, sea level rise (SLR), extreme heat and fires, which can damage infrastructure, slow production and add to operational costs (Smith, 2013). The electricity system is vulnerable to high temperatures reducing generator and network capacity and increasing failure rates and maintenance costs (AEMO, 2020a). Fires (including those sparked by electrical distribution lines) pose risks to assets. Smoke can cause electricity transmission to trip, and high winds reduce wind-energy capacity and threaten the integrity of transmission lines. Low rainfall reduces hydro-energy capacity and increases the demand for desalination energy. Higher sea level may affect some low-lying generation, distribution and transmission assets, and compound extreme weather events can cause outages (Vose and Applequist, 2014; Lawrence et al., 2016; AEMO, 2020b; AEMO, 2020a; ESCI, 2021). For example, in September 2016, a major windstorm in South Australia damaged 23 transmission towers and cut power to over 900,000 households. In February 2017, the South Australian energy system failed to cope with a heatwave-related jump in demand, causing power cuts to 40,000 homes (Steffen et al., 2017). In April 2018, a storm over Auckland, New Zealand left 182,000 properties without power (Bell, 2018). The 2019/2020 Australian heatwaves and fires caused widespread blackouts that disrupted communications, transport and emergency response capacity (Box 11.1).

11.3.10.2 Projected Impacts

Risks for the energy sector are projected to increase with climate change (*medium confidence*). Projected increases in the frequency and intensity of heatwaves, fires, droughts and wind-storms would increase risks for energy supply and demand (AEMO, 2020b; ESCI, 2021). Households are unevenly vulnerable to energy sector risks due to varying housing quality and health dependencies (11.3.6). In New Zealand, a warmer climate and increasing energy efficiency is projected to marginally reduce annual average peak electricity heating demand (Stroombergen et al., 2006; MBIE, 2019a). Winter and spring inflows to main hydro lakes are projected to increase 5–10% and may reduce hydroelectric

Table 11.8 | Adaptation options for energy sector.

Adaptation options	References
Diversification of electricity supplies geographically and technically, including distributed energy resources and variable renewable energy	(AEMO, 2020b)
Integrated planning, improved asset design and management and disaster recovery to build resilience to more extreme weather	(AEMO, 2020b; Transpower, 2020)
Augmentation of transmission grid to support change in generation mix using interconnectors and renewable energy zones, coupled with energy storage, adds capacity and helps balance variable resources across the network	(Blakers et al., 2017; ICCC, 2019; AEMO, 2020b)
Climate change risks included in the design, location and rating of future infrastructure and consideration of the implications for future transmission developments	(Bridge et al., 2018; AEMO, 2020b)
Increased design and construction standards, flood defence measures, insurance, improved water efficiency, improved insulation of supercooled LNG processes, more efficient air conditioning and creating fire breaks for the oil and gas sector	(Smith, 2013; Gasbarro et al., 2016)
Technological developments to strengthen existing resilience under climate change that reinforce the relative advantage of western Australia and Tasmania for new wind energy installations	(Evans et al., 2018)
Energy generation diversity, demand management, pumped hydro storage and battery storage	(Keck et al., 2019; Transpower, 2020)
Tools and strategies to manage winter energy deficits and dry years alongside renewable electricity generation deployment	(Transpower, 2020)
Improved insulation and heating of buildings and flexible electricity consumption to reduce significance of winter electricity demand peak	(Stroombergen et al., 2006; MBIE, 2019a; Transpower, 2020)

Table 11.9 | Examples of observed impacts that can be partly attributed to climate change.

Impact	Source
Mass bleaching of GBR in 2016/2017 due to a marine heatwave	Box 11.2
In the New Zealand southern Alps, extreme glacier mass loss, which was at least 6 times more likely in 2011 and 10 times more likely in 2018, due to warming	11.2.1, 11.3.3
In the Australian Alps bioregion, loss of habitat for endemic and obligate species due to snow loss and increases in fire, drought and temperature	Table 11.4
In the Australian wet tropics world heritage area, some vertebrate species have declined in distribution area and population size due to increasing temperatures and length of dry season	Table 11.4
Extinction of Bramble Cay melomys due to loss of habitat caused by storm surges and SLR in Torres Strait	Table 11.4
In New Zealand, increasing invasive predation pressure on endemic forest birds surviving in cool forest refugia due to anthropogenic warming	Table 11.4
In New Zealand, erosion of coastal habitats due to more severe storms and SLR	Table 11.4, Box 11.6
In Australia, estuaries warming and freshening with decreasing pH	Table 11.6
Changes in life-history traits, behaviour or recruitment of fish and invertebrates due to ocean acidification or warming, severe decline in recruitment of coral on GBR due to ocean warming, aquaculture stock deaths due to heat stress	Table 11.6
New diseases and toxins due to warming and extension of East Australian Current	Table 11.6
Changes in almost 200 marine species' distributions and abundance due to ocean warming	Table 11.6
Temperate marine species replaced by seaweeds, invertebrates, corals and fishes characteristic of sub-tropical and tropical waters	Table 11.6
River flow decline in southern Australia is largely due to the decline in cool-season rainfall partly attributed to anthropogenic climate change	11.3.3
In New Zealand, the 2007/2008 drought and 2012/2013 drought were 20% attributed to anthropogenic climate change	11.3.3
In New Zealand, about 30% of the insured damage for the 12 costliest flood events from 2007 to 2017 can be attributed to anthropogenic climate change	11.3.8
In Australia, 35–36% of heat-related excess mortality in Melbourne, Sydney and Brisbane from 1991–2018 can be attributed to anthropogenic climate change	11.3.6

energy vulnerability (McKerchar and Mullan, 2004; Poyck et al., 2011; Stevenson et al., 2018). However, major electricity supply disruptions are projected to increase as dependence on electricity grows from 25% of total energy in 2016 to 58% in 2050 (Transpower, 2020).

In Australia, the total heating and cooling energy demand of 5-star energy-rated houses is projected to change by 2100 (Wang et al., 2010). At 2°C global warming, the estimated change in demand is –27% in Hobart, –21% in Melbourne, +61% in Darwin, +67% in Alice Springs and +112% in Sydney. For a 4°C global warming, the changes are –48%, –14%, +135%, +213% and +350% respectively.

11.3.10.3 Adaptation

Options to manage risks include adaptation of energy markets, integrated planning, improved asset design standards, smart-grid technologies, energy generation diversification, distributed generation (e.g., roof-top solar, microgrids), energy efficiency, demand management, pumped hydro storage, battery storage and improved capacity to respond to supply deficits and balance variable energy resources across the network (Table 11.8) (*high confidence*). With increasing electrification, diversification and resilience can contribute to security of supply as fossil fuels are retired from the energy mix (AEMO, 2020b). In Australia, the AEMO (2020) Integrated System Plan has evaluated various options, costs and benefits. Risks associated with an increasing reliance on weather-dependent renewable energy (e.g., solar, wind, hydro) (ESCI, 2021) can be managed through strong long-distance interconnection via high-voltage powerlines and storage (Blakers et al., 2017; Blakers et al., 2021; Lu et al., 2021). However, implementation of adaptation options remains inadequate (Gasbarro et al., 2016).

11.3.11 Detection and Attribution of Observed Climate Impacts

Detection and attribution of observed climate trends and events is called 'climate attribution'. This has been assessed by IPCC WGI (Gutiérrez et al., 2021; Ranasinghe et al., 2021; Seneviratne et al., 2021) and summarised in Chapter 16. Trends that have been formally attributed in part to anthropogenic climate change include regional warming trends and sea level rise (SLR), decreasing rainfall and increasing fire risk in southern Australia. Events include extreme rainfall in New Zealand during 2007–2017, the 2007/2008 and 2012/2013 droughts in New Zealand, high temperatures in Australia during 2013–2020, the 2016 northern Australian marine heatwave, the 2016/2017 and 2017/18 Tasman Sea marine heatwaves and 2019/2020 fires in Australia.

Detection and attribution of climate impacts on natural and human systems is called 'impact attribution'. This often involves a two-step approach (joint attribution) that links climate attribution to observed impacts. Impact attribution is complicated by confounding factors, for example, changes in exposure arising from population growth, urban development and underlying vulnerabilities.

Impact attribution is considered in Sections 11.3.1–11.3.10 and summarised in Table 11.9. More literature is available for natural systems than human systems, which represents a knowledge gap rather than an absence of impacts that are attributable to anthropogenic climate change. Fundamental shifts in the structure and composition of some ecosystems are partly due to anthropogenic climate change (*high confidence*). In human systems, the costs of droughts and floods in New Zealand, and heat-related mortality and fire damage in Australia, are partly attributed to anthropogenic climate change (*medium confidence*).

11.4 Indigenous Peoples

Indigenous perspectives of well-being embrace physical, social, emotional and cultural domains, collectiveness and reciprocity and, more fundamentally, connections between all elements across past, present and future generations (Australia. NAHS Working Party, 1989; MfE, 2020a). Changing climate conditions are expected to exacerbate many of the social, economic and health inequalities faced by Aboriginal and Torres Strait Islander Peoples in Australia and Māori in New Zealand (*high confidence*) (Bennett et al., 2014; Hopkins et al., 2015; AIHW, 2016; Lyons et al., 2019). As a consequence, effective policy responses are those that take advantage of the interlinkages and dependencies between mitigation, adaptation and Indigenous Peoples' well-being (Jones, 2019) and those that address the transformative change needed from colonial legacies (*high confidence*) (Hill et al., 2020). There is a central role for Indigenous Peoples in climate change decision-making that helps address the enduring legacy of colonisation through building opportunities based on Indigenous governance regimes, cultural practices to care for land and water and intergenerational perspectives (*very high confidence*) (Nursey-Bray et al., 2019; Petzold et al., 2020) (Cross-Chapter Box INDIG in Chapter 18).

11.4.1 Aboriginal and Torres Strait Islander Peoples of Australia

The highly diverse Aboriginal and Torres Strait Islander Peoples of Australia have survived and adapted to climate changes such as sea level rise (SLR) and extreme rainfall variability during the late Pleistocene era, through intimate place-based Indigenous knowledge in practice and while losing traditional land and sea country ownership (Liedloff et al., 2013) (Cross-Chapter Box INDIG in Chapter 18) including during the Late Pleistocene era (Golding and Campbell, 2009; Nunn and Reid, 2016). They belong to the world's oldest living cultures, continually resident in their own ancestral lands, or 'country', for over 65,000 years (Kingsley et al., 2013; Marmion et al., 2014; Nagle et al., 2017; Tobler et al., 2017; Nursey-Bray and Palmer, 2018). The majority of the Australian Indigenous Peoples live in urban areas in southern and eastern Australia, but are the predominant population in remote areas.

Climate-related impacts on Aboriginal and Torres Strait Islander Peoples, countries (traditional estates) and cultures have been observed across Australia and are pervasive, complex and compounding (*high confidence*) (Green et al., 2009) (11.5.1), for example, the loss of biocultural diversity, nutritional changes through the availability of traditional foods and forced diet change, water security and loss of land and cultural resources through erosion and SLR (Table 11.10) (TSRA, 2018). Moreover, these impacts are being experienced now particularly in low-lying geographical areas—especially in the Torres Strait Islands (Mosby, 2012; Kelly, 2014; Murphy, 2019; Hall et al., 2021). Estimates of the loss from fire impacts on ecosystem services that contribute to the well-being of remotely located Indigenous Australians were found to be higher than the financial impacts from the same fires on pastoral and conservation lands (Sangha et al., 2020) and could increase with both financial and non-financial impacts (Box 11.1).

Due to ongoing impacts of colonisation, Aboriginal and Torres Strait Islander Peoples have, on average, lower income, poorer nutrition, lower school outcomes and employment opportunities, higher incarceration and higher levels of removal of children than non-Indigenous Australians, represented in high comorbidities of chronic diseases and mental health impacts (Marmot, 2011; Green and Minchin, 2014; AIHW, 2015). This relative poverty can reduce climate-adaptive capacities while exacerbating climate change vulnerabilities (Nursey-Bray and Palmer, 2018). In remote country, this can combine with lack of security for food and water, non-resilient housing and extreme weather events, contributing to migration off traditional country and into towns and cities—with flow-on social impacts such as homelessness, dislocation from community and family and disconnection from country and spirituality (Mosby, 2012; Brand et al., 2016).

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Table 11.10 | Climate-related impacts on Aboriginal and Torres Strait Islander Peoples, country and cultures.

Impacts	Implications
Loss of biocultural diversity (land, water and sky) (*medium confidence*)	Healthy country is critical to Indigenous Australians' livelihoods, caring for country responsibilities, health and well-being. Damage to land can magnify the loss of spiritual connection to land from dispossession from traditional country and leads to disruption of cultural structures. Climate change impacts can exacerbate and/or accelerate existing threats of habitat degradation and biodiversity loss and create challenges for traditional stewardship of landscapes (Mackey and Claudie, 2015)
Climate-driven loss of native title and other customary lands (*medium confidence*)	Traditional coastal lands lost through erosion and rising sea level, with associated mental health implications from loss of cultural and traditional artefacts and landscapes, including the destruction and exhumation of ancestral graves and burial grounds. This is also occurring and predicted to intensify in the low-lying islands of the Torres Strait (TSRA, 2018; Hall et al., 2021) and was also noted during the extreme bushfires in Eastern Australia in late 2019 and early 2020.
Changing availability of traditional foods and forced diet change (*medium confidence*)	Human health impacts can be exacerbated by climate change through the changing availability of traditional foods and medicines, while outages and the high costs of electricity can limit the storage of fresh food and medication (Kingsley et al., 2013; Spurway and Soldatic, 2016; Hall and Crosby, 2020)
Changing climatic conditions for subsistence food harvesting (*medium confidence*)	Climate-change-induced SLR and saltwater intrusion can limit the capacity for traditional Indigenous floodplain pastoralism and affect food security, access to and affordability of healthy, nutritional food (Ligtermoet, 2016; Spurway and Soldatic, 2016)
Extreme weather events triggering disasters (*high confidence*)	Increasing frequency or intensity of extreme weather events (floods, droughts, cyclones, heatwaves) can cause disaster responses in remote communities, including infrastructure damage of essential water and energy systems and health facilities (TSRA, 2018; Hall and Crosby, 2020)
Heatwave impacts on human health (*high confidence*)	Heatwaves can occur in many regions of Australia. Tropical regions can experience prolonged seasons of high temperatures and humidity levels, resulting in extreme heat stress risks. For example, the Torres Strait Islands are already categorised under the U.S. National Oceanic and Atmospheric Administration (NOAA) Heat Index as a danger zone for extreme human health risk during summer (TSRA, 2018)
Health impacts from changing conditions for vector-borne diseases (*high confidence*)	Climate change can alter exposure and increase risk for remote Indigenous Peoples to infection from waterborne and insect-borne diseases, especially if medical services are limited or damaged by extreme weather events. For example, in the Torres Strait Islands the changing climate is affecting the range and extension of the *Aedes albopictus* and *Aedes aegypti* mosquitoes that can carry and transmit dengue and other viruses (Horwood et al., 2018; TSRA, 2018)
Unadaptable infrastructure for changing environmental conditions (*high confidence*)	Poorly designed, inferior quality and unmaintained housing can create health challenges for tenants in extreme heat (Race et al., 2016). Essential community-scale water and energy service infrastructure, unpaved roads, sea walls and stormwater drains can fail in extreme weather events (McNamara et al., 2017)
Drinking water security (*medium confidence*)	Predicted continued increases in arid conditions in Australia are expected to reduce the recharge rate of finite groundwater supplies (Barron et al., 2011). For remote communities reliant on groundwater for drinking supplies, this water insecurity creates vulnerabilities from over-extraction and lack of access (Jackson et al., 2019; Hall and Crosby, 2020). This groundwater can also have microbial contamination from sewage and chemicals supporting bacterial growth, such as high iron levels supporting the growth of *Burkholderia pseudomallei* that causes melioidosis in humans and animals (Kaestli et al., 2019). In the Torres Strait, increasing reliance on desalination for drinking water raises costs for fuel and its associated transport (Beal et al., 2018)

Recognition of the role of Aboriginal and Torres Strait Islander Peoples in identifying solutions to the impacts of climate change is slowly emerging (UN, 2018), having been largely excluded from meaningful representation from the conception of climate change dialogue through to debate and decision-making (Nursey-Bray et al., 2019). Honouring the United Nations Declaration on the Rights of Indigenous Peoples and social justice values would support self-determination and the associated opportunity for Indigenous Australians to develop adaptation responses to climate change (Langton et al., 2012; Nursey-Bray and Palmer, 2018; Nursey-Bray et al., 2019), including the adaptive capacity opportunities available through Indigenous knowledge (Liedloff et al., 2013; Petheram et al., 2015; Stewart et al., 2019) (Cross-Chapter Box INDIG in Chapter 18). The Uluru Statement from the Heart proposes a pathway and roadmap forward for enhanced representation of Aboriginal and Torres Strait Islander Peoples in decision-making in Australia (Ululru Statement, 2017). Table 11.11 provides examples of traditional Indigenous practices of adaptation to a changing climate. However, due to Indigenous methods of knowledge sharing and knowledge holding, such knowledge relies disproportionately on elders and seniors, who form a very small portion of the total Aboriginal and Torres Strait Islander Peoples of Australia, and is limited in the formal literature (ABS, 2016).

11.4.2 Tangata Whenua—New Zealand Māori

Māori society faces diverse impacts, risks and opportunities from climate change (Table 11.12). Studies exploring climate change impacts, scenarios, policy implications, adaptation options and tools for Māori society have increased substantially (e.g., (King et al., 2012; Bargh et al., 2014; Jones et al., 2014; Bryant et al., 2017; Awatere et al., 2018; Colliar and Blackett, 2018). Māori priorities surrounding climate change risks and natural resource management have been articulated in planning documents by many Māori kin groups (e.g., (Ngāti Tahu-Ngāti Whaoa Rūnanga Trust, 2013; Raukawa Settlement Trust, 2015; Ngai-Tahu, 2018; Te Urunga Kea - Te Arawa Climate Change Working Group, 2021), reflecting the importance of reducing vulnerability and enhancing resilience to climate impacts and risks through adaptation and mitigation.

Māori have long-term interests in land and water and are heavily invested in climate-sensitive sectors (agriculture, forestry, fishing, tourism and renewable energy) (King et al., 2010). Large proportions of collectively owned land already suffer from high rates of erosion (Warmenhoven et al., 2014; Awatere et al., 2018), which are projected to be exacerbated by climate-change-induced extreme rainfalls (*high confidence*) (RSNZ, 2016; Awatere et al., 2018). Changing drought

Table 11.11 | Examples of Aboriginal and Torres Strait Islander Peoples' practices of adaptation to a changing climate

'Caring for Country': Traditional Practices for Holistic Land and Cultural Protection and Adaptation in a Changing Climate	Source
Indigenous Protected Area (IPA) management plans enable culturally and ecologically compatible development that contribute to local Indigenous economies	(Mackey and Claudie, 2015).
IPAs can avoid the potential for 'nature–culture dualism' that locks out Indigenous access in some protected area legislation because they are based on relational values informed by local Indigenous knowledge	(Lee, 2016)
Fire management using cultural practices can achieve greenhouse gas emission targets while maintaining Indigenous cultural heritage.	(Robinson et al., 2016)
Indigenous Ranger programmes provide a means for Indigenous-guided land management, including for fire management and carbon abatement, fauna studies, medicinal plant products, weed management and recovery of threatened species	(Mackey and Claudie, 2015)
Faunal field surveys can engage local, bounded and fine-scale intuitive species location by Indigenous knowledge holders and their knowledge used for conservation planning	(Wohling, 2009; Ziembicki et al., 2013)
Cultural flows in waterways are a demonstration of cultural knowledge, values and practice in action as they are informed by Indigenous knowledge, bound by water-dependent values, and define when and where water is to be delivered, particularly in a changing climate	(Bark et al., 2015; Taylor et al., 2017)

Table 11.12 | Climate-related impacts and risks for Tangata Whenua New Zealand Māori

Impact	Risks
Changes in drought occurrence and extreme weather events	Risks to Māori tribal investment in forestry, agriculture and horticulture sector operations and production, particularly across eastern and northern New Zealand (*medium confidence*) (King et al., 2010; Awatere et al., 2018; Hardy et al., 2019)
Changes in rainfall, temperature, drought, extreme weather events and ongoing SLR	Risks to potable water supplies (availability and quality) for remote Māori populations (*medium confidence*) (RSNZ, 2016; Henwood et al., 2019)
Changes in rainfall, temperature, drought, extreme weather events and ongoing SLR	Risks of exacerbating existing inequities (e.g., health, economic, education and social services), social cohesion and well-being (*medium confidence*) (Bennett et al., 2014; Jones et al., 2014)
Changes in rainfall regimes and more intense drought combined with degradation of lands and water	Risks to the distribution and survival of cultural keystone flora and fauna, as well as cascading risks for Māori customary practice, cultural identity and well-being (*high confidence*) (King et al., 2010; RSNZ, 2016; Bond et al., 2019)
Changes in ocean temperature and acidification	Risks to nearshore and ocean species productivity and distribution, as well as cascading risks for Māori tribal investment in the fisheries and aquaculture sectors (*medium confidence*) (King et al., 2010; Law et al., 2016)
Sea-level-rise-induced erosion, flooding and saltwater intrusion	Risks to Māori-owned coastal lands and economic investment as well as risks to community well-being from displacement of individuals, families and communities (*high confidence*) (Manning et al., 2014; Smith et al., 2017; Hardy et al., 2019)
Sea-level-rise-induced erosion, inundation and saltwater intrusion	Risks to Māori cultural heritage as well as cascading risks for tribal identity and spiritual well-being (*medium confidence*) (King et al., 2010; Manning et al., 2014; RSNZ, 2016)
Impacts of climate change, adaptation and mitigation actions	Risks that governments are unable to uphold Māori interests, values and practices under the Treaty of Waitangi, creating new, modern-day breaches of the Treaty of Waitangi (*high confidence*) (Iorns Magallanes, 2019; MfE, 2020a)

occurrence, particularly across eastern and northern New Zealand, is also projected to affect primary sector operations and production (*medium confidence*) (King et al., 2010; Smith et al., 2017; Awatere et al., 2018). Further, many Māori-owned lands and cultural assets, such as marae and urupa, are located on coastal lowlands vulnerable to sea level rise (SLR) impacts (*high confidence*) (Manning et al., 2014; Hardy et al., 2019). Māori tribal investment in fisheries and aquaculture faces substantial risks from changes in ocean temperature and acidification and the downstream impacts on species distribution, productivity and yields (*medium confidence*) (Law et al., 2016). A clearer understanding of climate change risks and the implications for sustainable outcomes can enable more informed decisions by tribal organisations and governance groups.

Changing climate conditions are projected to exacerbate health inequities faced by Māori (*medium confidence*) (Bennett et al., 2014; Jones et al., 2014; Hopkins, 2015). The production and ecology of some keystone cultural flora and fauna may be impacted by projected warming temperatures and reductions in rainfall (*medium confidence*) (RSNZ, 2016; Bond et al., 2019; Egan et al., 2020). Obstruction of access to keystone species is expected to adversely impact customary practice, cultural identity and well-being (*medium confidence*) (Jones et al., 2014; Bond et al., 2019). Social-cultural networks and conventions that promote collective action and mutual support are central features of many Māori communities, and these practices are invaluable for initiating responses to, and facilitating recovery from, climate stresses and extreme events (King et al., 2011; Hopkins et al., 2015). Māori tribal organisations have a critical role in defining climate risks and policy responses (Bargh et al., 2014; Parsons et al., 2019), as well as entering into strategic partnerships with business, science, research and government to address these risks (*high confidence*) (Manning et al., 2014; Beall and Brocklesby, 2017; CCATWG, 2017).

More integrated assessments of climate change impacts, adaptation and socioeconomic risk for different Māori groups and communities, in the context of multiple stresses, inequities and different ways of knowing and being (King et al., 2013; Schneider et al., 2017; Henwood et al., 2019), would assist those striving to evaluate impacts and risks and how to integrate these assessments into adaptation plans (*high confidence*). Better understanding of the social, cultural and fiscal implications of sea level rise (SLR) is urgent (PCE, 2015; Rouse et al., 2017; Colliar and Blackett, 2018), including what duties local and

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central government might have with respect to actively upholding Māori interests under the Treaty of Waitangi (*high confidence*) (Iorns Magallanes, 2019). Intergenerational approaches to climate change planning will become increasingly important, elevating political discussions about conceptions of rationality, diversity and the rights of non-human entities (*high confidence*) (Ritchie, 2013; Carter et al., 2018; Ruru, 2018; Munshi et al., 2020).

11.5 Cross-Sectoral and Cross-Regional Implications

The impacts and adaptation processes described in Sections 11.3 and 11.4 are focused on specific sectors, systems and Indigenous Peoples. Added complexity, risk and adaptation potential stem from cross-sectoral and cross-regional interdependencies.

11.5.1 Cascading, Compounding and Aggregate Impacts

11.5.1.1 Observed Impacts

Climate impacts are cascading, compounding and aggregating across sectors and systems due to complex interactions (*high confidence*) (Pescaroli and Alexander, 2016; Challinor et al., 2018; Zscheischler et al., 2018; Steffen et al., 2019; AghaKouchak et al., 2020; CoA, 2020e; Lawrence et al., 2020b; Simpson et al., 2021) (Boxes 11.1, 11.3, 11.4, 11.5 and 11.6). Cascading impacts propagate via interconnections and systemic factors, including supply chains, shared reliance on connected biophysical systems (e.g., water catchments and ecosystems), infrastructure, essential goods and services and the exercise of governance, leadership, regulation, resources and standard practices (e.g., in planning and building codes), including lock-in of past decisions and experience (CSIRO, 2018; Lawrence et al., 2020b). The capacity of critical systems such as information, communication and technology, water infrastructure, health care, electricity and transport networks, is being stretched, with impacts cascading to other systems and places, exacerbating existing hazards and generating new risks (Cradock-Henry, 2017) (11.3.6; 11.3.10; Box 11.1). Temporal or spatial overlap of hazards (e.g., drought, extreme heat and fire; drought followed by extreme rainfall) are compounding impacts (Zscheischler et al., 2018) and affecting multiple sectors.

Extreme events such as heatwaves, droughts, floods, storms and fires have caused deaths and injuries (Deloitte, 2017a) (11.3.5.1), and affected many households, communities and businesses via impacts on ecosystems, critical infrastructure, essential services, food production, the national economy, valued places and employment. This has created long-lasting impacts (e.g., mental health, homelessness, health incidents and reduced health services) (Brown et al., 2017; Brookfield and Fitzgerald, 2018; Rychetnik et al., 2019) and reduced adaptive capacity (Friel et al., 2014; O'Brien et al., 2014; Ding et al., 2015; CoA, 2020e) (Box 11.1, Box 11.3, 11.3.1–11.3.10).

In New Zealand, extreme snow, rainfall and wind events have combined to impact road networks, power and water supplies and have impeded interdependent wastewater and stormwater services and business activities (Deloitte, 2019; Lawrence et al., 2020b; MfE, 2020a) (Box 11.4). Community and infrastructure services are periodically disrupted during extreme weather events, triggering impacts from the interdependencies across enterprises and individuals (Glavovic, 2014; Paulik et al., 2021).

Slow-onset climate change impacts have also had cascading and compounding effects. For example, degradation of the GBR by ocean heating, acidification and non-climatic pressures (Marshall et al., 2019), repeated pluvial, fluvial and coastal flooding of some settlements (Paulik et al., 2019a; Paulik et al., 2020), long droughts and water insecurity in rural communities (Tschakert et al., 2017) and the gradual loss of species and ecological communities have caused substantial ecological, social and economic losses. Indigenous Peoples have especially been impacted by multiple and complex losses (Johnson et al., 2021) (11.4).

11.5.1.2 Projected Impacts

Cascading, compounding and aggregate impacts are projected to grow due to a concurrent increase in heatwaves, droughts, fires, storms, floods and sea level (*high confidence*) (CSIRO, 2020; Lawrence et al., 2020b). Urban wastewater, stormwater and water supply systems are particularly vulnerable in New Zealand (Paulik et al., 2019a; Hughes et al., 2021) to pluvial flooding (Box 11.4) and to sea level rise (SLR) (Box 11.6), with flow-on effects to settlements, insurance and finance sectors, and governments (Lawrence et al., 2020b). Furthermore, consecutive heavy rainfall events in late summer and autumn, following drought conditions in low-lying modified wetland areas, have implications for the operation of flood control infrastructure as increased rainfall intensity, land subsidence and sea level rise (SLR) compound and result in the retention of floodwaters (Pingram et al., 2021).

In Australia, the aggregate loss of wealth due to climate-induced reductions in productivity across agriculture, manufacturing and service sectors is projected to exceed AUD$19 billion by 2030, AUD$211 billion by 2050 and AUD$4 trillion by 2100 for RCP8.5 (Steffen et al., 2019) (Table 11.13). Projected impacts also cascade across national boundaries via value chains, markets, movement of humans and other organisms and geopolitics (e.g., migration from near-neighbours as a pathway for adaptation, mobile climate-sensitive diseases and changes in production and trade patterns) (Lee et al., 2018; Nalau and Handmer, 2018; Schwerdtle et al., 2018; Dellink et al., 2019). The scale of impacts is projected to challenge the adaptive capacity of sectors, governments and institutions (Steffen et al., 2019), including the insurability of assets and risks to lenders (Storey and Noy, 2017).

11.5.1.3 Adaptation

Coordinating adaptation strategies and addressing underlying exposure and vulnerability can increase resilience to cascading, compounding and aggregate impacts (*high confidence*) (Table 11.17; 11.7.3). Systems understanding, network analysis, stress testing, spatial mapping, collaboration, information sharing and interoperability across states, sectors, agencies and value chains, as well as national-scale facilitation, can increase adaptive capacity (Espada et al., 2015; CoA, 2020e; Cradock-Henry et al., 2020b; Jozaei et al., 2020). Greater system

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diversity, modularity, redundancy, adaptability and decentralised control can reduce the risk of cascading failures and system breakdown (Sinclair et al., 2017; Sellberg et al., 2018). Addressing existing vulnerabilities in systems can reduce susceptibility and improve the resilience of interdependent systems (11.7.3). Multi-level leadership, including national and sub-national policies, laws and finance can reduce and manage aggregate risks supported by the enablers in Table 11.17.

Anticipatory governance and agile decision-making can build resilience to cascading, compounding and aggregate impacts (*high confidence*) (Boston, 2016; Deloitte, 2016; Steffen et al., 2019; CoA, 2020e; CSIRO, 2020; Lawrence et al., 2020b; MfE, 2020c). There is uncertainty about whether standard integrated assessment models can estimate cascading and compounding impacts across systems and sectors, but systems methodologies and social network analysis hold promise (Stoerk et al., 2018; Cradock-Henry et al., 2020b). Interventions at the landscape, building and individual scales can reduce the negative health effects of current and future extreme heat, if integrated in well-communicated heat action plans with robust surveillance and monitoring (Jay et al., 2021).

In Australia, the National Disaster Risk Reduction Framework (CoA, 2018b), National Recovery and Resilience Agency and Australian Climate Service (CoA, 2021) can provide some support for adaptation across multiple sectors. New Zealand has effective partnerships across critical infrastructure through lifelines groups, but organisational silos and lack of stress testing of plans hamper coordinated decision-making during crises and for adaptation (Brown et al., 2017; Lawrence et al., 2020b). The New Zealand national risk assessment, national adaptation plan, forthcoming Climate Change Adaptation Act and monitoring of adaptation progress by the Climate Change Commission provide a framework for anticipating climate change risks (MfE, 2020a).

11.5.2 Implications for National Economies

The implications of climate change for national economies are significant (*high confidence*). The costs associated with lost productivity, disaster relief expenditure and unfunded contingent liabilities represent a major risk to financial system stability (MfE, 2020a). Costs include significant and often long-term social impacts, temporary dislocation, business disruption and impacts on employment, education, community networks, health and well-being (Deloitte, 2017a). Climate change disrupts international patterns of agricultural production and trade in ways that may be negative but that also may lead to new opportunities for agriculture (Mosnier et al., 2014; Nelson et al., 2014; Lee et al., 2018). Net exports may increase following global climate shocks (Lee et al., 2018), but the longer-term effects on GDP are *likely* to be negative (Dellink et al., 2019).

11.5.2.1 Observed Impacts

In Australia, during 2007–2016, total economic costs from natural disasters averaged AUD$18.2 billion per year (Deloitte, 2017a). Individual weather-related disaster costs across multiple sectors have exceeded AUD$4 billion, such as the 2009 fires in Victoria (Parliament of Victoria, 2010), the 2010–2011 floods in south-east Queensland (Deloitte, 2017b), the 2019 floods in northern Queensland (Deloitte, 2019) and the 2019–2020 fires in southern and eastern Australia (Box 11.1).

In New Zealand, the annual cost of rural fire to the economy has been estimated at NZD$67 million, with indirect 'costs' potentially two to three times the direct costs (Scion, 2018). Insured losses from weather-related disasters cost almost NZD$1 billion during 2015–2021 (ICNZ, 2021). Floods cost the New Zealand economy at least NZD$120 million for privately insured damages between 2007 and 2017 (D. Frame et al., 2018). The 2007/2008 drought cost NZD$3.2 billion and the 2012/13 drought cost NZD$1.6 billion, of which about 20% could be attributed to anthropogenic climate change (Frame et al., 2020) (11.3.11).

The intangible costs of climate impacts, including death and injury, impacts on health and well-being, education and employment, community connectedness and the loss of ancestral lands, cultural sites and ecosystems (Barnett et al., 2016; Warner et al., 2019), affect multiple sectors and systems and exacerbate existing vulnerabilities. While often incommensurable, intangible costs may be far higher than the tangible costs. For example, following the Victorian fires in 2009, the tangible costs were AUD$3.1 billion while the intangible costs were AUD$3.4 billion; following the Queensland floods in 2010/2011, the tangible costs were AUD$6.7 billion while the intangible costs were AUD$7.4 billion (Deloitte, 2016).

11.5.2.2 Projected Impacts

The economic long-run impact increases with higher levels of warming (*high confidence*), but there is a wide range in projections. Conservative estimates for the long-run impacts of a 1°C, 2°C or 3°C global warming (relative to 1986–2005) on Australian GDP are –0.3, –0.6 and –1.1%/year, respectively, while for New Zealand the estimates are –0.1, –0.4 and –0.8%/year respectively (Kompas et al., 2018). More detailed modelling indicates a loss in Australia's GDP of 6% by 2070 for 3°C global warming, while a 2.6% GDP rise by 2070 is possible for 1.5°C global warming (Deloitte, 2020). The potential for much more severe effects on GDP is shown in recent estimates, which attempt to account for the increased severity of uncertain effects (e.g., up to 18.5% reduction in Australia's GDP by mid-century) (Swiss Re, 2021).

In Australia, the total annual cost of damage due to floods, coastal inundation, forest fires, subsidence and wind (excluding cyclones) is estimated to increase 55% between 2020 and 2100 for RCP8.5 (Mallon et al., 2019). National damage costs and impacts on asset values could be significant (Table 11.13). The macroeconomic shocks induced from climate change, including reduced agricultural yields, damage to property and infrastructure and commodity price increases, could lead to significant market corrections and potential financial instability (Steffen et al., 2019). Under a 'slow decline' scenario by 2060 where Australia fails to adequately address climate change and sustainability challenges, GDP is projected to grow at 0.7% less per year and real wages would be 50% lower than under an 'outlook scenario' where Australia meets climate change and sustainability challenges (CSIRO, 2019).

In New Zealand, the value of buildings exposed to coastal inundation could increase by NZD$2.55 billion for every 0.1-m increment in sea

Table 11.13 | Economy-wide projected costs (AUD$) of climate change in Australia. (Estimates are not comparable across studies because different methods have been used. Estimates for later in the century are speculative because both impacts and adaptation are uncertain.)

Impact	2030	2050	2090	Reference
Damage-related loss of property value in Australia	$571 billion	$611 billion	$770 billion	(Steffen et al., 2019)
Property damage in Australia		$91 billion/year	$117 billion/year	(Steffen et al., 2019)
Loss of asset value of road infrastructure (including freeways, main roads and unsealed roads) in Australia at risk of a SLR of 1.1 m by 2100			$46–60 billion	(DCCEE, 2011)
Loss of asset value of rail and tramway infrastructure in Australia at risk of a SLR of 1.1 m by 2100			$4.9–6.4 billion	(DCCEE, 2011)
Loss of asset value of residential buildings in Australia at risk of a SLR of 1.1 m by 2100 (2008 replacement value)			$51–72 billion	(DCCEE, 2011)
Loss of asset value of light industrial buildings (used for warehousing, manufacturing and assembly activities and services) in Australia at risk of a SLR of 1.1 m by 2100			$4.2–6.7 billion	(DCCEE, 2011)
Loss of asset value of commercial buildings (used for wholesale, retail, office and transport activities) in Australia at risk of a SLR of 1.1 m by 2100 (2008 replacement value)			$58–81 billion	(DCCEE, 2011)
Accumulated loss of wealth due to reduced agricultural productivity and labour productivity	$19 billion	$211 billion	$4.2 trillion	(Steffen et al., 2019)
Wind damage to dwellings in Cairns, Townsville, Rockhampton and south-east Queensland (assuming a 4% discount rate)	$3.8 billion	$9.7 billion	$20 billion	(Stewart and Wang, 2011)
Damage to Australian coastal residential buildings due to SLR (A1B scenario, 3.5°C global warming)			$8 billion	(Wang et al., 2016)

level, that is, NZD$25.5 billion for a 1.0-m sea level rise (SLR) (Paulik et al., 2020). Greater understanding is required of the distributional impacts, the rate of change of costs over time and the economic implications of delayed action (Warner et al., 2020).

11.5.2.3 Adaptation

Investments in mitigation and adaptation can help reduce or prevent economic losses now and in the coming decades (IPCC, 2018; Steffen et al., 2019); however, the costs and benefits of mitigation and adaptation are not well understood in the region (*high confidence*) (CSIRO, 2019; MfE, 2020a).

In New Zealand, the emphasis has been on rebuilding after climate disasters, rather than anticipatory adaptation (Boston and Lawrence, 2018). Australia is similarly focused on disaster response and recovery, even though investment in disaster resilience can provide a cost:benefit ratio of 1:2 to 1:11 through reduced post-disaster recovery and reconstruction (GCA, 2019). Recent Australian and state government spending on direct recovery from disasters was around AUD$2.75 billion per year, compared to funding for natural disaster resilience of approximately AUD$0.1 billion per year (Deloitte, 2017b). The Australian government is supporting most of the 80 recommendations from the Royal Commission into National Natural Disaster Arrangements, including establishing a disaster advisory body and a resilience and recovery agency (CoA, 2020e; CoA, 2020b). Australia and New Zealand provide humanitarian and disaster assistance across the Pacific, which is increasingly focused on climate adaptation and the SDGs (Brolan et al., 2019) as cyclones and floods become amplified by climate change (Fletcher et al., 2013) (Table 11.3). Climate change may increase current migration flows to and impacts on diaspora in Australia and New Zealand from near-neighbour island nations as they become increasingly stressed by rising seas, higher temperatures, more droughts and stronger storms (Nalau and Handmer, 2018).

Delaying adaptation to climate risks may result in higher overall costs in future when adaptation is more urgent and impacts more extreme (*medium confidence*) (Boston and Lawrence, 2018; IPCC, 2018). Estimates of the magnitude of adaptation costs and benefits in the region are localised and sectoral (e.g., (Thamo et al., 2017) or regionally aggregated (Joshi et al., 2016). Adaptation costs are expected to increase markedly for higher RCPs, for example, a tripling of expected costs between RCP2.6 and RCP8.5 for sea level rise (SLR) protection in Australia (Ware et al., 2020). Existing governance arrangements for funding adaptation are inadequate for the scope and scale of climate change impacts anticipated; dedicated funding mechanisms that can be sustained over generations can enable more timely adaptation (Boston and Lawrence, 2018).

11.6 Key Risks and Benefits

Nine key risks have been identified (Table 11.14) based on four criteria: magnitude, likelihood, timing and adaptive capacity (Chapter 16). Most of the key risks are similar to those in the IPCC AR5 Australasia chapter (Reisinger et al., 2014), but the emphasis here is on specific systems affected by multiple hazards rather than specific hazards affecting multiple systems. The selection of key risks reflects what has been observed, projected and documented, noting that there are gaps in knowledge, and a lack of knowledge does not imply a lack of risk (11.7.3.3). Key risks are grouped into four categories:

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Ecosystems at critical thresholds where recent climate change has caused significant damage and further climate change may cause irreversible damage, with limited scope for adaptation

1) Loss and degradation of coral reefs in Australia and associated biodiversity and ecosystem service values due to ocean warming and marine heatwaves (11.3.2.1, 11.3.2.2, Box 11.2).
2) Loss of alpine biodiversity in Australia due to less snow (11.3.1.1, 11.3.1.2).

Key risks that have potential to be severe but can be reduced substantially by rapid, large-scale and effective mitigation and adaptation

3) Transition or collapse of alpine ash, snow gum woodland, pencil pine and northern jarrah forests in southern Australia due to hotter and drier conditions with more fires (11.3.1.1, 11.3.1.2)
4) Loss of kelp forests in southern Australia and southeast New Zealand due to ocean warming, marine heatwaves and overgrazing by climate-driven range extensions of herbivore fish and urchins (11.3.2.1, 11.3.2.2).
5) Loss of natural and human systems in low-lying coastal areas due to sea level rise (SLR) (11.3.5, Box 11.6).
6) Disruption and decline in agricultural production and increased stress in rural communities in southwestern, southern and eastern mainland Australia due to hotter and drier conditions (11.3.4, 11.3.5, Box 11.3).
7) Increase in heat-related mortality and morbidity for people and wildlife in Australia due to heatwaves (11.3.5.1, 11.3.5.2, 11.3.6.1, 11.3.6.2).

Key cross-sectoral and system-wide risk

8) Cascading, compounding and aggregate impacts on cities, settlements, infrastructure, supply chains and services due to wildfires, floods, droughts, heatwaves, storms and sea level rise (SLR) (11.5.1.1, 11.5.1.2, Box 11.1, Box 11.4, Box 11.6).

Key implementation risk

9) Inability of institutions and governance systems to manage climate risks (11.5; 11.7.1, 11.7.2, 11.7.3).

At higher levels of global warming, adaptation costs increase, options become limited and risks grow. The 'burning embers' diagram in Figure 11.6 has four IPCC risk categories: undetectable, moderate, high and very high, with transition points defined by different global warming ranges. The embers are indicative, based on an assessment of available literature and expert judgement (Supplementary Material SM 11.2). Outcomes for low and moderate adaptation have been compared, with the latter including both incremental and transformative options. Illustrative examples of adaptation pathways are shown in Figure 11.7 for low-lying coastal areas and Figure 11.8 for heat-related mortality. These figures highlight thresholds at which adaptation options become ineffective and possible combinations of strategies and options implemented at different times to manage emerging risks and changing risk profiles.

Caveats: (a) key risks are assessed at regional scales, so they do not include other risks for finer scales or specific groups; (b) non-climatic vulnerabilities are held constant for simplicity; (c) the assessment of risk ratings at different levels of global warming is limited by available literature; (d) risks increase with global warming, despite the lack of an IPCC risk rating beyond *very high*; and (e) the feasibility and effectiveness of adaptations options were not assessed due to limited literature (11.7.3.3).

The New Zealand National Climate Change Risk Assessment (MfE, 2020a) identified the priority risks from climate change for New Zealand based on a literature review and expert elicitation. The top two risks in each of five domains are as follows:

1. *Natural environment*
a) risks to coastal ecosystems due to ongoing sea level rise (SLR) and extreme weather events
b) risks to indigenous ecosystems and species from invasive species

2. *Human environment*
a) risks to social cohesion and community well-being from displacement of people
b) risks of exacerbating existing inequities and creating new and additional inequities from distribution impacts

3. *Economy*
a) risks to governments from economic costs associated with lost productivity, disaster relief expenditure and unfunded contingent liabilities
b) risks to the financial system from instability

4. *Built environment*
a) risk to potable water supplies due to changes in rainfall, temperature, drought, extreme weather events and ongoing sea level rise (SLR)
b) risks to buildings due to extreme weather events, drought, increased fire weather and ongoing sea level rise (SLR)

5. *Governance*
a) risk of maladaptation due to practices, processes and tools that do not account for uncertainty and change over long time frames
b) risk that climate change impacts across all domains will be exacerbated, because current institutional arrangements are not fit for adaptation

Not all of these risks feature as key risks for the wider Australasia region; nonetheless, they are reflected across Chapter 11 and remain

Table 11.14 | Key risks from climate change based on assessment of the literature and expert judgement (Supplementary Material SM 11.2). Assessment criteria are magnitude, timing, likelihood and adaptive capacity. Risk drivers are hazards, exposure and vulnerability. Adaptation options describe ways in which risks can be reduced. Confidence ratings are based on the amount of evidence and agreement between lines of evidence.

Key risk (*confidence rating*) (Chapter reference)	Consequences influenced by hazards, exposure, vulnerability and adaptation options
1. Loss and degradation of tropical shallow coral reefs and associated biodiversity and ecosystem service values in Australia due to ocean warming and marine heatwaves (*very high confidence*) (11.3.2, Box 11.2)	Consequences: Widespread destruction of coral reef ecosystems and dependent socio-ecological systems. Three mass bleaching events from 2016 to 2020 have already caused significant loss of corals in shallow-water habitats across the GBR. Globally, bleaching is projected to occur twice each decade from 2035 and annually after 2044 under RCP 8.5 and annually after 2051 under RCP4.5. A 3°C global warming could cause over six times the 2016 level of thermal stress. Hazards: Increase in background warming and marine heatwave events degrade reef-building corals by triggering coral bleaching events at a frequency greater than the recovery time. Fish populations also decline during and following heatwave events. Exposure: Increasing geographic area affected by rate and severity of ocean warming Vulnerability: Vulnerability to increases in sea temperature is already very high because of other stressors on the ecosystem, including sediment, pollutants and overfishing. Adaptation options: Minimising other stressors. Efforts on the GBR may slow the impacts of climate change in small sections or reduce short-term socioeconomic ramifications, but they will not prevent widespread bleaching.
2. Loss of alpine biodiversity in Australia due to less snow (*high confidence*) (11.3.1, Table 11.2, Table 11.3, Table 11.4, Table 11.5)	Consequences: Loss of endemic and obligate alpine wildlife species and plant communities (feldmark and short alpine herb fields) as well as increased stress on snow-dependent plant and animal species. Hazards: Projected decline in annual maximum snow depth by 2050 is 30–70% (low emissions) and 45–90% (high emissions); projected increases in temperature and decreases in precipitation. Exposure: Alpine species face elevation squeeze due to lack of nival zone, and alpine environments have restricted geographic extent. Vulnerability: Narrow ecological niche of species including snow-related habitat requirements; encroachment from sub-Alpine woody shrubs; vulnerability generated by non-climatic stressors including weeds and feral animals, especially horses Adaptation options: Reducing pressure on alpine biodiversity from land uses that degrade vegetation and ecological condition, along with weed and pest management.
3. Transition or collapse of alpine ash, snow gum woodland, pencil pine and northern jarrah forests in southern Australia due to hotter and drier conditions with more fires (*high confidence*) (11.2, 11.3.1, 11.3.2, Box 11.1)	Consequences: If regenerative capacities of the dominant (framework) canopy tree species are exceeded, a long-lasting or irreversible transition to a new ecosystem state is projected with loss of characteristic and framework species, including loss of some narrow-range endemics. Hazards: Hotter and drier conditions have increased extreme fire weather risk since 1950, especially in southern and eastern Australia. The number of severe fire weather days is projected to increase 5–35% (RCP2.6) and 10–70% (RCP8.5) by 2050 Exposure: Shift in landscape fire regimes to larger, more intense and frequent wildfires over extensive areas (~10 million hectares) of forests and woodlands from longer fire seasons and more hazardous fire conditions and increasing human-sourced ignitions from urbanisation and projected increase in frequency of lightning strikes Vulnerability: The resilience and adaptive capacity of the forests is being reduced by ongoing land clearing and degrading land management practices Adaptation options: Increased capacity to extinguish wildfires during extreme fire weather conditions; avoiding and reducing forest degradation from inappropriate forest management practices and land use.
4. Loss of kelp forests in southern Australia and southeast New Zealand due to ocean warming, marine heatwaves and overgrazing by climate-driven range extensions of herbivore fish and urchins (*high confidence*) (11.3.2)	Consequences: Observed decline in giant kelp in Tasmania since 1990, with less than 10% remaining by 2011 due to ocean warming. Extensive loss of kelp, ~140,187 hectares across Australia, loss of bull kelp in southern New Zealand, replaced by the introduced kelp following the 2017/2018 marine heatwave. Further loss of native kelp is projected with warming oceans. Hazards: Ocean warming and marine heatwave events Exposure: Coastal waters around Australia and New Zealand Vulnerability: Giant kelp are already federally listed in Australia as an endangered marine community type. In Australia, kelp forests are vulnerable to nutrient-poor East Australian Current waters pushing further south, warming waters and increased herbivory from range-extending species. Adaptation options: Minimising other stressors, local restoration and transplantation of heat-tolerant phenotypes.
5. Loss of human and natural systems in low-lying coastal areas from ongoing SLR (*high confidence*) (11.2, 11.3.2, 11.3.5, 11.3.10, 11.4, Table 11.3; Box 11.6)	Consequences: Nuisance and extreme coastal flooding are already occurring due to SLR. For 0.2- to 0.3-m SLR, coastal flooding is projected to become more frequent, for example, the current 1-in-100-year flood would occur every year in Wellington and Christchurch. For 0.5-m SLR, the value of buildings in New Zealand exposed to coastal inundation could increase by NZD$12.75 billion and the current 1-in-100-year flood in Australia could occur several times a year. For 1.0-m SLR, the value of exposed assets in New Zealand would be NZD$25.5 billion. For 1.1-m SLR, the value of exposed assets in Australia would be AUD$164–226 billion. This would be associated with the displacement of people, disruption and reduced social cohesion, degraded ecosystems, loss of cultural heritage and livelihoods and loss of traditional lands and sacred sites. Hazards: Rising sea level (0.2–0.3 m by 2050, 0.4–0.7 m by 2090), storm surges, rising groundwater tables. Exposure: Population growth, new and infill urbanisation, tourism developments in low-lying coastal areas. Buildings, roads, railways, electricity and water infrastructure. Torres Strait Island and remote Māori communities are particularly exposed and sensitive. Vulnerability: Ineffective planning regulations, reduced availability and increased cost of insurance and costs to governments as insurers of last resort. Inadequate investment in avoidance and preparedness exacerbating underlying social vulnerabilities. Financial and physical capacities to cope and adapt are uneven across populations, creating equity issues. Adaptation options: Risk reduction coordinated across all levels of government with communities. Statutory planning frameworks, decision tools and funding mechanisms that can address the changing risk. Planning and land use decisions, including managed retreat where it is inevitable. Improved capacity of emergency services, early-warning systems, improved planning and regulatory practice and building and infrastructure design standards. Options that anticipate risk and adjust as conditions change.

Key risk (*confidence rating*) (Chapter reference)	Consequences influenced by hazards, exposure, vulnerability and adaptation options
6. Disruption and decline in agricultural production and increased stress in rural communities across south western, southern and eastern mainland Australia due to hotter and drier conditions. (*high confidence*) (11.2, 11.3.4, 11.3.6.3, 11.4.1, Table 11.11, Boxes 11.1, 11.3)	Consequences: Projected decline in crop, horticulture and dairy production, for example, decline in median wheat yields by 2050 of up to 30% in southwest Australia and up to 15% in southern Australia. Increased heat stress in livestock by 31–42 days per year by 2050. Reduced winter chilling for horticulture. Increased smoke impacts for viticulture. Flow-on effects for agricultural supply chains, farming families and rural communities across southwestern, southern and southeastern Australia, including the MDB. Hazards: Hotter and drier conditions with constraints on water resources and more frequent and severe droughts in southwestern, southern and eastern Australia. Exposure: Across southwestern, southern and eastern Australia, many production regions are exposed, including the MDB, which supports agriculture worth AUD$24 billion/year, 2.6 million people in diverse rural communities and important environmental assets containing 16 Ramsar Convention-listed wetlands. Vulnerability: Existing financial, social, health and environmental pressures on rural, regional and remote communities. Existing competition for water resources among communities, industries and environment and uncertainty about sharing of water under a drying climate. Adaptation options: Improved governance and collaboration to build rural resilience, including regional and basin-scale initiatives. Improved water policies and initiatives (e.g., MDB plan) and changes in management and technologies. Resilience-focused planning for rural settlements, land use, industry, infrastructure and value chains. Adoption of information, tools and methods to better manage uncertainty, variability and change. Incremental changes in farm management practices (e.g., stubble retention, weed control, water-use efficiency, sowing dates, cultivars). In some regions, major changes may be necessary, for example, diversification in agricultural enterprises, transition to different land uses (e.g., carbon sequestration, renewable energy production, biodiversity conservation) or migration to another area. Flows in waterways based on Indigenous knowledge to protect cultural assets.
7. Increase in heat-related mortality and morbidity for people and wildlife in Australia (*high confidence*) (11.2, 11.3.1, 11.3.5, 11.3.6, 11.4)	Consequences: During 1987–2016, natural disasters caused 971 deaths and 4370 injuries, with more than 50% due to heatwaves. Annual increases are projected for excess deaths, additional hospitalisations and ambulance callouts. Heatwave-related excess deaths in Melbourne, Sydney and Brisbane are projected to increase by about 300/year (RCP2.6) to 600/year (RCP8.5) during 2031–2080 relative to 142/year during 1971–2020, assuming no adaptation. Significant heat-related mortality of wildlife species (flying foxes, freshwater fish) has been observed and is projected to increase. Hazards: Increased frequency, intensity and duration of extreme heat events Exposure: Pervasive but differentially affecting some wildlife species depending on their thermal tolerances and occupational groups (e.g., outdoor workers) and those living in high exposure areas (e.g., urban heat islands). Health risks multiply with other harmful exposures, for example, to wildfire smoke. Vulnerability: Lower adaptive capacity for young/old/sick people, those in low-quality housing and of lower socioeconomic status, and areas served by fragile utilities (power, water). Remote locations with extreme heat and inadequate cooling in housing infrastructure (such as remote indigenous communities). For wildlife, impacts of extreme heat events are being amplified by habitat loss and degradation. Adaptation options: Urban cooling interventions including irrigated green infrastructure and increased albedo, education to reduce heat stress, heatwave/fire early-warning systems, battery/generator systems for energy system security, building standards that improve insulation/cooling, accessible / well-resourced primary health care. For wildlife, removing human stressors, reducing pressures from ferals and weeds, and ensuring suitable habitat.
8. Cascading, compounding and aggregate impacts on cities, settlements, infrastructure, supply chains and services due to extreme events (*high confidence*) (11.2, 11.3.4, 11.3.5, 11.3.6, 11.3.7, 11.3.8, 11.3.9, 11.3.10, 11.4, 11.5.1, Boxes 11.1, 11.4, 11.6)	Consequences: Widespread and pervasive damage and disruption to human activities generated by the interdependencies and interconnectedness of physical, social and natural systems. Examples include failure of transport, energy and communication infrastructure and services, heat stress, injuries and deaths, air pollution, stress on hospital services, damage to agriculture and tourism, insurance loss from heatwaves and fires; failure of transport, stormwater and flood-control infrastructure and services from floods and storms; water restrictions, reduced agricultural production, stress for rural communities, mental health issues, lack of potable water from droughts; damage to buildings, roads, railways, electricity and water infrastructure, loss of assets and lives, displacement of people, reduced social cohesion, degraded ecosystems from extreme SLR. Large aggregate costs due to lost productivity and major disaster relief expenditures, creating unfunded liabilities and supply chain disruption, e.g., 2019–2020 Australian fires cost AUD$8 billion. The long-run impact of a 1°C, 2°C or 3°C global warming (relative to 1986–2005) on Australian GDP is estimated at –0.3%/year, –0.6%/year and –1.1%/year respectively, while for New Zealand estimates are –0.1%/year, –0.4%/year and –0.8%/year respectively. Impacts on Māori tribal investments in forestry, agriculture, horticulture, fisheries and aquaculture. Hazards: Heatwaves, droughts, fires, floods, storms and SLR. This includes cascading and compound events such as heatwaves with fires, storms with floods or droughts followed by heavy rainfall and extreme sea levels. Exposure: Highly populated areas, rural and remote settlements, traditional lands and sacred sites. Greater urban density and population growth increases exposure in high-risk areas. Different exposure for different hazards, for example, heatwaves: urban and peri-urban areas; fire: peri-urban areas and settlements near forests; floods: people, property and infrastructure from pluvial floods in cities and settlements and fluvial floods on floodplains; storms: buildings and infrastructure in cities and settlements. Vulnerability: Existing social and economic challenges (e.g., those caused by COVID-19) and socioeconomic and cultural inequalities; competing resource and land use demands across sectors; inadequate planning, policy, governance, decision-making and disaster resilience capacity; and non-climatic stresses on ecosystems. Vulnerabilities generated by interdependencies and interconnectedness of physical, social and natural systems. Adaptation options: Flexible and timely adaptation strategies that prepare socioeconomic and natural systems for surprises and unexpected threats. Multi-sector coordinated actions that address widespread impacts, redress existing vulnerabilities and building adaptive capacity and systemic resilience. Improved coordination between and within levels of governments, communities and private sector. Greater use of dynamic decision frameworks and suitable economic and social assessment tools. Improved emergency services and early-warning systems; use of climate-resilient standards for buildings and infrastructure. Transformational adaptations (e.g., managed retreat) that can be planned in stages.

Key risk (*confidence rating*) (Chapter reference)	Consequences influenced by hazards, exposure, vulnerability and adaptation options
9. Inability of institutions and governance systems to manage climate risks (*high confidence*) (11.2, 11.3.5, 11.3.6, 11.3.7, 11.3.8, 11.3.10, 11.4, 11.5.1, 11.7.2, Boxes 11.1–11.6)	Consequences: Climate hazards overwhelm the capacity of institutions, organisations, systems and leaders to provide necessary policies, services, resources, coordination and leadership. Failed adaptation at the institutional and governance levels has widespread, pervasive impacts on all areas of society. This includes a reliance on reactive, short-term decision-making that locks in existing exposures, leaves perverse incentives and interconnected and systemic impacts unaddressed and generates high costs and fiscal impacts. This worsens vulnerability and leads to maladaptation, inequities and injustices within and across generations, as well as actions that do not uphold the rights, interests, values and practices of Indigenous Peoples. Resultant failure to take adaptation action generates litigation risk. Hazards: Increasing frequency, duration, severity and complexity of extreme weather events, droughts and SLR Exposure: All sectors, communities, organisations and governments Vulnerability: Fragmented institutional and legal arrangements, under-resourcing of services, lack of dedicated adaptation funding instruments and resources to support communities and local government, uneven capability to manage uncertainty and conflicting values and competing policy and political interests. Adaptation options: Pre-emptive options that avoid and reduce risks. Redesign of policy and statutory frameworks and funding instruments for addressing changing risks and uncertainties that enable just and collaborative governance across scales and domains. Addressing existing vulnerabilities and capacity, capability and leadership deficits within and across all levels of government, all sectors, Indigenous Peoples and communities. Risk and vulnerability assessment methodologies and decision-making tools that build resilience and address changing risks and vulnerabilities. Co-designed adaptation approaches implemented with communities, including Māori tribal organisations and Australian Aboriginal and Torres Strait Island peoples.

Burning embers diagram for each of the nine key risks for low and moderate adaptation

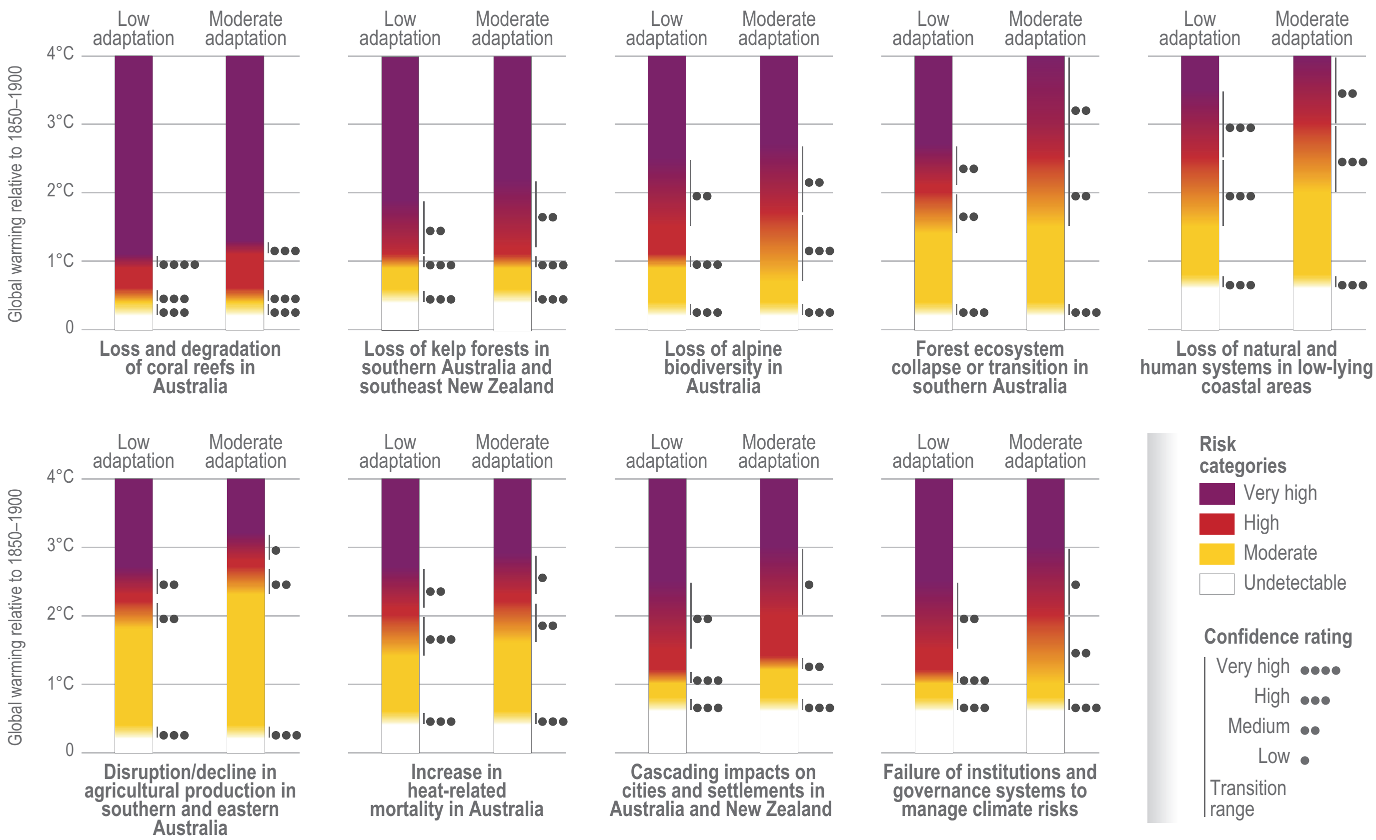

Figure 11.6 | Burning embers diagram for each of the nine key risks for low and moderate adaptation. The risk categories are undetectable, moderate, high and very high. While there is no risk category beyond very high, risks obviously get worse with further global warming, and the risk for coral reefs is already very high. The assessment is based on available literature and expert judgement, summarised in Table 11.14 and described in Supplementary Material SM 11.2. The global warming range associated with each risk transition has a confidence rating (**** *very high*, *** *high*, ** *moderate*, * *low*) based on the amount of evidence and level of agreement between lines of evidence

Illustrative adaptation pathway for risk to natural and human systems in low-lying coastal areas due to sea level rise

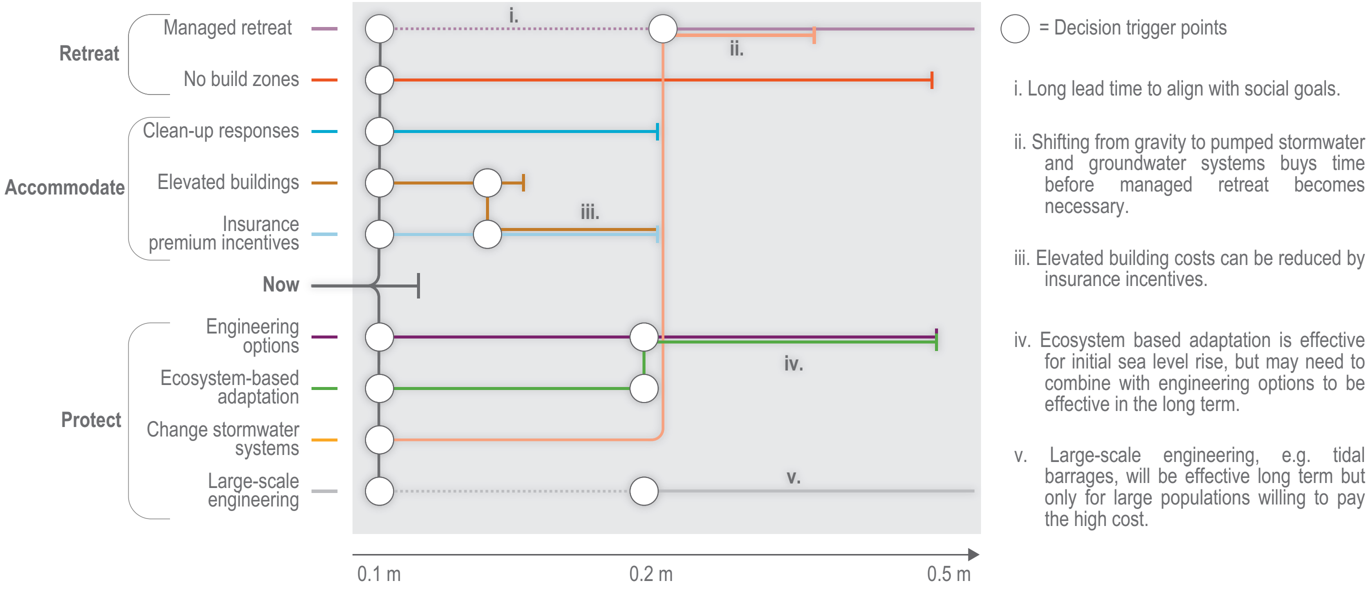

Figure 11.7 | Illustrative adaptation pathway for risk to natural and human systems in low-lying coastal areas due to sea level rise.

Illustrative adaptation pathway for risk of heat-related mortality and morbidity for people and wildlife in Australia due to heatwaves

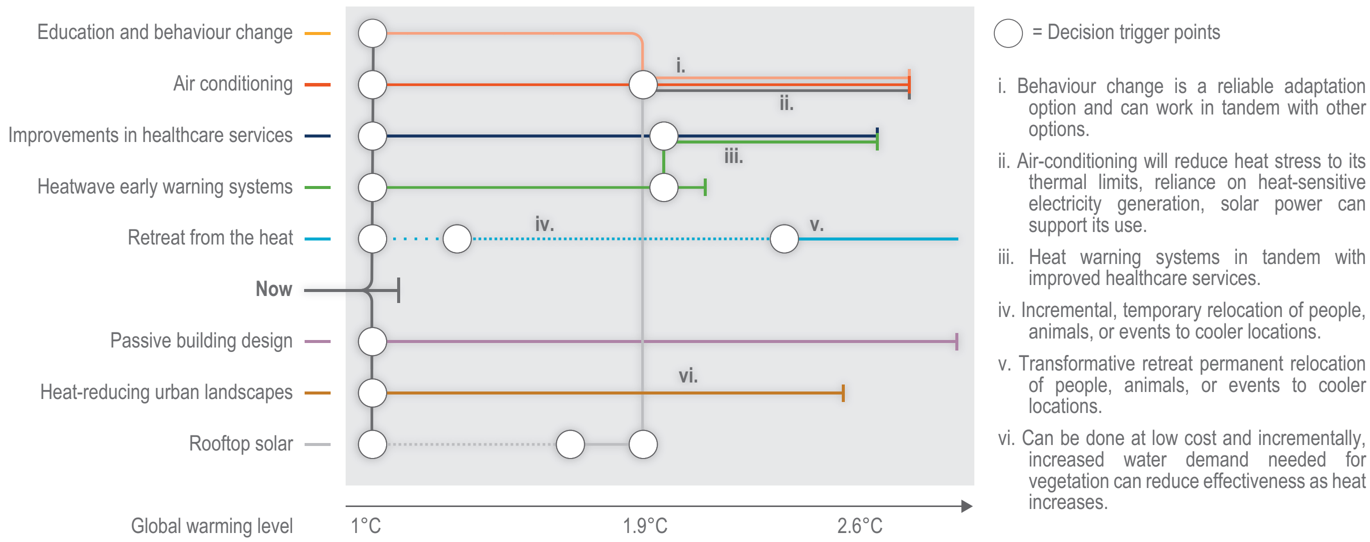

Figure 11.8 | Illustrative adaptation pathway for risk of heat-related mortality and morbidity for people and wildlife in Australia due to heatwaves.

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priorities for New Zealand to address through the National Adaptation Plan, its implementation and monitoring.

Short-term benefits from climate change may include reduced winter mortality, reduced energy demand for winter heating, increased agriculture productivity and forest growth in south and west New Zealand and increased forest and pasture growth in southern Australia, except where rainfall and soil nutrients are limiting (11.3.4, 11.3.6, 11.3.10) (*medium confidence*).

11.7 Enabling Adaptation Decision-Making

11.7.1 Observed Adaptation Decision-Making

The ambition, scope and progress on adaptation by governments have risen but are uneven, with a focus on high-level strategies at the national level, adaptation planning at sub-national levels and new enabling legislation (*very high confidence*) (Table 11.15a, Table 11.15b) (Lawrence et al., 2015; Macintosh et al., 2015; MfE, 2020a). The adaptation process comprises vulnerability and risk assessments, identification of options, planning, implementation, monitoring, evaluation and review. Large gaps remain, especially in effective implementation, monitoring and evaluation (Supplementary Material SM 11.1) (CCATWG, 2017; Warnken and Mosadeghi, 2018), and current adaptation is largely incremental and reactive (*very high confidence*) (Box 11.4, Box 11.6, Table 11.14).

Australia has a National Climate Resilience and Adaptation Strategy, a National Recovery and Resilience Agency (11.5.2.3), and the First National Action Plan to implement the National Disaster Risk Reduction Framework which acknowledges climate change as a disaster risk driver (Home Affairs, 2020). States and territories have climate change adaptation strategies with plans to address them (Table 11.15a), with some adaptation implementation at the state level and, increasingly, at the local government level (Jacobs et al., 2016; Warnken and Mosadeghi, 2018) (Table 11.15a). In coastal zones, however, few local government planning instruments are being applied (Warnken and Mosadeghi, 2018; Harvey, 2019; Robb et al., 2019; Elrick-Barr and Smith, 2021). Some businesses and industry sectors are recognising climate-related risks and adaptation planning (11.3.4; 11.3.7; 11.3.10) (Harris et al., 2016; Hennessy et al., 2016; CBA, 2019). There is an opportunity for Australia to undertake a national risk assessment and to develop a national climate adaptation implementation plan that is aligned with Paris Agreement expectations of a national-level system for adaptation planning, monitoring and reporting (Morgan et al., 2019).

New Zealand's Climate Change Response Act 2019 creates a legal mandate for national climate change risk assessments (first one completed) (MfE, 2020a) and national adaptation plans (first in preparation), as well as a Climate Change Commission to monitor and report on adaptation implementation. Preparation of natural and built environment, strategic planning and climate change adaptation acts is under way, including provision for funding and managed retreat (MfE, 2020c). National coastal guidance is available for adaptation planning to address changing climate risks (MfE, 2017a) (Table 11.15b). Meanwhile, several local authorities have developed integrated climate change strategies and plans and revised policies and rules to enable adaptation (Table 11.15b). Different adaptation approaches continue to create confusion and inertia while development pressures continue (Schneider et al., 2017). Opportunities for integrated adaptation and mitigation planning in regional policies and plans have arisen through the Resource Management Amendment Act 2020 (Dickie, 2020), the National Policy Statement on Freshwater Management (MfE, 2020b) and the revised national coastal guidance (MfE, 2017a), but rely on funding instruments to be in place and statutes are aligned for their effectiveness (*very high confidence*) (Boston and Lawrence, 2018; CCATWG, 2018).

There is growing awareness of the need for more proactive adaptation planning at multiple scales and across sectors, and a better understanding of future risks and limits to adaptation is emerging (*medium confidence*) (Evans et al., 2014; Archie et al., 2018; Christie et al., 2020; MfE, 2020a). Disaster risk reduction is being positioned as part of climate change adaptation (Forino et al., 2017; CDEM, 2019; Forino et al., 2019; CoA, 2020e; CSIRO, 2020). Public and private climate adaptation services are informing climate risk assessments, but they are characterised by fragmentation, duplication, inconsistencies, poor governance and inadequate funding; addressing these gaps presents adaptation opportunities (CCATWG, 2018; Webb et al., 2019; NESP ESCC, 2021) (Table 11.15a, Table 11.15b). Large infrastructure asset planning is starting to factor in climate risks, but implementation is uneven (Gibbs, 2020). Local governments in Australia are increasingly implementing adaptation plans, but few monitor or evaluate actual outcomes or know how to (Scott and Moloney, 2021).

Observed and projected rates of sea level rise (SLR) (Box 11.6) and increased flood frequency (11.3.3) are challenging established uses of modelling, risk assessment and cost-benefit analysis, where climate change damage functions cannot be projected or are unknown (deep uncertainty) or impacts on communities are ambiguous (Infometrics and PSConsulting, 2015; Lawrence et al., 2019a; MfE, 2020a). New tools are available in the region (Table 11.17), but uptake cannot be assumed (*high confidence*) (Lawrence and Haasnoot, 2017; Palutikof et al., 2019c).

Resilience and adaptation approaches are beginning to converge (White and O'Hare, 2014; Aldunce et al., 2015) (Supplementary Material SM 11.1) but widespread 'bounce-back' resilience-driven responses that lock in risk by discounting ongoing and changing climate risk (Leitch and Bohensky, 2014; O'Hare et al., 2016; Wenger, 2017; Torabi et al., 2018) can create maladaptation and impede long-term adaptation goals (*high confidence*) (Glavovic and Smith, 2014; Dudney et al., 2018).

Local government engagement with communities on adaptation is starting to motivate a change towards more collaborative engagement practices (Archie et al., 2018; Bendall, 2018; MfE, 2019; Schneider et al., 2020). Nature-based adaptations (Colloff et al., 2016; Lavorel et al., 2019; Della Bosca and Gillespie, 2020) and 'green infrastructure' (*medium confidence*) (Lin et al., 2016; Alexandra and Norman, 2020) are increasingly being adopted (Rogers et al., 2020a).

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Table 11.15a | Examples of Australian adaptation strategies, plans and initiatives by government agencies at national, sub-national and regional or local levels. These examples have not been assessed for their effectiveness (see Supplementary Material Table SM11.1a).

Jurisdiction	Strategies/Plans/Actions
National Level	
Australia	National Climate Resilience and Adaptation Strategy 2015 (CoA, 2015) National Disaster Risk Reduction Framework (2018) (CoA, 2018b) National Recovery and Resilience Agency and Australian Climate Service (CoA, 2021)
Sub-national	
Australian Capital Territory (ACT)	ACT Climate Change Strategy 2019–2025 (ACT Government, 2019) Canberra's Living Infrastructure Plan: Cooling the City (ACT Government, 2020b); ACT Well-being Framework (ACT Government, 2020a)
New South Wales	NSW Climate Change Policy Framework (NSW Government, 2016)
	Coastal Management Framework (OEH, 2018b) including Coastal Management Act 2016, State Environmental Planning Policy (Coastal Management) 2018, NSW Coastal Management Manual (OEH, 2018c; OEH, 2018a)
Northern Territory	Northern Territory Climate Change Response: Towards 2050 (DENR, 2020b) three-year action plan (DENR, 2020a)
Queensland	Pathways to climate-resilient Queensland: Queensland Climate Adaptation Strategy 2017–2030 (DEHP, 2013)
	Sector adaptation plans: https://www.qld.gov.au/environment/climate/climate-change/adapting/sectors-systems
	State heatwave risk assessment, 2019 (QFES, 2019)
	Planning Act 2016 (Queensland Government, 2020) and the Coastal Protection and Management Act 1995 (Queensland Government, 1995), plus supporting initiatives: Coastal Management Plan (DEHP, 2013) and Shoreline Erosion Management Plans (DES, 2018) Queensland's QCoast2100 program
South Australia	Directions for a Climate Smart South Australia (SA Government, 2019a)
Tasmania	Climate Action 21: Tasmania's Climate Change Action Plan 2017–2021 (State of Tasmania, 2017a)
	Tasmania's 2016 State Natural Disaster Risk Assessment (White et al., 2016a)
	Tasmanian Planning Scheme—State Planning Provisions 2017, Coastal Inundation Hazard Code and a Coastal Erosion Hazard Code (Government of Tasmania, 2017).
Victoria	In accordance with the Climate Change Act 2017, Victoria has a Climate Change Adaptation Plan 2017–2020 (Victoria State Government DELWP, 2016) including a Monitoring, Evaluation, Reporting and Improvement (MERI) framework for Climate Change Adaptation in Victoria (DELWP, 2018), Victorian Climate Projections (2019) and multiple resources for regions and local government (Victoria DELWP 2020).
	Heatwaves in Victoria. A 2018 vulnerability assessment of the state to heatwaves using a Damage and Loss Assessment methodology (Natural Capital Economics, 2018)
Western Australia	Western Australian Government Adapting to our changing climate 2012 (WA Government, 2016)
	State Planning Policy 2.6 – Coastal Planning (SPP2.6)
Regional and local (examples only)	
104 have declared climate emergencies to leverage climate action as of September 2021 covering 36.6% of the Australian population (Climate Emergency Declaration, 2022)	
Tasmania	2017: Tasmanian Planning Scheme – State Planning Provisions. State of Tasmania, 514. (State of Tasmania, 2017a; State of Tasmania, 2017b)
South Australia	Regional integrated vulnerability assessments (IVAs) and adaptation plans (SA Government, 2019a)
NSW	Enabling Regional Adaptation (Jacobs et al., 2016)
Victoria	Every region and catchment management authority in Victoria has an adaptation plan, as does virtually every local government. There are also three alliances of multiple local governments working on climate change and new initiatives such as the Climate Change Exchange: https://www.parliament.vic.gov.au/967-epc-la/inquiry-into-tackling-climate-change-in-victorian-communities
NSW	Coastal Zone Management Plan for Bilgola Beach (Bilgola) and Basin Beach (Mona Vale) (Haskoning Australia, 2016)
Queensland	Torres Strait Climate Change Strategy (TSRA, 2014), Torres Strait Regional Adaptation and Resilience Plan 2016–2021 (TSRA, 2016)
	Climate Risk Management Framework for Queensland Local Government (Erhart et al., 2020)
	Douglas Shire Coast Strategic Plan 2019 (Douglas Shire Council, 2019)
Northern Territory	Climate Change Action Plan (2011–2020) (Darwin City Council, 2011)

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Table 11.15b | Examples of New Zealand's adaptation strategies, plans and initiatives by government agencies at national, sub-national and regional or local levels. NB: These examples have not been assessed for their effectiveness (see Supplementary Material Table SM11.1b)

Jurisdiction	Strategies/Plans/Actions
New Zealand central Government	The New Zealand Government's adaptation policy framework is based on the following legislation: Resource Management Act 1991, Local Government Act 2002, National Disaster Resilience Strategy 2019 (CDEM, 2019) and the Climate Change Response (Zero Carbon Amendment) Act 2002 (CCRA 2002) Adaptation preparedness report 2020/2021 baseline is the reporting organisation responses from the first information request under the CCRA 2002 (MfE, 2021) to assist the monitoring of progress and effectiveness of adaptation by the Climate Change Commission The Department of Conservation's Climate Change Adaptation Action plan sets out a long-term strategy for climate research, monitoring and action; DOC climate adaptation plan
Local Government	In July 2017, a group of 66 local government mayors and council chairs (of 78 in total) endorsed a 2015 local government declaration calling for urgent responsive leadership and a holistic approach on climate change, with the government needing to play a vital enabling leadership role (LGNZ, 2017; Schneider et al., 2017). Seventeen councils have declared climate emergencies to leverage climate action plans as of September 2021, covering 75.3% of the New Zealand population. The MfE adaptation preparedness report states that 18% of councils (11 of 61 surveyed in 2021) have some sort of plan or strategy to increase resilience to climate impacts (MfE, 2021). Out of New Zealand's 15 regional and unitary councils, 2 have climate adaptation strategies in place. One council has conducted a climate risk assessment, and four have one in development. Five councils have climate action plans, and three are in development.
Regional Councils (examples only)	
Bay of Plenty Regional Council	Climate Action Plan July 2019 (non-statutory) Climate Action Plan
Waikato Regional Council	Long-Term Plan 2018–2028 (LTP)
Greater Wellington Regional Council	GWRC's Climate Change Strategy (October 2015) Climate change strategy implementation Hutt River Flood Risk Management Plan
Unitary Authorities (examples only)	
Auckland Council	Auckland Unitary Plan AUP RPS B10 Table B11.9 (bottom of doc) E36. Natural hazards and flooding
Marlborough District Council	Marlborough Environment Plan first to integrate DAPP into plan policies.
Gisborne District Council	Tairāwhiti Resource Management Plan (District Plan) March 2020
District Council (example only)	
Waimakariri District Council	Infrastructure Strategy in the Long Term Plan 2017. Long-Term-Plan-Further-Information-Document-WEB.pdf Page 113/31

Some businesses have initiated active adaptation (Aldum et al., 2014; Linnenluecke et al., 2015; Bremer and Linnenluecke, 2017; CCATWG, 2017; MfE, 2018), with most focused on identifying climate risks (Aldum et al., 2014; Gasbarro et al., 2016; Cradock-Henry, 2017). Businesses are more likely to engage in anticipatory adaptation when the frequency of climate events is known (McKnight and Linnenluecke, 2019). Effective cooperation and a positive innovation culture can contribute to the collaborative development of climate change adaptation pathways (*medium confidence*) (Bardsley et al., 2018).

Some areas in northern Australia and New Zealand, especially those with higher proportions of Indigenous populations, face severe housing, health, education, employment and services deficits that exacerbate the impacts of climate change (Kotey, 2015) (11.3.5; 11.4; 11.6).

Where adaptation relies upon an ageing population and an overstretched volunteer base, vulnerability to climate change impacts is being exacerbated (Astill and Miller, 2018; Davies et al., 2018). Adaptation options that succeed within remote Indigenous communities are founded on connections to traditional lands, alignment with cultural values and contribute to social, cultural and economic goals (Nursey-Bray and Palmer, 2018). Knowledge co-production for Indigenous adaptation pathways can enable transformative change from colonial legacies (Hill et al., 2020). Learning and experimentation across governance boundaries and between agencies and local communities enable adaptation to be better aligned with changing climate risks and community (*high confidence*) (Fünfgeld, 2015; Howes et al., 2015; Bardsley and Wiseman, 2016; Lawrence et al., 2019b).

There is increasing focus on improving adaptive capacity for transitional and transformational responses, but reactive responses dominate (*very high confidence*) (Smith et al., 2015; Schlosberg et al., 2017; Boston and Lawrence, 2018). While extreme events can provide opportunities for positive transitions within communities (Cradock-Henry et al., 2018b) (e.g., Queensland Reconstruction Authority Building Back Better scheme), often rebuilding occurs in at-risk places to aid quick recovery (Lawrence and Saunders, 2017). Community-based adaptation innovations (Bendall, 2018; Kench et al., 2018; Forino et al., 2019) include relationship building; use of new decision tools, pathways planning with communities, visualisation and serious games (Lawrence and Haasnoot, 2017; Schlosberg et al., 2017; Flood et al., 2018; Reiter

Table 11.16 | Examples of barriers to adaptation action in the region

Barrier	Source
Governments	
Lack of consistent policy direction from higher levels and frequent policy reversals	(Dedekorkut-Howes et al., 2020)
Conflicts between community-based initiatives, city councils and business interests	(Forino et al., 2019)
Different framings of adaptation between local governments (risk) and community groups (vulnerability, transformation)	(Smith et al., 2015; Schlosberg et al., 2017; McClure and Baker, 2018)
Competing planning objectives	(McClure and Baker, 2018)
Divergent perceptions of risk concepts	(Button and Harvey, 2015; Mills et al., 2016b; Tonmoy et al., 2018)
Focus on climate variability rather than climate change	(Dedekorkut-Howes and Vickers, 2017)
Low prioritisation of climate change adaptation among competing institutional objectives	(Glavovic and Smith, 2014; Lawrence et al., 2015; McClure and Baker, 2018)
Constraints in using new knowledge	(Temby et al., 2016)
Lack of institutional and professional capabilities and capacity (e.g., to monitor and evaluate adaptation outcomes)	(Lawrence et al., 2015; Scott and Moloney, 2021)
Lack of understanding of Indigenous knowledge and practices	(Parsons et al., 2019)
Lack of authority and political legitimacy	(Hayward, 2008; Boston and Lawrence, 2018; CCATWG, 2018; Parsons et al., 2019)
Fear of litigation	(Tombs et al., 2018; Iorns Magallanes and Watts, 2019; O'Donnell et al., 2019)
Upfront costs of adaptation relative to competing demands on government expenditure	(Gawith et al., 2020; Warren-Myers et al., 2020b)
Private sector	
Governance and policy uncertainty, lack of cross-sector coordination, lack of capital investment in climate solutions	(CCATWG, 2017; Forino et al., 2017; IGCC, 2021a)
Inconsistent hazard information and incomplete understanding of adaptation	(CCATWG, 2017; Harvey, 2019)
Mismatch in duration of insurance cover (annual) lending (decades) and infrastructure and housing investment (50–100 years)	(Storey and Noy, 2017; O'Donnell, 2020)
Perceived unaffordability of adaptation, lack of client demand and awareness of climate change risks and limited and inconsistent climate risk regulation in the construction industry	(Hurlimann, 2008; Hurlimann et al., 2018)
Translating information into organisations to address disinterest among clients in the property industry	(Warren-Myers et al., 2020b; Warren-Myers et al., 2020a)
Erosion of adaptive capacity and challenges of transformational adaptation in agriculture and rural communities	(Jakku et al., 2016)
Communities	
Nature of government engagement with communities	(Public Participation, 2014; MfE, 2017a; Archie et al., 2018; OECD, 2019b)
Lack of clarity regarding roles and responsibilities	(Gorddard et al., 2016; Elrick-Barr et al., 2017; Goode et al., 2017; Waters and Barnett, 2018)
Lack of resourcing of adaptation	(Singh-Peterson et al., 2015; Lukasiewicz et al., 2017; Brookfield and Fitzgerald, 2018)
Lack of deep engagement with climate change	(Kench et al., 2018; Pearce, 2018)
Diverging perceptions, values and goals within communities	(Austin et al., 2018; Fitzgerald et al., 2019; Marshall et al., 2019)
Inequities within and between communities	(Eriksen, 2014; Parkinson, 2019)
Lack of sustained engagement, learning and trust between community, scientists and policy makers	(Serrao-Neumann et al., 2020)

et al., 2018; Serrao-Neumann and Choy, 2018); communities of practice; and climate information sharing (Astill et al., 2019; Stone et al., 2019).

11.7.2 Barriers and Limits to Adaptation

Major gaps in the adaptation process remain across all sectors and at all levels of decision-making (*very high confidence*) (11.3; Table 11.115a, Table 15b). Efforts to build, resource and deploy adaptive capacity are slow compared to escalating impacts and risks (Stephenson et al., 2018; CoA, 2020e). Barriers to effective adaptation include governance inertia at all levels, hindering the development of careful and comprehensive adaptation plans and their implementation (Boston and Lawrence, 2018; MfE and Hawke's Bay Regional Council, 2020; White and Lawrence, 2020). Lack of clarity about mandate, roles and leadership and inadequate funding for adaptation by national and state governments and sectors, are slowing adaptation (Lukasiewicz et al., 2017; Waters and Barnett, 2018; LGNZ, 2019; MfE, 2020c) (11.3; 11.7.1). Established planning tools and measures were designed for static risk profiles, and practitioners are slow to take up tools better suited to changing climate risks (CoA, 2020e; Schneider et al., 2020) (11.5; Box 11.5). The communication of relevant climate change

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information remains ad hoc (Stevens and O'Connor, 2015; CCATWG, 2017; Palutikof et al., 2019c; Salmon, 2019). In Australia, the lack of national guidance or adaptation laws creates barriers to adaptation, reflected in uneven coastal adaptation based on a wait-and-see approach (Dedekorkut-Howes et al., 2020).

There are many barriers to starting adaptation pre-emptively (*very high confidence*) (CCATWG, 2018) (Table 11.16). Recent institutional changes in New Zealand indicate that this is changing (11.7.1; Table 15b). Many groups are yet to engage deeply with climate change adaptation (Kench et al., 2018), and some adaptation processes are being blocked (Pearce et al., 2018; Garmestani et al., 2019; Alexandra, 2020) or exploited to deflect from mitigation responsibilities (Smith and Lawrence, 2018; Nyberg and Wright, 2020). Some actors are resistant to using climate change information (Tangney and Howes, 2016; Alexandra, 2020). Fear of litigation and demands for compensation can contribute to this reluctance (Tombs et al., 2018; O'Donnell et al., 2019)and is increasingly inviting litigation and other costs (Hodder, 2019; Bell-James and Collins, 2020). Jurisprudence is evolving from cases on projects to cases about decision-making accountability in the public and private sectors (Bell-James and Collins, 2020; Peel et al., 2020) and rights-based cases (Peel and Osofsky, 2018). National and sub-national governments may become exposed to unsustainable fiscal risk as insurers of last resort, which can lead to inequitable outcomes for vulnerable groups and future generations (11.3.8), path dependencies and negative effects on physical, social, economic and cultural systems (Hamin and Gurran, 2015; Boston and Lawrence, 2018). Cross-scale governance tensions can prevent local adaptation initiatives from performing as intended (Tschakert et al., 2016; Piggott-McKellar et al., 2019). Adaptation that draws on Māori cultural understanding in partnership with local government in New Zealand can lead to more effective and equitable adaptation outcomes (MfE, 2020a).

Communities' vulnerabilities are dynamic and uneven (*high confidence*). In Australia, 435,000 people in remote areas face particular challenges (CoA, 2020e). Some groups do not have the time, resources or opportunity to participate in formal adaptation planning as it is currently organised (Victorian Council of Social Service, 2016; Tschakert et al., 2017; Mathew et al., 2018). Linguistically diverse groups can be disadvantaged by social isolation, language barriers and others' ignorance of the knowledge and skills they can bring to adaptation (Shepherd and van Vuuren, 2014; Dun et al., 2018) (11.1.2). Social, cultural and economic vulnerabilities, biases and injustices, such as those faced by many women (Eriksen, 2014; Parkinson, 2019) and non-heterosexual groups and gender minorities (Dominey-Howes et al., 2016; Gorman-Murray et al., 2017), can deepen impacts and impede adaptation; (Fitzgerald et al., 2019; Marshall et al., 2019) (Cross-Chapter Box GENDER in Chapter 18).

Potential biophysical limits to adaptation for non-human species and ecosystems where impacts are projected to be irreversible, with limited scope for adaptation, are signalled in key risks 1–4 (11.6). In some human systems, fundamental limits to adaptation include thermal thresholds and safe freshwater (Alston et al., 2018) (Table 11.14) and the inability of some low-lying coastal communities to adapt in place (Box 11.6) (*very high confidence*). Some individuals and communities are already reaching their psycho-social adaptation limits (Evans et al., 2016). A lack of robust and timely adaptation means key risks will increasingly manifest as impacts, and numerous systems, communities and institutions are projected to reach limits (Table 11.14, Figure 11.6), compounding current adaptation deficits and undermining society's capacity to adapt to future impacts (*very high confidence*).

11.7.3 Adaptation Enablers

Adaptation enablers include understanding relevant knowledge, diverse values and governance, institutions and resources (*very high confidence*) (Gorddard et al., 2016). Skills and learning, community networks, people–place connections, trust-building, community resources and support and engaged governance build social resilience that support adaptation (Maclean et al., 2014; Eriksen, 2019; Phelps and Kelly, 2019). A multi-faceted focus on the role societal inequalities and environmental degradation play in generating climate change vulnerability can enable fairer adaptation outcomes (McManus et al., 2014; Ambrey et al., 2017; Schlosberg et al., 2017; Graham et al., 2018).

The feasibility and effectiveness of adaptation options will change over time depending on place, values, cultural appropriateness, social acceptability, ongoing cost-effectiveness, leadership and the ability to implement them through the prevailing governance regime (Singh et al., 2020). The capacity and commitment of the political system can drive early action that can reduce risks (Boston, 2017).

Decision makers face the challenge of how to adapt when there are ongoing knowledge gaps and uncertainties about when some climate change impacts will occur and their scale, for example coastal flooding (Box 11.6) or extreme rainfall events and their cascading effects (Box 11.4) (*very high confidence*). No-regrets decisions are *likely* to be insufficient (Hallegatte et al., 2012). A perception exists in some sectors that all climate risks are manageable based on past experience (CCATWG, 2017). Projected impacts, however, are outside the range experienced, meaning that decisions must be made now for long-lived assets, land uses and communities exposed to the key risks (Paulik et al., 2019a; Paulik et al., 2020) often under contested conditions where adaptation competes with other public expenditures (Kwakkel et al., 2016). New planning approaches being used across the region can enable more effective adaptation, for example continual iterative adaptation (Khan et al., 2015), rapid deployment of decision tools appropriate for addressing uncertainties (Marchau et al., 2019) and transformation of governance and institutional arrangements (Boston and Lawrence, 2018) (Table 11.17). Recognising co-benefits for mitigation and sustainable development can help incentivise adaptation (11.3.5.3, 11.8.2).

11.7.3.1 Planning and Tools

Adaptation decision support tools enable a shift from reactive to anticipatory planning for changing climate risks (*high confidence*). The available tools are diversifying with futures and systems methodologies and dynamic adaptive policy pathways being increasingly used (Bosomworth et al., 2017; Prober et al., 2017; Lawrence et al., 2018a; CoA, 2020e; Rogers et al., 2020a; Schneider et al., 2020) (11.5; Box 11.6) to facilitate the shift from static to dynamic adaptation by highlighting

Table 11.17 | Key enablers for adaptation

Enabler	Example
Governance frameworks	Clear climate change adaptation mandate Measures that inform a shift from reactive to anticipatory decision-making (e.g., decision tools that have long time frames) Institutional frameworks integrated across all levels of government for better coordination Revised design standards for buildings, infrastructure, landscape such as common land use planning guidance and codes of practice that integrate consideration of climate risks to address existing and future exposures and vulnerability of people and physical and cultural assets (11.3.1, 11.3.2, 11.3.3, 11.3.4.3, 11.3.5, 1.3.6, 11.4.1, 11.4.2, 11.5.1, 11.5.2, 11.6, 11.7.1, 11.7.2, 11.8.1, 11.8.2, Table 11.7, Table 11.14, Box 11.1, Box 11.3, Box 11.5, Box 11.6)
Building capacity for adaptation	Provision of nationally consistent risk information through agreed methodologies for risk assessment that address non-stationarity Targeted research including understanding the projected scope and scale of cascading and compounding risks Education, training and professional development for adaptation under changing risk conditions Accessible adaptation tools and information (11.1.2, 11.3.4, 11.3.5, 11.4.1, 11.5.1, 11.6, 11.7.1, 11.7.2, Table 11.14, Table 11.16, Table 11.18, Box 11.6)
Community partnership and collaborative engagement	Community engagement based on principles that consider social and cultural and Indigenous Peoples' contexts and an understanding of what people value and wish to protect (e.g., International Association of Public Participation) (Public Participation, 2014) Use of collaborative and learning-oriented engagement approaches tailored for the social and informed by the cultural context Community awareness and network building Building on Indigenous Australian and Māori communities' social-cultural networks and conventions that promote collective action and mutual support (11.3.5, 11.4, 11.7.1, 11.7.3.2, Table Box 11.1.1, Table 11.14, Box 11.6)
Dynamic adaptive decision-making	Increased understanding and use of decision-making tools to address uncertainties and changing risks, such as scenario planning and DAPP to enable effective adaptation as climate risk profiles worsen (11.7.3.1, 11.7.3.2, Table 11.14, Table 15b, Table 11.18, Box 11.4, Box 11.6)
Funding mechanisms	Adaptation funding framework to increase investment in adaptation actions New private-sector financial instruments to support adaptation (11.7.1, 11.7.2, Table 11.16)
Reducing systemic vulnerabilities	Economic and social policies that reduce income and wealth inequalities Strengthening social capital and cohesion Identifying and redressing rigid or fragmented administrative and service delivery systems Reviewing land use and spatial planning to reduce exposure to climate risks Restoring degraded ecosystems and avoiding further environmental degradation and loss. (11.1.1, 11.1.2, 11.3.5, 11.3.11, 11.4.1, 11.5.1.3, 11.7.2, 11.8.1; Table 11.10, Table 11.13)

path dependencies and potential lock-in of decisions, system dependencies and the potential for cascading impacts (Table 11.17) (Wilson et al., 2013; Clarvis et al., 2015; Pearson et al., 2018; Cradock-Henry et al., 2020b; Lawrence et al., 2020b). Modelling and tools to test the robustness and cost-effectiveness of options (Infometrics and PSConsulting, 2015; Qin and Stewart, 2020) can be used alongside adaptation strategies with decision-relevant and usable information (Smith et al., 2016; Tangney, 2019; Serrao-Neumann et al., 2020), particularly when supported by effective governance and national and sub-national guidance (Box 11.6).

More inclusive, collaborative and learning-oriented community engagement processes are fundamental to effective adaptation outcomes (11.7.3.2) (*very high confidence*) (Boston, 2016; Lawrence and Haasnoot, 2017; Sellberg et al., 2018; Serrao-Neumann et al., 2019a; Simon et al., 2020). More participatory vulnerability and risk assessments can better reflect different knowledge systems, values, perspectives, trade-offs, dilemmas, synergies, costs and risks (Jacobs et al., 2019; Ogier et al., 2020; Tonmoy et al., 2020). A shift from hierarchical to more cooperative governance modalities can assist effective adaptation (Vermeulen et al., 2018; Steffen et al., 2019; CoA, 2020e; Lawrence et al., 2020b; MfE, 2020a; Hanna et al., 2021).

Regular monitoring, evaluation, communication and coordination of adaptation are essential for accelerating learning and adjusting to dynamic climate impacts and changes in socioeconomic and cultural conditions (*high confidence*) (Moloney and McClaren, 2018; Palutikof et al., 2019a; Cradock-Henry et al., 2020a). Training to improve decision makers' 'evaluative capacity' can play a role (Scott and Moloney, 2021). Climate action benchmarking, diagnostic tools and networking can enhance the adaptation process across diverse decision settings (e.g., water, coasts, protected areas and Indigenous Peoples) (Ayre and Nettle, 2017; Davidson and Gleeson, 2018; Coenen et al., 2019; Gibbs, 2020). Effective adaptation requires cross-jurisdictional and cross-sectoral policy coherence and national coordination (Delany-Crowe et al., 2019; Rychetnik et al., 2019; MfE, 2020c).

11.7.3.2 Attitudes, Engagement and Accessible Information as Enablers

Concern for climate change has become widespread (Hopkins, 2015; Borchers Arriagada et al., 2020), giving climate adaptation social legitimacy (*high confidence*). Over three quarters of Australians (77%) agree that climate change is occurring, and 61% believe climate change is caused by humans (Merzian et al., 2019). A growing proportion of Australians perceive links between climate change and high temperatures experienced during heatwaves and extremely hot days (Summer 2018/2019) (48%), droughts and flooding (42%) and urban water shortages (30%) (Merzian et al., 2019). Rural populations in NSW perceive climate change impacts as stressing their well-being and mental health and requiring leadership and action (Austin et al., 2020). In New Zealand, between 2009 and 2018, the proportion of New

Table 11.18 | Examples of adaptation decision tools

Tools	Application	Source
Scenario analysis, modelling, futures narratives	For futures planning in coastal, urban, agriculture and health sectors	(Randall et al., 2012; Jones et al., 2013; CSIRO, 2014; Bosomworth et al., 2015; Infometrics and PSConsulting, 2015; Knight-Lenihan, 2016; Maier et al., 2016; Stephens et al., 2017; B. Frame et al., 2018; Stephens et al., 2018; Ausseil et al., 2019a; Coulter et al., 2019; Serrao-Neumann et al., 2019b)
Dynamic Adaptive Pathways Planning (DAPP)	For conditions of deep uncertainty for short-term and long-term options and flexibility, and with communities	(Cradock-Henry et al., 2018b; Cradock-Henry et al., 2020a) (agriculture); (Lawrence et al., 2019b) (flood risk management) (Lawrence and Haasnoot, 2017; Colliar and Blackett, 2018) (coastal communities) (Tasmanian Climate Change Office, 2012; Lin et al., 2017; Ramm et al., 2018) (capacity building) (Moran et al., 2014; Colloff et al., 2016; Dunlop et al., 2016; Bosomworth et al., 2017) (natural resource, management) (Hadwen et al., 2012; Barnett et al., 2014; Fazey et al., 2015; Lazarow, 2017; Ramm et al., 2018) (coastal) (Siebentritt et al., 2014; Zografos et al., 2016) (regional development) (Maru et al., 2014) (disadvantaged communities) (Hertzler et al., 2013; Sanderson et al., 2015) (agriculture) (Ren et al., 2011) (infrastructure and resilient cities) (Cunningham et al., 2017) (social network analysis with communities)
Serious Games	To catalyse learning, raise awareness and explore attitudes and values	(Lawrence and Haasnoot, 2017; Colliar and Blackett, 2018; Flood et al., 2018; Edwards et al., 2019)
Signals and Triggers for monitoring DAPP	For where there is near-term certainty and longer-term deep uncertainty (e.g., SLR)	(Stephens et al., 2017; Stephens et al., 2018)
Shared Socioeconomic Pathways	For where there is deep uncertainty and scenarios are used	(B. Frame et al., 2018)
Hybrid Multi-criteria analysis and DAPP (deep uncertainty)	For conditions of deep uncertainty for short-term and long-term options and flexibility desired	(Lawrence et al., 2019a)
Real Options Analysis (ROA)	For conditions of deep uncertainty	(Infometrics and PSConsulting, 2015; Infometrics, 2017; Lawrence et al., 2019a; Wreford et al., 2020)
Scenario-based cost-benefit analysis	For conditions of deep uncertainty	(Guthrie, 2019)
Portfolio analysis	For uncertainties in the land use sector	(Monge et al., 2016; Awatere et al., 2018; West et al., 2021)
Cost Benefit Analysis	Where decisions can be easily reversed	(Hadwen et al., 2012; Little and Lin, 2015; Stewart, 2015; Luo et al., 2017; Thamo et al., 2017)
Vulnerability assessment	For assessing and prioritising physical and social place-based risks, using indices, modelling and participatory approaches	(Ramm et al., 2017; Moglia et al., 2018; Pearce et al., 2018; Tonmoy and El-Zein, 2018)
Statutory tools	For planning direction For planning and design of adaptation	(DoC NZ, 2010; DoC NZ, 2017a; DoC NZ, 2017b; NSW Government, 2018) (MfE, 2017a)
Standards	For adaptation best practice	(ISO, 2019)
Jurisprudence	For adaptation implementation and legal interpretation	(O'Donnell and Gates, 2013; McAdam, 2015; Iorns Magallanes and Watts, 2019; Peel et al., 2020)
Guidance	For adaptation and use of uncertainty tools	(CSIRO and BOM, 2015; MfE, 2017a; Lawrence et al., 2018b; Palutikof et al., 2019b)
Information delivery and decision support portal	For adaptation decision making	https://coastadapt.com.au/
Monitoring, evaluation and reporting on adaptation progress (incl. adaptation indices and web-based tools)	For local government, private sector and finance sector to benchmark, track progress	(Goodhue et al., 2012; Little et al., 2015; IGCC, 2017; Lawrence et al., 2020a; LGAQ and DES, 2020; Rogers et al., 2020b; WAGA, 2020) (Moloney and McClaren, 2018)

Zealanders who agreed or strongly agreed that climate change is real increased from 58% to 78% (a 34.5% increase), while those agreeing or strongly agreeing that it was caused by humans increased from 41% to 64% (a 56.1% increase) (Milfont et al., 2021). Nevertheless, New Zealanders have a tendency to overestimate the amount of sea level rise (SLR), especially among those most concerned about climate change and incorrectly associate it with melting sea ice, which has implications for engagement and communication strategies (Priestley et al., 2021).

The use of more systemic, collaborative and future-oriented engagement approaches is facilitating adaptation in local contexts (*high confidence*) (Rouse et al., 2013; MfE, 2017a; Leitch et al., 2019). Local 'adaptation champions' and experimental and tailored engagement processes can enhance learning (McFadgen and Huitema, 2017; Lindsay et al., 2019). Dynamic adaptive pathways planning (Lawrence et al., 2019a) and inclusive community governance (Schneider et al., 2020) can help progress difficult decisions such as the relocation of cultural assets and managed retreat, and contestation about which public goods

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to prioritise and how adaptation should be implemented (Kwakkel et al., 2016) (Colliar and Blackett, 2018). Participatory climate change scenario planning can test assumptions about the present and the future (Mitchell et al., 2017; Serrao-Neumann and Choy, 2018; Chambers et al., 2019; Serrao-Neumann et al., 2019c) and help envision people-centred, place-based adaptation (Barnett et al., 2014; Lindsay et al., 2019). Social network analysis can inform engagement and communication of adaptation (Cunningham et al., 2017). Knowledge brokers, information portals and alliances can help communities, governments and sector groups to better access and use climate change information (Shaw et al., 2013; Fünfgeld, 2015; Lawrence and Haasnoot, 2017). Novel approaches to building climate change literacy and adaptation capability go hand in hand with dedicated expert organisational support (Stevens and O'Connor, 2015; CCATWG, 2018; Palutikof et al., 2019c; Salmon, 2019). All of these approaches depend on adequate resourcing (*very high confidence*).

11.7.3.3 Knowledge Gaps and Implementation Enablers

There are two priority areas where new knowledge is critical for accelerating adaptation implementation.

1) *System complexity and uncertainty in observed and projected impacts*

- Regionally relevant projections of rainfall, runoff, compound and extreme weather (11.2.1, 11.3.3; Box 11.4)
- Inclusion of cascading and compounding impacts in integrated assessments (11.5.1), including for infrastructure (11.3.5), tourism (11.3.7) and health (11.3.6) and for different groups, including Aboriginal and Torres Strait Islander Peoples and Tangata Whenua Māori communities (11.4)
- Impacts on terrestrial and freshwater ecosystems, including *in situ* monitoring to detect ongoing changes especially in New Zealand (11.3.1), and marine biodiversity, including environmental tolerances of key life stages (11.3.2)
- Repository of indigenous species distribution data for monitoring responses to climate change and climate advisory services for New Zealand (11.3.1.3)
- National risk assessment for Australia (11.7.1)
- The interactions between adaptation and mitigation, particularly where land carbon mitigation is impacted by climate change (11.3.4.3; Box 11.5)

2) *Supporting adaptation decision making*

- Better understanding of who and what is exposed and where and their vulnerability to climate hazards (11.3, 11.4)
- National assessments of the costs and benefits of climate change, with and without different levels and timings of adaptation and mitigation (11.5.2.3) (11.7.1)
- Understanding available adaptation strategies and options, their feasibility and effectiveness as the climate changes, including their intended and unintended outcomes (11.7, 11.8)
- Understanding how to embed robust planning approaches into decision making that retain flexibility to change course in the future (11.7.1).
- Mechanisms for sharing knowledge and practice of adaptation (11.7).
- The role of development paradigms, values and political economy in adaptation framing and effective implementation (11.8).
- Understanding social transitions and social licence, for timely, robust and transformational adaptation (11.8.2).

11.8 Climate Resilient Development Pathways

Adaptation to climate risks and global mitigation of greenhouse emissions determine whether development pathways are climate-resilient (Chapter 18). In the near term, progress towards climate resilient development can be monitored by progress on the SDGs. According to government reports (Figure 11.6) (OECD, 2019a), current and projected trajectories fall short of meeting all targets (Allen et al., 2019). Key climate risks for the region (11.6, Table 11.14) affect all of the SDGs, and pre-existing societal inequalities exacerbate climate risks (11.3.5). Projected climate risks combined with underlying SDG indicators will increasingly impede the region's capacity to achieve and maintain a number of SDGs, including sustainable agriculture, affordable and clean energy, sustainable cities and communities, life below water and life on land (OECD, 2019a). Reducing these risks would require significant and rapid emission reductions to keep global warming to 1.5°C–2.0°C and robust and timely adaptation (IPCC, 2018).

11.8.1 System Adaptations and Transitions

A step change in adaptation action is needed to address climate risks and to be consistent with climate resilient development (*very high confidence*). Current adaptation falls short on the assessment of complex risks, implementation, monitoring and evaluation. It is largely incremental and temporary given the scale of projected impacts; it has limits and is mainly reactive rather than anticipatory. Furthermore, risks are projected to cascade and compound, with impacts and costs that challenge adaptive capacities (11.5) and call for transformational responses (11.6, Table 11.15a, Table 11.15b; Supplementary Tables SM11.1a and SM11.1b).

Current global emissions reduction policies are projected to lead to a global warming of 2.1°C–3.9°C by 2100 (Liu and Raftery, 2021), leaving many of the region's human and natural systems at very high risk and beyond adaptation limits (*high confidence*). With higher levels of warming, adaptation costs increase, loss and damages grow, and governance and institutional responses reduce adaptive capacity. Underlying social and economic vulnerabilities and injustices further reduce adaptive capacity, exacerbating disadvantage in particular groups in society. Sustainable development across and beyond the region will help reduce shared adaptation challenges (11.5.1.2). Effective adaptation avoids lock-in and path dependency, reduces vulnerabilities, increases flexibility to change, builds adaptive capacity and advances SDGs, thereby improving intra- and intergenerational justice (11.5, 11.6, 11.7). Reducing greenhouse gas emissions and structural inequalities is key to achieving the SDGs and contributing to climate resilient development.

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Integrated and inclusive adaptation decision-making can contribute to climate resilient development by better mediating competing values, interests and priorities and helping to reconcile short- and long-term objectives, as well as public and private costs and benefits, in the face of rapidly and continuously changing risk profiles (*very high confidence*) (Gorddard et al., 2016; MfE, 2017a; Schlosberg et al., 2017) (11.5.2). Use of new tools and approaches (Table 11.18) to address system interactions that match the scale and scope of the problem can result in more effective adaptation, including proactive and anticipatory governance and institutional enablers (11.7, Table 11.17) (Schlosberg et al., 2017; Boston and Lawrence, 2018). Building cities and settlements that are resilient to the impacts of climate change requires the simultaneous consideration of infrastructural, ecological, social, economic, institutional and political dimensions of resilience, including political will, leadership, commitment, community support, multi-level governance and policy continuity (Torabi et al., 2021).

11.8.2 Challenges for Climate Resilient Development Pathways

Implementing enablers can help drive adaptation ambition and action consistent with climate resilient development (*very high confidence*) (11.7.3, Table 11.17). However, the scale and scope of cascading, compounding and aggregate impacts (11.5.1) calls for new and timely adaptation, including more effective ongoing monitoring, evaluation, review and continual adjustment (11.7.3) towards the transformations that can break through the path dependencies that define the way things are done now (Cradock-Henry et al., 2018b; UN et al., 2018; Head, 2020). However, complex interactions between objectives can create social and economic trade-offs (Table 11.1, 11.3.5.3, 11.7.3.1, Box 11.6).

Delay in implementing climate change adaptation and emissions reductions will impede climate resilient development, resulting in more costly climate impacts and greater scale of adjustments in the future

Frequently Asked Questions

FAQ 11.1 | How is climate change affecting Australia and New Zealand?

Climate change is affecting Australia and New Zealand in profound ways. Some natural systems of cultural, environmental, social and economic significance are at risk of irreversible change. The socioeconomic costs of climate change are substantial, with impacts that cascade and compound across sectors and regions, as demonstrated by heatwaves, wildfire, cyclone, drought and flood events.

Temperature has increased by 1.4°C in Australia and 1.1°C in New Zealand over the last 110 years, with more extreme hot days. The oceans in the region have warmed significantly, resulting in longer and more frequent marine heatwaves. Sea levels have risen and the oceans have become more acidic. Snow depths have declined and glaciers have receded. Northwestern Australia and most of southern New Zealand have become wetter, while southern Australia and most of northern New Zealand have become drier. The frequency, severity and duration of extreme wildfire weather conditions have increased in southern and eastern Australia and northeastern New Zealand.

The impacts of climate change on marine, terrestrial and freshwater ecosystems and species are evident. The mass mortality of corals throughout the Great Barrier Reef during marine heatwaves in 2016–2020 is a striking example. Climate change has contributed to the unprecedented south-eastern Australia wildfires in the spring and summer of 2019–2020, loss of alpine habitats in Australia, extensive loss of kelp forests, shifts further south in the distribution of almost 200 marine species, decline and extinction in some vertebrate species in the Australian wet tropics, expansion of invasive plants, animals and pathogens in New Zealand, erosion and flooding of coastal habitats in New Zealand, river flow decline in southern Australia, increased stress in rural communities, insurance losses for floods in New Zealand, increase in heatwave mortalities in Australian capital cities and fish deaths in the Murray-Darling River in the summer of 2018–2019.

Frequently Asked Questions

FAQ 11.2 | What systems in Australia and New Zealand are most at risk from ongoing climate change?

The nine key risks to human systems and ecosystems in Australia and New Zealand from ongoing climate change are shown in Figure FAQ 11.2.1. Some risks, especially on ecosystems, are now difficult to avoid. Other risks can be reduced by adaptation if global mitigation is effective.

Risk is the combination of hazard, exposure and vulnerability. For a given hazard (e.g., fire), the risk will be greater in areas with high exposure (e.g., many houses) and/or high vulnerability (e.g., remote communities with limited escape routes). The severity and type of climate risk varies geographically (Figure FAQ11.2.1). Everyone will be affected by climate change, with disadvantaged and remote people and communities the most vulnerable.

Box FAQ 11.2 (continued)

The risks to natural and human systems are often compounded by impacts across multiple spatial and temporal scales. For example, fires damage property, farms, forests and nature with short- and long-term effects on biodiversity, natural resources, human health, communities and the economy. Major impacts across multiple sectors can disrupt supply chains to industries and communities and constrain delivery of health, energy, water and food services. These impacts create challenges for the adaptation and governance of climate risks. When combined, they have far-reaching socioeconomic and environmental impacts.

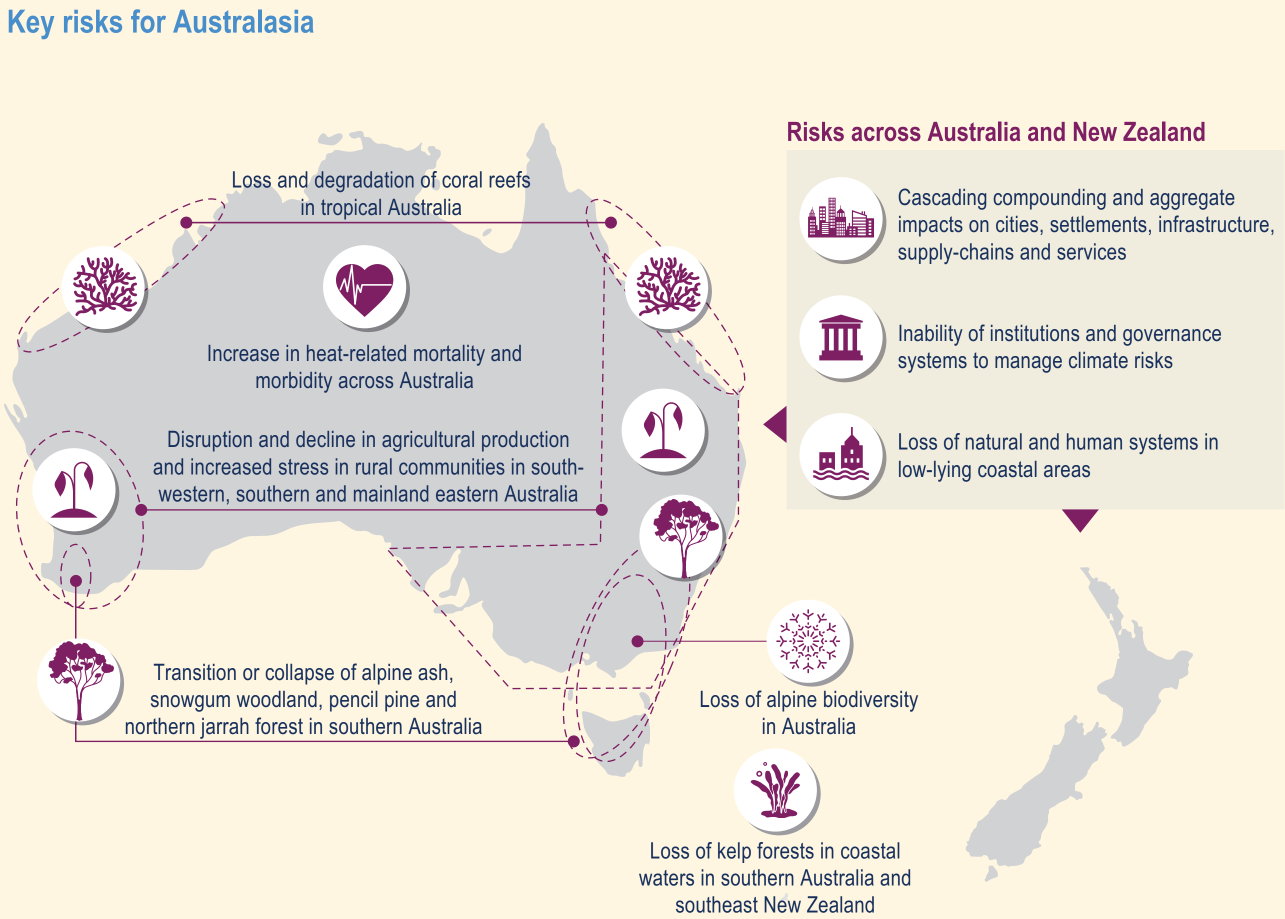

Figure FAQ11.2.1 | Key risks from climate change

Frequently Asked Questions

FAQ 11.3 | How can Indigenous Peoples' knowledge and practice help us understand contemporary climate impacts and inform adaptation in Australia and New Zealand?

In Australia and New Zealand, as with many places around the world, Indigenous Peoples with connections to their traditional country and extensive histories hold deep knowledge from observing and living in a changing climate. This provides insights that inform adaptation to climate change.

Indigenous Australians—Aboriginal and Torres Strait Islanders—maintain knowledge regarding previous sea level rise, climate patterns and shifts in seasonal change associated with the flowering of trees and emergence of food sources, developed over thousands of generations of observation of their traditional country. Knowledge of localised contemporary adaptation is also held by many Indigenous Australians with connections to traditional lands. With assured free and prior informed consent, this provides a means for Indigenous-guided land management, including for fire management and carbon abatement, fauna studies, medicinal plant products, threatened species recovery, water management and weed management.

Tangata Whenua Māori in New Zealand are grounded in Mātauranga Māori knowledge, which is based on human–nature relationships and ecological integrity and incorporates practices used to detect and anticipate changes taking place in the environment. Social-cultural networks and conventions that promote collective action and mutual support are central features of many Māori communities and these customary approaches are critical to responding to, and recovering from, adverse environmental conditions. Intergenerational approaches to planning for the future are also intrinsic to Māori social-cultural organisation and are expected to become increasingly important, elevating political discussions about conceptions of rationality, diversity and the rights of non-human entities in climate change policy and adaptation.

Frequently Asked Questions

FAQ 11.4 | How can Australia and New Zealand adapt to climate change?

There is already work under way by governments, businesses, communities and Indigenous Peoples to help us adapt to climate change. However, much more adaptation is needed in light of the ongoing and intensifying climate risks. This includes coordinated laws, plans, guidance and funding that enable society to adapt and the information, education and training that can support it. Everyone has a part to play working together.

We currently mainly react to climate events such as wildfires, heatwaves, floods and droughts and generally rebuild in the same places. However, climate change is making these events more frequent and intense, and ongoing sea level rise and changes in natural ecosystems are advancing. Better coordination and collaboration between government agencies, communities, Aboriginal and Torres Strait Islanders and Tangata Whenua Indigenous Peoples, not-for-profit organisations and businesses will help prepare for these climate impacts more proactively, in combination with future climate risks integrated into their decisions and planning. This will reduce the impacts we experience now and the risks that will affect future generations.

Some of the risks for natural systems are close to critical thresholds and adaptation may be unable to prevent ecosystem collapse. Other risks will be severe, but we can reduce their impact by acting now, for example coastal flooding from sea level rise, heat-related mortality and managing water stresses. Many of the risks have the potential to cascade across social and economic sectors with widespread societal impacts. In such cases, really significant system-wide changes will be needed in the way we currently live and govern. To facilitate such changes, new governance frameworks, nationally consistent and accessible information, collaborative engagement and partnerships with all sectors, communities and Indigenous Peoples and the resources to address the risks are needed (Figure FAQ11.4.1).

However, our ability to adapt to climate change impacts also rests on every region in the world playing its part in reducing greenhouse gas emissions. If mitigation is ineffective, global warming will be rapid and adaptation costs will increase, with worsening losses and damages.

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Box FAQ 11.4 (continued)

Adaptation pathways for Australia and New Zealand

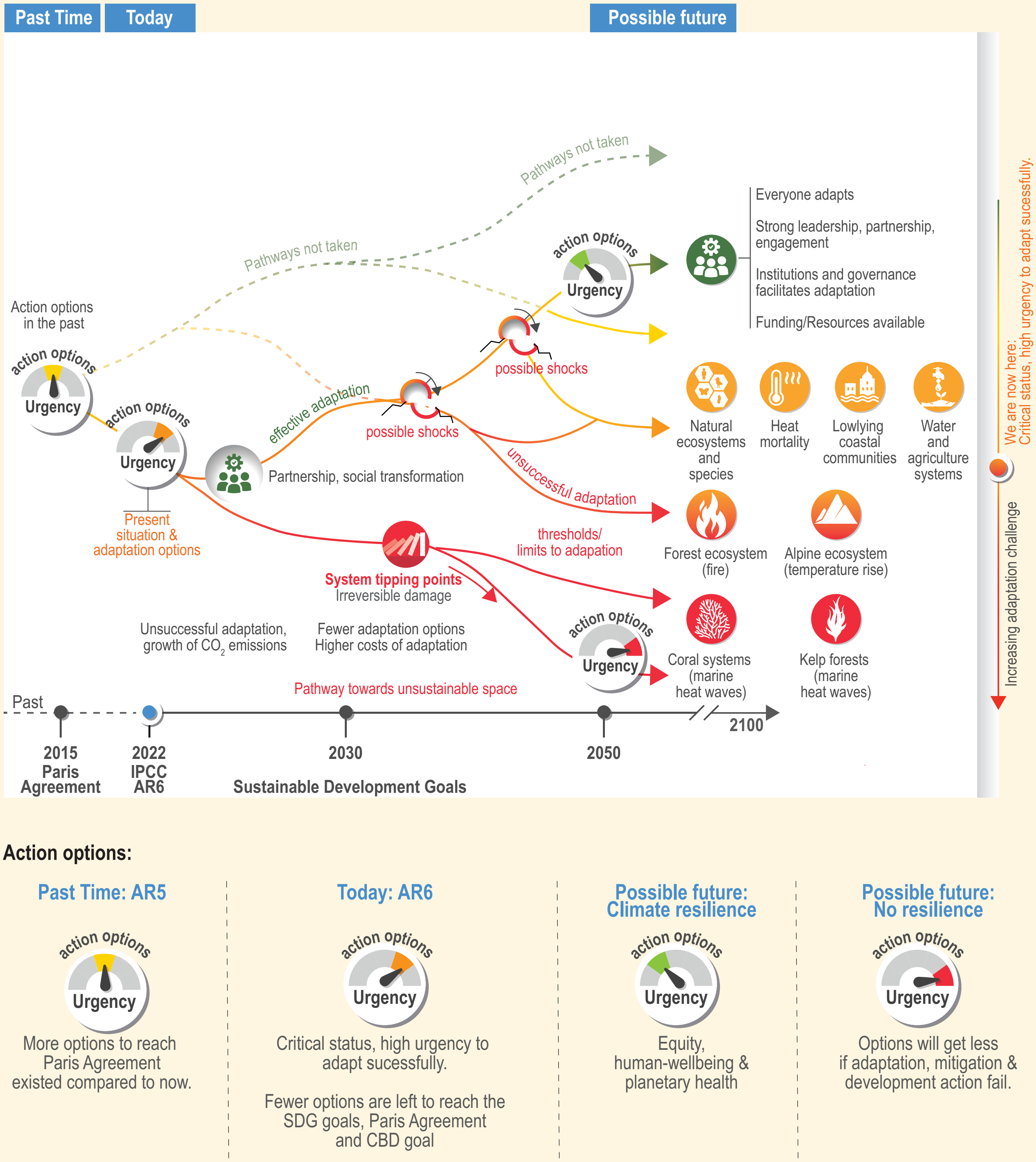

Figure FAQ11.4.1 | Developing adaptation plans in the solutions space showing system tipping points, thresholds and limits to adaptation, unsustainable pathways, critical systems and enablers to climate resilient development

(IPCC, 2018) (11.5.1, 11.5.2, Box 11.6) and legal risks for those with adaptation mandates and for financial institutions (11.5.1) (*very high confidence*). The scale and scope of societal change needed for the region to transition to more climate resilient development pathways requires close attention to governance, ethical questions, the role of civil society and the place of Aboriginal and Torres Strait Islander Peoples and Tangata Whenua Māori in the co-production of ongoing adaptation at multiple scales (Loorbach et al., 2017; Koehler et al., 2019; Hill et al., 2020).

The region faces an extremely challenging future that will be highly disruptive for many human and natural systems (IPCC, 2018) (UNEP, 2020; AAS, 2021; IPCC, 2021) (11.5.1, 11.6, 11.7; Boxes 11.1–11.6; Table 11.14). The extent to which the limits to adaptation are reached depends on whether global warming peaks this century at 1.5°C, 2°C or 3+°C above pre-industrial levels. Whatever the outcome, adaptation and mitigation are essential and urgent (*very high confidence*).

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