ANNEX 12

EXPERT OPINION OF PROFESSOR DR WIM THIERY, DR MARIE CAVITTE, AND AMAURY LARIDON

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Climate change attribution, projections of extreme weather events, and exposure risks for young generations in Australia

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Expert Report on attribution and projections of extreme events Over Australia and exposure for young generations.

Brussels, 02/06/2026

For this report, we were asked to address the following questions:

1. What attribution evidence exists regarding recent extreme events that occurred over Australia?
2. What is the current state of knowledge regarding future projections of climate and extreme events for Australia?
3. What percentage of Australia's surface area will be affected by heat waves per year under pathways leading to 1.5°C and 2.0°C of warming by 2100, and under Current Policies (2.8°C), respectively?
4. How many heat waves will young generations born in Australia face under pathways leading to 1.5°C and 2.0°C of warming by 2100, and under Current Policies (2.8°C), respectively?
5. How does the lifetime heat wave exposure for young generations compare with those for the 1950 birth cohort?
6. How many young people born in Australia between 1990 and 2020 will face unprecedented lifetime exposure to heat waves?

Question 1 is addressed through a review of the scientific literature. Question 2 is addressed through a review of two recent reports by the Intergovernmental Panel on Climate Change (IPCC), the Working group 1 and Working Group 2 contributions to the Sixth Assessment Report (AR6), published in 2021 and 2022, respectively. These IPCC reports themselves represent a critical assessment of the scientific literature on the topic and are approved by all governments constituting the IPCC. We note that the former report only assesses scientific publications accepted before 31 January 2021, while the latter report only assesses scientific publications accepted before 15 September 2021. Scientific publications published after these dates are therefore not considered in our review for Question 2.

Questions 3-6 are addressed through dedicated calculations by the author team of this report. The results are derived from three scientific studies conducted in the research team of the authors of this report: Thiery et al. (2021, *Science*)[1], Grant et al. (2025, *Nature*)[2], and Pietroiusti et al. (forthcoming)[3]. All results presented in response to the questions 1-4 are for Australia only.

[1] Thiery, W., Lange, S., Rogelj, J., Schleussner, C.-F., Gudmundsson, L., Seneviratne, S.I., Frieler, K., Emanuel, K., Geiger, T., Bresch, D.N., Zhao, F., Willner, S.N., Büchner, M., Volkholz, J., Andrijevic, M., Bauer, N., Chang, J., Ciais, P., Dury, M., François, L., Grillakis, M., Gosling, S.N., Hanasaki, N., Hickler, T., Huber, V., Ito, A., Jägermeyr, J., Khabarov, N., Koutroulis, A., Liu, W., Lutz, W., Mengel, M., Müller, C., Ostberg, S., Reyer, C.P.O., Stacke, T., Wada, Y., (2021) Intergenerational inequities in exposure to climate extremes, Science, 374(6564), 158-160. [pdf, Research highlights in Nature, Nature Climate Change, and The Lancet Planetary Health]. (This study introduces the lifetime extreme event exposure framework)

[2] Grant, L., Vanderkelen, I., Gudmundsson, L., Fischer, E., Seneviratne, S. I., and Thiery, W., (2025) Global emergence of unprecedented lifetime exposure to climate extremes, Nature, 641, 374–379, 2021. [pdf, Research highlights in Nature News and Views; Nature Editorial; Nature News]. (This study updates the global warming pathways feeding into the lifetime extreme event exposure framework to the latest generation)

[3] Pietroiusti, R., Hetzer, J., Turco, M., Prudencio Montano, S., Laridon, A., Lejeune, Q., Prapotny, D., Thiery, W., Increasing lifetime exposure to extreme fire weather under climate change in Portugal and Europe, in review. (This study updates the demographic data feeding into the lifetime extreme event exposure framework to the latest generation)

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1 Geographic division convention for Australia

To systematically analyse consistent spatial units, regional and sub-regional conventions are defined in the scientific literature. Throughout this report, we adopt (see Figure 1) the convention established in the IPCC Sixth Assessment Report (AR6).

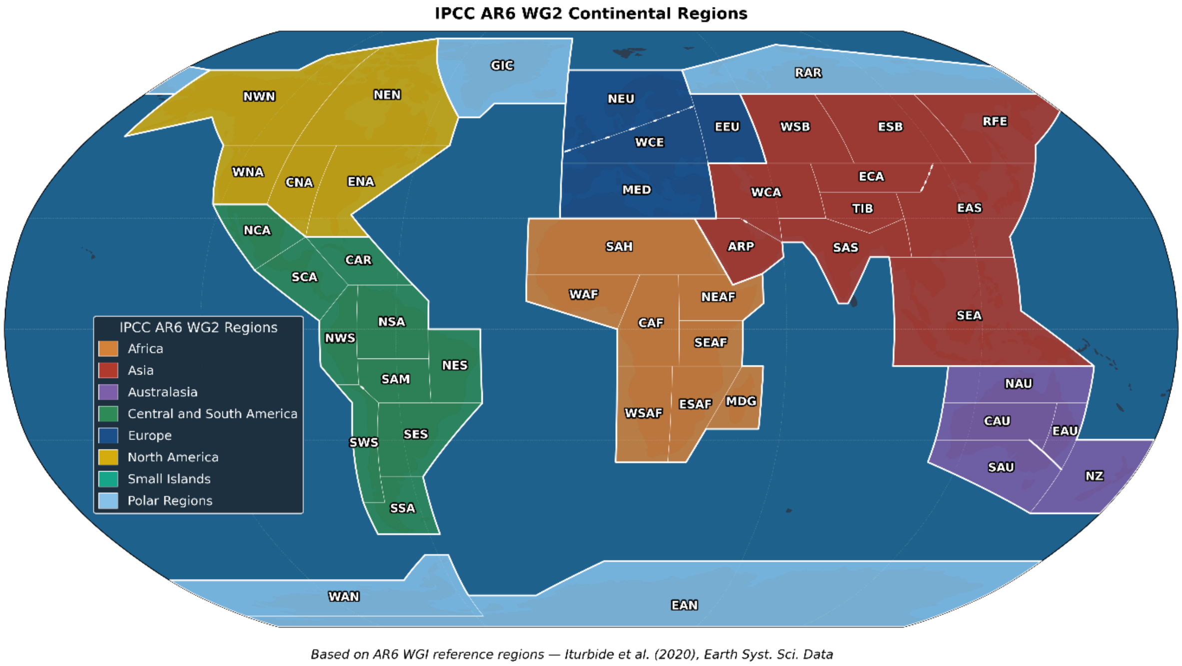


Figure 1. Continental regions adopted since IPCC AR6 in much of the scientific literature

Figure 2 illustrates the regional subdivisions encompassing Australia, along with the precise locations of the authors in this case.

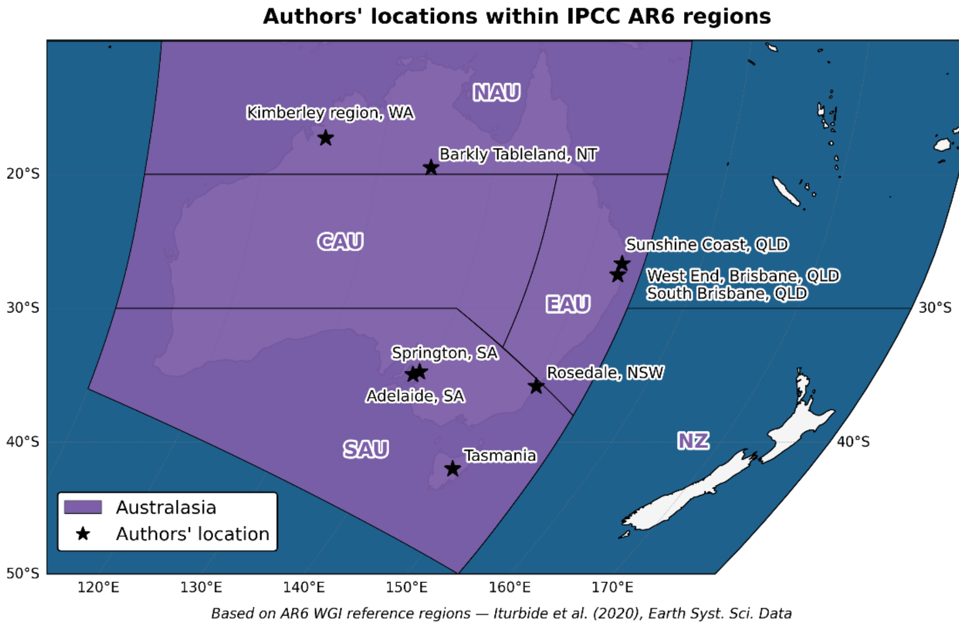


Figure 2. Regional subdivisions of Australasia containing Australia. Authors' locations are indicated by black stars.

2 Review of extreme event attribution studies over Australia

2.1 Attribution studies

We provide a review of all published attribution studies that attribute to climate change extreme climate events that occurred over Australia. We found 31 attribution studies focusing on extreme climate events in Australia concluding that climate change increased the intensity or likelihood of occurrence of the event. We list these studies in chronological order; *text in italics* provides extracts from the manuscripts where the extreme climate events are described, boxed statements reproduce the climate change attribution statements extracted from the respective manuscripts.

2.1.1 Lewis, S. C., and D. J.Karoly (2013)

Anthropogenic contributions to Australia's record summer temperatures of 2013, Geophys. Res. Lett., 40, 3705–3709, doi:10.1002/grl.50673.

This study describes the **extreme heat event during the Australian summer of 2012-2013**: *"The Australian summer of December 2012 to February 2013 was the hottest on record (Figure 1a), with average conditions exceeding the observed 1911–1940 mean by 1.32 K (Figure 1b). Summer temperature records were broken on daily through to seasonal timescales: the hottest month on record occurred as well as the hottest day for the entire Australian continent [Bureau of Meteorology, 2013a]. By late summer, sustained high temperatures were also coincident with bushfires in south-eastern Australia in Victoria and Tasmania, and severe flooding in north-eastern Australia in Queensland and New South Wales [Bureau of Meteorology, 2013b]. Conditions were so severe, it was dubbed the "angry summer" [Steffen, 2013]."*

> "It was very likely (>90% confidence) there was at least a 2.5 times increase in the odds of extreme heat due to human influences using simulations to 2005, and a fivefold increase in this risk using simulations for 2006–2020."

2.1.2 Knutson, T. et al., 2014

Multi-model assessment of extreme annual-mean warm anomalies during 2013 over regions of Australia and the western tropical Pacific [in "Explaining Extremes of 2013 from a Climate Perspective"]. Bull. Amer. Meteor. Soc., 95 (9), S34-S37, https://doi.org/10.1175/1520-0477-95.9.S1.1.

This study describes the **extreme heat that occurred over calendar year 2013**: *"A global survey of surface temperature anomalies occurring during 2013 […] reveals pronounced warm annual and seasonal mean anomalies. Two regions with prominent record or near-record annual mean warm anomalies include large regions of Australia and a region in the far western tropical Pacific encompassing the Philippines and part of the Maritime Continent (Fig. 8.1b). The 2013 anomalies appear particularly extreme during austral fall and winter (MAM, JJA) in Australia and during MAM in the far western Pacific."*

"CMIP5 simulations suggest that the extremely warm year observed over Australia and the far western Pacific during 2013 was largely attributable to human forcing of the climate system."

2.1.3 Lewis, L & Karoly, D., 2014

The role of anthropogenic forcing in the record 2013 Australia-wide annual and spring temperatures [in "Explaining Extremes of 2013 from a Climate Perspective"]. Bull. Amer. Meteor. Soc., 95 (9), S31-S34, https://doi.org/10.1175/1520-0477-95.9.S1.1.

This study describes the **extreme heat that occurred over calendar year 2013**: *"The 2013 Australian calendar year was the hottest in the observational record of over 100 years in terms of area-average mean surface air temperature (Fig. 9.1a). Averaged over Australia, the observed 2013 annual temperature exceeded the 1911–40 mean by 1.53°C (ΔTANN1), with the previous record anomaly of 1.36°C recorded in 2005 (ΔTANN2)."*

"Anthropogenic climate change has caused a very large increase in the likelihood of extreme events such as the record Australia-wide average temperatures in September, spring, and the 2013 calendar year."

2.1.4 Perkins, S. et al., 2014

Increased simulated risk of the hot Australian summer of 2012/13 due to anthropogenic activity as measured by heat wave frequency and intensity [in "Explaining Extremes of 2013 from a Climate Perspective"]. Bull. Amer. Meteor. Soc., 95 (9), S34-S37, https://doi.org/10.1175/1520-0477-95.9.S1.1.

This study describes the **extreme heat that occurred during summer 2012-2013**: *"The Australian summer of 2012/13 was the warmest since records began in 1910 (Bureau of Meteorology 2013a). The season was characterized by the hottest month on record (January), where the continental mean temperature reached 36.9°C. Averaged nationally, the last four months of 2012 were 1.61°C higher than the long-term mean."*

"Human activity has increased the risk of experiencing the hot Australian summer of 2012/13, as measured by simulated heat wave frequency and intensity, by two- and three-fold, respectively."

2.1.5 Arblaster, J et al., 2014

Understanding Australia's hottest September on record [in "Explaining Extremes of 2013 from a Climate Perspective"]. Bull. Amer. Meteor. Soc., 95 (9), S37-S41, https://doi.org/10.1175/1520-0477-95.9.S1.1.

This study describes the **extreme heat event in September 2013**: *"September 2013 was Australia's warmest September since records began in 1910, with anomalous heat across most of the country (Fig. 11.1a). Maximum temperatures, averaged nationally, were 3.32°C above the 1961–90 average—the highest anomaly for any month on record and almost a full degree ahead of the previous September record set in 1980 (Bureau of Meteorology 2013b). September marked the peak of a record warm* *period for Australia, which commenced in mid-2012. The most unusual heat began from the last week of August 2013 and continued into the first half of September. Temperatures moderated from 10 September before extreme heat returned to northern and eastern Australia in the final week of the month."*

"To the extent that global temperature changes have been attributed to anthropogenic climate change (Bindoff et al. 2014), a multi-step attribution process suggests that anthropogenic climate change played an important role in the record Australian maximum temperatures in September 2013."

2.1.6 King, A. et al., 2014

Climate change turns Australia's 2013 big dry into a year of record-breaking heat [in "Explaining Extremes of 2013 from a Climate Perspective"]. Bull. Amer. Meteor. Soc., 95 (9), S41-S45, https://doi.org/10.1175/1520-0477-95.9.S1.1.

This study describes the **extreme heat and drought event of 2013**: *"During 2013, Australia experienced its hottest year on record (23°C on average, 0.17°C above the previous 2005 record) as well as a series of extreme heat wave events […]. Besides being the hottest year in a record dating back to 1910, a drought set in across much of the east of the country leading the federal government to announce an AUD320 million (~USD 300 million) drought assistance package for affected farmers. The severe lack of water in the region came after the exceptionally wet 2010–12 period, which brought devastating floods to Queensland and New South Wales in particular. Across almost the entirety of Australia, maximum temperatures were warmer than average in 2013 (Fig. 12.1a), and for much of the continent, it was also considerably drier than average (Fig. 12.1b). The area of greatest rainfall deficit, covering inland eastern Australia, coincided with the region where the heat anomalies were strongest."*

"The record heat of 2013 across inland eastern Australia was caused by a combination of anthropogenic warming and extreme drought."

2.1.7 Cai, W. et al., 2014

Did Climate Change–Induced Rainfall Trends Contribute to the Australian Millennium Drought? Journal of Climate, 3145-3168, https://doi.org/10.1175/JCLI-D-13-00322.1.

This study describes the **extreme drought event over 2010-2011**: *"The Australian decade-long ''Millennium Drought'' broke in the summer of 2010/11 and was considered the most severe drought since instrumental records began in the 1900s."*

"Although climate models generally suggest that Australia's Millennium Drought was mostly due to multidecadal variability, some late-twentieth-century changes in climate modes that influence regional rainfall are partially attributable to anthropogenic greenhouse warming."

2.1.8 King, A. et al., 2015

Increased Likelihood of Brisbane, Australia, G20 Heat Event Due to Anthropogenic Climate Change [in "Explaining Extremes of 2014 from a Climate Perspective"]. Bull. Amer. Meteor. Soc., 96 (12), S141-144, https://doi.org/10.1175/BAMS-ExplainingExtremeEvents2014.1.

This study describes the **extreme heat event in the Australian spring of 2014**: *"During the G20 summit, there was unseasonably hot weather in Brisbane and southeast Queensland generally as part of Australia's hottest spring on record. The daytime maximum temperatures were well-above average from 14 to 16 November with Saturday (15th) and Sunday (16th) being the main days of the summit. The temperatures on 15 November surpassed 34°C and on the 16th reached close to 39°C. While these were not record hot temperatures they were well-above normal for late spring (the average being approximately 27°C for November in 1911–40) and attracted media attention."*

> "Climate model simulations for 2014 indicate anthropogenic climate change very likely increased the likelihood of hot and very hot November days in Brisbane by at least 25% and 44% respectively."

2.1.9 Black, M. et al., 2015

The Contribution of Anthropogenic Forcing to the Adelaide and Melbourne, Australia, Heat Waves of January 2014 [in "Explaining Extremes of 2014 from a Climate Perspective"]. Bull. Amer. Meteor. Soc., 96 (12), S145-S148, https://doi.org/10.1175/BAMS-ExplainingExtremeEvents2014.1.

This study describes the **extreme heat event in the month of January 2014**: *"Southeast Australia experienced one of the most significant heat waves on record in January 2014. A near-stationary high pressure system over the Tasman Sea directed very hot air from the interior of the continent to the southeast, where extreme temperatures persisted from 13 to 18 January. Records were broken for extended periods of heat at a number of locations (Australian Bureau of Meteorology 2014), including the major cities of Adelaide and Melbourne. Adelaide recorded five consecutive days above 42°C (13–17 January), while Melbourne recorded four consecutive days above 41°C (14–17 January)."*

> "Anthropogenic climate change very likely increased the likelihood of prolonged heat waves like that experienced in Adelaide in January 2014 by at least 16%. The influence for Melbourne is less clear."

2.1.10 Hope, P. et al., 2015

Contributors to the Record High Temperatures Across Australia in Late Spring 2014 [in "Explaining Extremes of 2014 from a Climate Perspective"]. Bull. Amer. Meteor. Soc., 96 (12), S149-S153, https://doi.org/10.1175/BAMS-ExplainingExtremeEvents2014.1.

The study describes the **extreme heat event in the spring of 2014**: *"Australia experienced in 2014 its highest springtime mean maximum temperature (Tmax) since records began in 1910. The Australian-mean Tmax was 2.32°C above the 1961–90 mean, and 0.26°C warmer than the previous record set in 2013 (Bureau of Meteorology 2014). While September was very warm, both October and November* *had the hottest Australia-average Tmax on record, with maximum temperatures 2.76°C and 2.18°C above their 1961–90 means, respectively, and the south-east was particularly warm"*

"The record warm Australian spring of 2014 would likely not have occurred without increases in CO_2 over the last 50 years working in concert with an upper-level wave train."

2.1.11 Perkins, S. & Gibson, P., 2015

Increased Risk of the 2014 Australian May Heatwave Due to Anthropogenic Activity [in "Explaining Extremes of 2014 from a Climate Perspective"]. Bull. Amer. Meteor. Soc., 96 (12), S154-S157, https://doi.org/10.1175/BAMS-ExplainingExtremeEvents2014.1.

This study describes the **extreme heat event across Australia in May 2014**: *"The year 2014 was the hottest globally on record (Deng 2015), and the third hottest on record for Australia (Bureau of Meteorology 2015). From 8–26 May, Australia experienced a 19-day heatwave, with the continentally averaged maximum temperature 2.52°C above the monthly mean (Bureau of Meteorology 2014)."*

"Anthropogenic activity has increased the risk of Australian heatwaves during late autumn similar to the 2014 event by up to 23-fold, compared to climate conditions under no anthropogenic influence."

2.1.12 Black, M. & Karoly, D., 2016

Southern Australia's Warmest October on Record: The Role of ENSO and Climate Change [in "Explaining Extremes of 2015 from a Climate Perspective"] Bull. Amer. Meteor. Soc., 97 (12), S118-S121, https://doi.org/10.1175/BAMS-D-16-0124.1

This study describes the **extreme heat event in October 2015 in Australia**: *"Australia experienced its warmest October on record in 2015 (Australian Bureau of Meteorology 2015). This was primarily the result of an early season heat wave in the beginning of the month, concentrated over southern Australia (SAUS; Fig. 23.1a). The monthly anomaly for maximum temperature over SAUS (5.16°C; Fig. 23.1b) was the largest ever recorded for the region for any month of the year. This unseasonably warm weather over SAUS led to an early start to the bushfire season and caused significant crop losses across one of Australia's most important agricultural regions, the Murray–Darling basin"*

"Anthropogenic climate change was found to have a substantial influence on southern Australia's extreme heat in October 2015. The relative influence of El Niño conditions was less clear"

2.1.13 Hope, P. et al., 2016

What Caused the Record-Breaking Heat Across Australia in October 2015? [in "Explaining Extremes of 2015 from a Climate Perspective"] Bull. Amer. Meteor. Soc., 97 (12), S122-S126, https://doi.org/10.1175/BAMS-D-16-0141.1.

This study also describes the **extreme heat event in October 2015 in Australia**: *"In 2015, Australia experienced another exceptionally warm spring, making the spring seasons of 2013, 2014, and 2015* *the three warmest from 105 years of record (Trewin 2013). In 2015, October was the most extreme month (Fig. 24.1a), with the largest monthly mean daily maximum temperature (AusTmax) anomaly (+3.44°C, relative to 1961–90; 33.54°C absolute) of any month, surpassing the September 2013 AusTmax record of +3.41°C. The monthly mean daily minimum temperature was also a record high for October (+2.34°C), and the fourth largest positive anomaly of any month. More than half of the continent (54.7%) recorded the highest-on-record October maximum temperatures, exceeding the previous record of 22.3% in 1988"*

"Using a seasonal forecasting framework for attribution, we find that half of the record heat anomaly across Australia in October 2015 can be attributed to increasing CO_2, with much of the rest due to internal atmospheric variability."

2.1.14 Karoly, D. et al., 2016

The Roles of Climate Change and El Niño in the Record Low Rainfall in October 2015 in Tasmania, Australia [in "Explaining Extremes of 2015 from a Climate Perspective"] Bull. Amer. Meteor. Soc., 97 (12), S127-S130, doi:10.1175/BAMS-D-16-0139.1.

This study describes the **extreme drought event in October 2015 in Tasmania, Australia**: *"The island state of Tasmania, in southeast Australia, received record low average rainfall of 21 mm in October 2015, 17% of the 1961–90 normal (Fig. 25.1a; Bureau of Meteorology 2015). This had major impacts across the state, affecting agriculture and hydroelectric power generation and preconditioning the landscape for major bushfires the following summer (Hobday et al. 2016)."*

"Anthropogenic climate change and El Niño made small but significant contributions to increasing the likelihood of record low rainfall in October 2015 in Tasmania. Atmospheric variability was the main contributor."

2.1.15 World Weather Attribution, 2016

Great Barrier reef bleaching, 2016 (rapid study), https://www.worldweatherattribution.org/great-barrier-reef-bleaching-march-2016.

This study describes the **extreme coral bleaching event that affected 93% of the Great Barrier Reef by March 2016**: *"Daily sea surface temperature anomalies in March 2016 show unusual warmth around much of Australia."*

"We found that climate change has dramatically increased the likelihood of very hot March months like that of 2016 in the Coral Sea. We estimate that there is at least a 175 times increase in likelihood of hot March months because of the human influence on the climate."

2.1.16 King, A. et al. 2017

Extreme heat in southeast Australia, February 2017, World Weather Attribution (rapid study), https://www.worldweatherattribution.org/extreme-heat-australia-february-2017.

This study describes the **extreme heat event in southeast Australia in February 2017**: *"New South Wales, southeastern Australia, its hottest summer on record in 2017. Temperature records across the central and the eastern parts of Australia were broken, leading the Australian Bureau of Meteorology to issue a Special Climate Statement on the exceptional heat."*

"[…] we see that average summer temperatures like those seen during 2016-2017 are now at least 50 times more likely in the current climate than in the past, before global warming began. […] maximum summer temperatures like those seen during 2016-2017 are now at least 10 times more likely in the current climate than in the past, before global warming began."

2.1.17 Oliver, E. et al., 2017

The unprecedented 2015/16 Tasman Sea marine heatwave. Nat. Commun. 8, 16101, doi:10.1038/ncomms16101.

This study describes the **extreme marine heatwave in the Tasman Sea over 2015/2016**: *"This marine heatwave lasted for 251 days reaching a maximum intensity of 2.9 °C above climatology."*

"Global climate models indicate it is very likely to be that the occurrence of an extreme warming event of this duration or intensity in this region is respectively ≥330 times and ≥6.8 times as likely to be due to the influence of anthropogenic climate change."

2.1.18 Tett, S.F.B. et al., 2018

Anthropogenic Forcings and Associated Changes in Fire Risk in Western North America and Australia During 2015/16 [in "Explaining Extreme Events of 2016 from a Climate Perspective"]. Bull. Amer. Meteor. Soc., 99 (1), S60-S64, https://doi.org/10.1175/BAMS-ExplainingExtremeEvents2016.1.

This study describes the **extreme wildfires that occurred in Australia over summer of 2015/2016**: *"During the Australian summer of 2015/16, the country experienced high numbers of bushfires: the southwest and southeast of the country were most affected with more than 100000 hectares of vegetation burned in Tasmania (ABC News 2016a). Over the course of this summer, 408 residential and 500 non-residential buildings were destroyed nationwide. This fire season was moderately destructive with insured losses of about AUD $350 million (ABC News 2016b)"*

"Extreme vapor pressure deficits (VPD) have been associated with enhanced wildfire risk. Using one model, we found for 2015/16 that human influences quintupled the risk of extreme VPD for western North America and increased the risk for extratropical Australia."

2.1.19 Perkins-Kirkpatrick, S. et al., 2018

The Role of Natural Variability and Anthropogenic Climate Change in the 2017/18 Tasman Sea Marine Heatwave [in "Explaining Extreme Events of 2017 from a Climate Perspective"]. Bull. Amer. Meteor. Soc., https://doi.org/10.1175/BAMS-D-18-0116.1.

This study describes the **extreme marine heatwave in the Tasman Sea over 2017/2018**: *"Commencing in November 2017, a marine heatwave (MHW) developed over a very large area extending from west of Tasmania to east of New Zealand (ABoM and NIWA 2018)."*

"Two GCM ensembles indicate that the record sea surface temperatures during the 2017/18 Tasman Sea marine heatwave were virtually impossible without anthropogenic influence. However, natural variability was important in the atmospheric initiation of the event."

2.1.20 Oliver, E. et al., 2018

Anthropogenic and Natural Influences on Record 2016 Marine Heat waves [in "Explaining Extreme Events of 2016 from a Climate Perspective"]. Bull. Amer. Meteor. Soc., 99 (1), S44-S48, https://doi.org/10.1175/BAMS-D-17-0093.1.

This study describes the **extreme marine heat waves of 2016**: *"In 2016 a quarter of the ocean surface experienced either the longest or most intense marine heatwave (Hobday et al. 2016) since satellite records began in 1982. Here we investigate two regions— Northern Australia (NA) and the Bering Sea/Gulf of Alaska (BSGA)—which, in 2016, experienced their most intense marine heat waves (MHWs) in the 35-year record. The NA event triggered mass bleaching of corals in the Great Barrier Reef (Hughes et al. 2017)."*

"Two of the longest and most intense marine heat waves in 2016 were up to fifty times more likely due to anthropogenic climate change."

2.1.21 Lewis, C. & Mallela, J., 2018

A Multifactor Risk Analysis of the Record 2016 Great Barrier Reef Bleaching [in "Explaining Extreme Events of 2016 from a Climate Perspective"]. Bull. Amer. Meteor. Soc., 99 (1), S144-S149, https://doi.org/10.1175/BAMS-D-17-0074.1.

This study also describes the **extreme marine heat wave of 2016**: *"The 2016 global coral bleaching event was severe: 93% of the northern, 700km stretch, of the Australian Great Barrier Reef (GBR) coral was bleached and by June, >60% of this coral was killed in association with heat stress (Hughes et al. 2017; Fig. ES28.1)."*

"Anthropogenic greenhouse gases likely increased the risk of the extreme Great Barrier Reef bleaching event through anomalously high sea surface temperature and the accumulation of thermal stress."

2.1.22 Lewis, S. C. et al., 2019

Deconstructing Factors Contributing to the 2018 Fire Weather in Queensland, Australia [in "Explaining Extreme Events of 2018 from a Climate Perspective"]. Bull. Amer. Meteor. Soc., https://doi.org/10.1175/BAMS-D-19-0144.1.

This study describes the **extreme wildfires in Queensland, Australia, over 2018**: *"Significant wildfires occurred across various regions in 2018. The 2018 bushfire season was declared early in many Australian jurisdictions. By 30 November 2018, 130 bushfires in Queensland, northern Australia, had caused significant damage and burned nearly 3/4 million hectares (see Australian Bureau of Meteorology 2018). Bushfires on the scale of the 24 to 29 November event (hereafter simply called "the fires") occurring in this coastal Queensland location (see Fig. 1) were unprecedented."*

"Factors including the circulation pattern and antecedent conditions contributed to 2018 northeast Australian fires. High background temperatures also played a role for which model evidence suggests an anthropogenic influence."

2.1.23 Wang, G. et al., 2021

An Initialized Attribution Method for Extreme Events on Subseasonal to Seasonal Time Scales, Journal of Climate, DOI:10.1175/JCLI-D-19-1021.1.

This study describes the **extreme heat event of October 2015 over Australia:** *"The maximum Tmax anomaly is in the southeast but high Tmax covers all of subtropical Australia. […] the Australian averaged Tmax […] was at record levels in both 2014 and 2015, but the 2015 event is much stronger (3.6°C vs 2.8°C relative to 1961–90 […] and 2.3°C vs 1.6°C relative to 2000–14)."*

"We find that about half of the October 2015 Australia-wide temperature anomaly is due to the increase in atmospheric CO_2 since 1960."

2.1.24 van Oldenborgh, G. J. 2021

Attribution of the Australian bushfire risk to anthropogenic climate change, Nat. Hazards Earth Syst. Sci, DOI: 10.5194/nhess-21-941-2021.

This study describes the **extreme wildfires over summer 2019-2020 over Australia**: *"The bushfire activity across the states of Queensland (QLD), New South Wales (NSW), Victoria (VIC), South Australia (SA) and Western Australia (WA) and in the Australian Capital Territory (ACT) was unprecedented in terms of the area burned in densely populated regions."*

"The four climate models investigated show that the probability of a Fire Weather Index this high has increased by at least 30 % since 1900 as a result of anthropogenic climate change. As the trend in extreme temperature is a driving factor behind this increase and the climate models underestimate the observed trend in extreme temperature, the attributable increase in fire risk could be much higher."

2.1.25 Rauniyar S.P. et al., 2023

The role of internal variability and external forcing on southwestern Australian rainfall: prospects for very wet or dry years, Scientific Reports, doi:10.1038/s41598-023-48877-w.

This study describes the **reduced rainfall over southwestern Australia during 2001-2020**: *"The cool-season (May to October) rainfall decline in southwestern Australia deepened during 2001–2020 to* *become 20.5% less than the 1901–1960 reference period average, with a complete absence of very wet years (i.e., rainfall > 90th percentile)."*

"In the more recent period (2001–2020), the signal of global warming is very clear, as the [multi-model mean] 20-year averages are more than two standard deviations drier than the multi-model preindustrial decadal variability."

2.1.26 Hope. F. et al., 2024

Lessons learnt from a real-time attribution and contextualisation trial in a National Meteorological and Hydrological Service, Environmental Research Letters, DOI: 10.1088/2752-5295/ad7da8.

This study describes the **extreme heat event in Tasmania, Australia, in July 2023**: *"The state of Tasmania in Australia's south had its warmest July on record in 2023 since statewide records began in 1910 (figure 1). Tmax was about 11 °C and Tmin about 5 °C with associated anomalies of +1.4 and +2.6 °C relative to the 1961–90 climatological reference period."*

"Approximately half of the unusual warmth was attributed to climate change, with the likelihood of breaking the previous record at least 17 times higher in the current climate compared to a stationary pre-industrial climate (14% vs. 0.4%)."

2.1.27 Devanand A. et al., 2024

Australia's Tinderbox Drought: An extreme natural event likely worsened by human-caused climate change, Science Advances, doi:10.1126/sciadv.adj3460.

This study describes the **extreme drought that carried on over 2017-2019 over southeast Australia**: *"The Tinderbox Drought was characterized by cool season rainfall deficits of around −50% in three consecutive years."*

"Anthropogenic forcing intensified the rainfall deficits of the Tinderbox Drought by around 18% with an interquartile range of 34.9 to −13.3% highlighting the considerable uncertainty in attributing droughts of this kind to human activity."

2.1.28 Henley B.J. et al., 2024

Highest ocean heat in four centuries places Great Barrier Reef in danger, Nature, doi:10.1038/s41586-024-07672-x.

This study describes the **extreme coral bleaching events in summers of 2024, 2017 and 2020**: *"However, in the nine January–March periods from 2016 to 2024 (inclusive) there were five mass coral bleaching events on the [Great Barrier Reef]."*

"The reconstruction shows that SSTs were relatively cool and stable for hundreds of years, and that recent January–March ocean surface heat in the Coral Sea is unprecedented in at least the past 400 years. The coral colonies and reefs that have lived through the past several centuries, and that yielded the valuable Sr/Ca and δ18O data on which our reconstruction is based, are themselves under serious threat. Our analysis of climate-model simulations confirms that human influence is the driver of recent January–March Coral Sea surface warming."

2.1.29 Deng, X. et al., 2025

Contributions of Greenhouse Gases and Anthropogenic Aerosols to Temperature Extremes over Australia, Journal of Climate, https://doi.org/10.1175/JCLI-D-24-0493.1.

This study describes the **heat and cold extremes that have impacted Australia over recent decades (1950-2014)**, focusing on the annual maxima of daily maximum temperature TXx and the annual minima of daily minimum temperature TNn (temperature extremes).

"As expected, GHG dominate warming but with the signal partially offset by a more subtle AER-induced cooling. Based on 40-yr running trends, we find that recent decades show faster warming of hot extremes, likely due to a more rapid increase under [greenhouse gases] combined with a decrease under [anthropogenic aerosols]."

2.1.30 Perkins-Kirkpatrick, S.E. et al., 2025

Attributing heatwave-related mortality to climate change: a case study of the 2009 Victorian heatwave in Australia, Environmental Research: Climate, doi:10.1088/2752-5295/ada8cd.

This study describes the **extreme heat event and excess mortality related occurring in Australia in 2009**: *"In the 2009 summer, one of Australia's most prolonged and intense periods of high temperatures occurred over the southeast of Australia (National Climate Centre 2009), (27 January–8 February; figure 1), with two periods of exceptional daytime heat (>44 °C) during 28–31 January and 6–8 February. Of notable concern were the high daily minimum (night-time) temperatures concurrent with the high daily maxima (daytime), which resulted in the city of Melbourne exceeding an average daily temperature of 35 °C for the first time on record (10.9 °C above average)."*

"Across all models, the frequency of a heatwave-related mortality event similar to the 2009 Victorian event has, on average, doubled under factual conditions relative to counterfactual conditions. Moreover, on average, around 6 ± 3–4 extra individuals out of 31 (an increase of 20%) died as a direct result of extreme temperatures due to anthropogenic influence on the climate."

2.1.31 Wang, S. et al., 2025

Intensifying Climatic Effects of the Indian Ocean Dipole Exaggerates Australia Bushfires Risk, Journal of Geophysical Research: Atmospheres, doi:10.1029/2025JD043936.

This study describes the **extreme wildfires of the 2019-2020 summer over southeastern Australia**: *"Southeastern Australia (SEA) is no stranger to bushfires, but the 2019–2020 season was unprecedented in both size and intensity, accompanied with record-breaking high temperature and rainfall deficit"*

"Due to anthropogenic climate change, the likelihood of [positive Indian Ocean Dipole]-induced severe bushfires danger has risen by 16%–32%."

2.1.32 Abram, N. J. et al., 2025

Quantifying the regional to global climate impacts of individual fossil fuel projects to inform decision-making. npj Clim. Action 4, 92 (2025). https://doi.org/10.1038/s44168-025-00296-5

This study describes the **mass bleaching events on the Great Barrier Reef**: *"The [Great Barrier Reef] has experienced six mass bleaching events during the last decade (2016, 2017, 2020, 2022, 2024, and 2025), caused by heat extremes that are beyond the range of natural climate variability"*

"The 0.00039 °C (0.00024 °C–0.00055 °C likely range) of additional global warming caused by CO2 emissions from the Scarborough project would increase accumulated thermal exposure on the GBR by 0.0017 °C-weeks (0.00060 °C–0.0037 °C-weeks likely range; Methods; Supplementary Fig. 3). Over the entire GBR, this would result in the death of an additional 16 million coral colonies (4.7 to 37 million likely range) during every future mass bleaching event (Fig. 2c, Methods).

2.2 Detection studies

In addition to attribution studies, we highlight one detection study also over Australia characterizing marine thermal stress and impacts on tropical coral bleaching occurring across the world, including Australia. According to AR6 WG1 Chapter 1, detection of change is defined as "*the process of demonstrating that some aspect of the climate, or a system affected by climate, has changed in some defined statistical sense, often using spatially aggregating methods that try to maximize S/N, such as 'fingerprints' (e.g., Hegerl et al., 1996), without providing a reason for that change. An identified change is detected in observations if its likelihood of occurrence by chance due to internal variability alone is determined to be small, for example, <10%*."

2.2.1 Lough, J.M. et al., 2018

Increasing thermal stress for tropical coral reefs: 1871–2017. Sci Rep 8, 6079 (2018). https://doi.org/10.1038/s41598-018-24530-9.

This study documents mass coral bleaching over the historical period: *"We examine the historical level of stress for 100 coral reef locations with robust bleaching histories."*

"The level of thermal stress (based on a degree heating month index, DHMI) at these locations during the 2015–2016 El Niño was unprecedented over the period 1871–2017 and exceeded that of the strong 1997–1998 El Niño. The DHMI was also 5 times the level of thermal stress associated with the 'pre-industrial', 1877–1878, El Niño. Estimates of future levels of thermal stress suggest that even the optimistic 1.5 °C Paris Agreement target is insufficient to prevent more frequent mass bleaching events for the world's reefs."

The study further provides information regarding future projections: "*For the 100 reef locations examined here and given current rates of warming, the 1.5 °C global warming target represents twice* *the thermal stress they experienced in 2016. The 2 °C global target would result in 3 times the 2016 level of thermal stress and 3 °C, which is currently being tracked with the NDCs32, would be over 6 times the 2016 level of stress. The optimistic global targets of +1.5 °C and 2.0 °C, even if achieved, are unlikely to provide the thermal environment necessary for the maintenance of coral reef communities typical of the mid-20th century.*"

3 Review of climate and extreme event projections for Australia

In this section, we provide extracts from the IPCC 6th Assessment Reports (AR6), from Working Group I (including the Interactive Atlas) and II, describing projected changes in climate and extreme climate events for Australia as a whole or for sub-regions. **In Section 2, a vast majority of text consists of literal citations from IPCC reports, highlighted by quotation marks.**

3.1 Working Group 1 contribution to the Sixth Assessment Report (AR6)

3.1.1 Chapter 11: Weather and Climate Extreme Events in a Changing Climate

Table 11.10. This table describes "Observed trends, human contribution to observed trends, and projected changes at 1.5°C, 2°C and 4°C of global warming for temperature extremes in Australasia, subdivided by AR6 regions". The colors used describe the confidence in the statements (scale is provided at the top of the first panel).

Fact	*Virtually certain*	*Extremely likely*	*Very likely*	*Likely*	*High confidence*	*Medium confidence*	*Low confidence*
Increasing hot extremes, decreasing cold extremes							All

Region	Observed Trends	Detection and Attribution; Event Attribution	Projections		
			1.5°C	2°C	4°C
All Australasia	Significant increases in the intensity and frequency of hot extremes and decreases in the intensity and frequency of cold extremes (CSIRO and BOM, 2015; Jakob and Walland, 2016; Alexander and Arblaster, 2017)	*Robust evidence* of a human contribution to the observed increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes (Z. Wang et al., 2017a; Hu et al., 2020; Seong et al., 2021)	CMIP6 models project a robust increase in the intensity and frequency of TXx events and a robust decrease in the intensity and frequency of TNn events (Li et al., 2021). Median increase of more than 0°C in the 50-year TXx and TNn events compared to the 1°C warming level (Li et al., 2021) Additional evidence from CMIP5 simulations for an increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes (Alexander and Arblaster, 2017; Herold et al., 2018; Grose et al., 2020; Evans et al., 2021)	CMIP6 models project a robust increase in the intensity and frequency of TXx events and a robust decrease in the intensity and frequency of TNn events (Li et al., 2021). Median increase of more than 0.5°C in the 50-year TXx and TNn events compared to the 1°C warming level (Li et al., 2021) Additional evidence from CMIP5 simulations for an increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes (Alexander and Arblaster, 2017; Herold et al., 2018; Grose et al., 2020; Evans et al., 2021)	CMIP6 models project a robust increase in the intensity and frequency of TXx events and a robust decrease in the intensity and frequency of TNn events (Li et al., 2021). Median increase of more than 2.5°C in the 50-year TXx and TNn events compared to the 1°C warming level (Li et al., 2021) Additional evidence from CMIP5 simulations for an increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes (Alexander and Arblaster, 2017; Herold et al., 2018; Grose et al., 2020; Evans et al., 2021)
Region	Observed Trends	Detection and Attribution; Event Attribution	Projections		
			1.5°C	2°C	4°C
All Australasia *continued*	*Very likely* increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes	Human influence *very likely* contributed to the observed increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes	Increase in the intensity and frequency of hot extremes: *Very likely* (compared with the recent past, 1995–2014) *Extremely likely* (compared with pre-industrial) Decrease in the intensity and frequency of cold extremes: *Very likely* (compared with the recent past, 1995–2014) *Extremely likely* (compared with pre-industrial)	Increase in the intensity and frequency of hot extremes: *Extremely likely* (compared with the recent past, 1995–2014) *Virtually certain* (compared with pre-industrial) Decrease in the intensity and frequency of cold extremes: *Extremely likely* (compared with the recent past, 1995–2014) *Virtually certain* (compared with pre-industrial)	Increase in the intensity and frequency of hot extremes: *Virtually certain* (compared with the recent past, 1995–2014) *Virtually certain* (compared with pre-industrial) Decrease in the intensity and frequency of cold extremes: *Virtually certain* (compared with the recent past, 1995–2014) *Virtually certain* (compared with pre-industrial)

Northern Australia (NAU)	Significant increases in the intensity and frequency of hot extremes and significant decreases in the intensity and frequency of cold extremes (Perkins and Alexander, 2013; X.L. Wang et al., 2013a; CSIRO and BOM, 2015; Donat et al., 2016a; Alexander and Arblaster, 2017; Dunn et al., 2020)	*Robust evidence* of a human contribution to the observed increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes (Arblaster et al., 2014; Knutson et al., 2014b; Lewis and Karoly, 2014; Perkins et al., 2014; Hope et al., 2015, 2016; Perkins and Gibson, 2015; Z. Wang et al., 2017a; Hu et al., 2020; Seong et al., 2021).	CMIP6 models project a robust increase in the intensity and frequency of TXx events and a robust decrease in the intensity and frequency of TNn events (Li et al., 2021; 11.SM). Median increase of more than 0°C in the 50-year TXx and TNn events compared to the 1°C warming level (Li et al., 2021) and more than 1.5°C in annual TXx and TNn compared to pre-industrial (11.SM) Additional evidence from CMIP5 simulations for an increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes (Alexander and Arblaster, 2017; Herold et al., 2018; Grose et al., 2020; Evans et al., 2021)	CMIP6 models project a robust increase in the intensity and frequency of TXx events and a robust decrease in the intensity and frequency of TNn events (Li et al., 2021; 11.SM). Median increase of more than 0.5°C in the 50-year TXx and TNn events compared to the 1°C warming level (Li et al., 2021) and more than 2°C in annual TXx and TNn compared to pre-industrial (11.SM) Additional evidence from CMIP5 simulations for an increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes (Alexander and Arblaster, 2017; Herold et al., 2018; Grose et al., 2020; Evans et al., 2021)	CMIP6 models project a robust increase in the intensity and frequency of TXx events and a robust decrease in the intensity and frequency of TNn events (Li et al., 2021; 11.SM). Median increase of more than 3°C in the 50-year TXx and TNn events compared to the 1°C warming level (Li et al., 2021) and more than 3.5°C in annual TXx and TNn compared to pre-industrial (11.SM) Additional evidence from CMIP5 simulations for an increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes (Alexander and Arblaster, 2017; Herold et al., 2018; Grose et al., 2020; Evans et al., 2021)
	High confidence in the increase in the intensity and frequency of hot extremes and *likely* decrease in the intensity and frequency of cold extremes	*High confidence* in a human contribution to the observed increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes	Increase in the intensity and frequency of hot extremes: *Likely* (compared with the recent past, 1995–2014) *Very likely* (compared with pre-industrial) Decrease in the intensity and frequency of cold extremes: *Likely* (compared with the recent past, 1995–2014) *Very likely* (compared with pre-industrial)	Increase in the intensity and frequency of hot extremes: *Very likely* (compared with the recent past, 1995–2014) *Extremely likely* (compared with pre-industrial) Decrease in the intensity and frequency of cold extremes: *Very likely* (compared with the recent past, 1995–2014) *Extremely likely* (compared with pre-industrial)	Increase in the intensity and frequency of hot extremes: *Virtually certain* (compared with the recent past, 1995–2014) *Virtually certain* (compared with pre-industrial) Decrease in the intensity and frequency of cold extremes: *Virtually certain* (compared with the recent past, 1995–2014) *Virtually certain* (compared with pre-industrial)

Region	Observed Trends	Detection and Attribution; Event Attribution	Projections 1.5°C	Projections 2°C	Projections 4°C
Central Australia (CAU)	Significant increases in the intensity and frequency of hot extremes and significant decreases in the intensity and frequency of cold extremes (Perkins and Alexander, 2013; X.L. Wang et al., 2013a; CSIRO and BOM, 2015; Donat et al., 2016a; Alexander and Arblaster, 2017; Dunn et al., 2020)	*Robust evidence* of a human contribution to the observed increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes (Arblaster et al., 2014; King et al., 2014; Knutson et al., 2014b; Lewis and Karoly, 2014; Perkins et al., 2014; Hope et al., 2015, 2016; Perkins and Gibson, 2015; Z. Wang et al., 2017a; Hu et al., 2020; Seong et al., 2021)	CMIP6 models project a robust increase in the intensity and frequency of TXx events and a robust decrease in the intensity and frequency of TNn events (Li et al., 2021; 11.SM). Median increase of more than 0°C in the 50-year TXx and TNn events compared to the 1°C warming level (Li et al., 2021) and more than 1.5°C in annual TXx and TNn compared to pre-industrial (11.SM) Additional evidence from CMIP5 simulations for an increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes (Alexander and Arblaster, 2017; Herold et al., 2018; Grose et al., 2020; Evans et al., 2021)	CMIP6 models project a robust increase in the intensity and frequency of TXx events and a robust decrease in the intensity and frequency of TNn events (Li et al., 2021; 11.SM). Median increase of more than 0.5°C in the 50-year TXx and TNn events compared to the 1°C warming level (Li et al., 2021) and more than 2°C in annual TXx and TNn compared to pre-industrial (11.SM) Additional evidence from CMIP5 simulations for an increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes (Alexander and Arblaster, 2017; Herold et al., 2018; Grose et al., 2020; Evans et al., 2021)	CMIP6 models project a robust increase in the intensity and frequency of TXx events and a robust decrease in the intensity and frequency of TNn events (Li et al., 2021; 11.SM). Median increase of more than 2.5°C in the 50-year TXx and TNn events compared to the 1°C warming level (Li et al., 2021) and more than 4°C in annual TXx and TNn compared to pre-industrial (11.SM) Additional evidence from CMIP5 simulations for an increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes (Alexander and Arblaster, 2017; Herold et al., 2018; Grose et al., 2020; Evans et al., 2021)
	Likely increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes	Human influence *likely* contributed to the observed increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes	Increase in the intensity and frequency of hot extremes: *Likely* (compared with the recent past, 1995–2014) *Very likely* (compared with pre-industrial) Decrease in the intensity and frequency of cold extremes: *Likely* (compared with the recent past, 1995–2014) *Very likely* (compared with pre-industrial)	Increase in the intensity and frequency of hot extremes: *Very likely* (compared with the recent past, 1995–2014) *Extremely likely* (compared with pre-industrial) Decrease in the intensity and frequency of cold extremes: *Very likely* (compared with the recent past, 1995–2014) *Extremely likely* (compared with pre-industrial)	Increase in the intensity and frequency of hot extremes: *Virtually certain* (compared with the recent past, 1995–2014) *Virtually certain* (compared with pre-industrial) Decrease in the intensity and frequency of cold extremes: *Virtually certain* (compared with the recent past, 1995–2014) *Virtually certain* (compared with pre-industrial)
Eastern Australia (EAU)	Significant increases in the intensity and frequency of hot extremes and significant decreases in the intensity and frequency of cold extremes (Perkins and Alexander, 2013; X.L. Wang et al., 2013a; CSIRO and BOM, 2015; Donat et al., 2016a; Alexander and Arblaster, 2017; Dunn et al., 2020)	*Robust evidence* of a human contribution to the observed increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes (Arblaster et al., 2014; Knutson et al., 2014b; Lewis and Karoly, 2014; Perkins et al., 2014; Hope et al., 2015, 2016; King et al., 2015a; Perkins and Gibson, 2015; Z. Wang et al., 2017a; Hu et al., 2020; Seong et al., 2021)	CMIP6 models project a robust increase in the intensity and frequency of TXx events and a robust decrease in the intensity and frequency of TNn events (Li et al., 2021; 11.SM). Median increase of more than 0.5°C in the 50-year TXx and TNn events compared to the 1°C warming level (Li et al., 2021) and more than 1°C in annual TXx and TNn compared to pre-industrial (11.SM) Additional evidence from CMIP5 simulations for an increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes (Alexander and Arblaster, 2017; Herold et al., 2018; Grose et al., 2020; Evans et al., 2021)	CMIP6 models project a robust increase in the intensity and frequency of TXx events and a robust decrease in the intensity and frequency of TNn events (Li et al., 2021; 11.SM). Median increase of more than 0.5°C in the 50-year TXx and TNn events compared to the 1°C warming level (Li et al., 2021) and more than 1.5°C in annual TXx and TNn compared to pre-industrial (11.SM) Additional evidence from CMIP5 simulations for an increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes (Alexander and Arblaster, 2017; Herold et al., 2018; Grose et al., 2020; Evans et al., 2021)	CMIP6 models project a robust increase in the intensity and frequency of TXx events and a robust decrease in the intensity and frequency of TNn events (Li et al., 2021; 11.SM). Median increase of more than 2.5°C in the 50-year TXx and TNn events compared to the 1°C warming level (Li et al., 2021) and more than 3.5°C in annual TXx and TNn compared to pre-industrial (11.SM) Additional evidence from CMIP5 simulations for an increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes (Alexander and Arblaster, 2017; Herold et al., 2018; Grose et al., 2020; Evans et al., 2021)

Region	Observed Trends	Detection and Attribution; Event Attribution	Projections 1.5°C	2°C	4°C
Eastern Australia (EAU) *continued*	*Likely* increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes	Human influence *likely* contributed to the observed increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes	Increase in the intensity and frequency of hot extremes: *Likely* (compared with the recent past, 1995–2014) *Very likely* (compared with pre-industrial) Decrease in the intensity and frequency of cold extremes: *Likely* (compared with the recent past, 1995–2014) *Very likely* (compared with pre-industrial)	Increase in the intensity and frequency of hot extremes: *Very likely* (compared with the recent past, 1995–2014) *Extremely likely* (compared with pre-industrial) Decrease in the intensity and frequency of cold extremes: *Very likely* (compared with the recent past, 1995–2014) *Extremely likely* (compared with pre-industrial)	Increase in the intensity and frequency of hot extremes: *Virtually certain* (compared with the recent past, 1995–2014) *Virtually certain* (compared with pre-industrial) Decrease in the intensity and frequency of cold extremes: *Virtually certain* (compared with the recent past, 1995–2014) *Virtually certain* (compared with pre-industrial)
Southern Australia (SAU)	Significant increases in the intensity and frequency of hot extremes and significant decreases in the intensity and frequency of cold extremes (Perkins and Alexander, 2013; X.L. Wang et al., 2013a; Dittus et al., 2014; CSIRO and BOM, 2015; Crimp et al., 2016; Donat et al., 2016a; Alexander and Arblaster, 2017; Dunn et al., 2020)	*Robust evidence* of a human contribution to the observed increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes (Arblaster et al., 2014; Knutson et al., 2014b; Lewis and Karoly, 2014; Perkins et al., 2014; Hope et al., 2015, 2016; Perkins and Gibson, 2015; Black and Karoly, 2016; Z. Wang et al., 2017a; Hu et al., 2020; Seong et al., 2021)	CMIP6 models project a robust increase in the intensity and frequency of TXx events and a robust decrease in the intensity and frequency of TNn events (Li et al., 2021; 11.SM). Median increase of more than 0°C in the 50-year TXx and TNn events compared to the 1°C warming level (Li et al., 2021) and more than 1°C in annual TXx and TNn compared to pre-industrial (11.SM) Additional evidence from CMIP5 simulations for an increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes (Alexander and Arblaster, 2017; Herold et al., 2018; Grose et al., 2020; Evans et al., 2021)	CMIP6 models project a robust increase in the intensity and frequency of TXx events and a robust decrease in the intensity and frequency of TNn events (Li et al., 2021; 11.SM). Median increase of more than 0.5°C in the 50-year TXx and TNn events compared to the 1°C warming level (Li et al., 2021) and more than 1.5°C in annual TXx and TNn compared to pre-industrial (11.SM) Additional evidence from CMIP5 simulations for an increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes (Alexander and Arblaster, 2017; Herold et al., 2018; Grose et al., 2020; Evans et al., 2021)	CMIP6 models project a robust increase in the intensity and frequency of TXx events and a robust decrease in the intensity and frequency of TNn events (Li et al., 2021; 11.SM). Median increase of more than 2°C in the 50-year TXx and TNn events compared to the 1°C warming level (Li et al., 2021) and more than 2.5°C in annual TXx and TNn compared to pre-industrial (11.SM) Additional evidence from CMIP5 simulations for an increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes (Alexander and Arblaster, 2017; Herold et al., 2018; Grose et al., 2020; Evans et al., 2021)
	Likely increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes	Human influence *likely* contributed to the observed increase in the intensity and frequency of hot extremes and decrease in the intensity and frequency of cold extremes	Increase in the intensity and frequency of hot extremes: *Likely* (compared with the recent past, 1995–2014) *Very likely* (compared with pre-industrial) Decrease in the intensity and frequency of cold extremes: *Likely* (compared with the recent past, 1995–2014) *Very likely* (compared with pre-industrial)	Increase in the intensity and frequency of hot extremes: *Very likely* (compared with the recent past, 1995–2014) *Extremely likely* (compared with pre-industrial) Decrease in the intensity and frequency of cold extremes: *Very likely* (compared with the recent past, 1995–2014) *Extremely likely* (compared with pre-industrial)	Increase in the intensity and frequency of hot extremes: *Virtually certain* (compared with the recent past, 1995–2014) *Virtually certain* (compared with pre-industrial) Decrease in the intensity and frequency of cold extremes: *Virtually certain* (compared with the recent past, 1995–2014) *Virtually certain* (compared with pre-industrial)

Table 11.11. This tables describes "Observed trends, human contribution to observed trends, and projected changes at 1.5°C, 2°C and 4°C of global warming for heavy precipitation in Australasia, subdivided by AR6 regions". The colors describe the confidence in the statements (scale is provided at the top of the first panel).

Fact	*Virtually certain*	*Extremely likely*	*Very likely*	*Likely*	*High confidence*	*Medium confidence*	*Low confidence*
Increasing heavy precipitation							All

Region	Observed Trends	Detection and Attribution; Event Attribution	Projections		
			1.5°C	2°C	4°C
All Australasia	*Limited evidence* (Jakob and Walland, 2016; Guerreiro et al., 2018b; Dey et al., 2019b; Dunn et al., 2020; Sun et al., 2021)	*Limited evidence*	CMIP6 models project inconsistent changes in the region (Li et al., 2021)	CMIP6 models project an increase in the intensity and frequency of heavy precipitation (Li et al., 2021). Median increase of more than 4% in the 50-year Rx1day and Rx5day events compared to the 1°C warming level (Li et al., 2021)	CMIP6 models project a robust increase in the intensity and frequency of heavy precipitation (Li et al., 2021). Median increase of more than 10% in the 50-year Rx1day and Rx5day events compared to the 1°C warming level (Li et al., 2021)
	Low confidence	*Low confidence*	Intensification of heavy precipitation: *Low confidence* (compared with the recent past, 1995–2014) *Medium confidence* (compared with pre-industrial)	Intensification of heavy precipitation: *Medium confidence* (compared with the recent past, 1995–2014) *Likely* (compared with pre-industrial)	Intensification of heavy precipitation: *Likely* (compared with the recent past, 1995–2014) *Very likely* (compared with pre-industrial)
Northern Australia (NAU)	Intensification of heavy precipitation (Donat et al., 2016a; Alexander and Arblaster, 2017; Evans et al., 2017; Dey et al., 2019b; Dunn et al., 2020; Sun et al., 2021)	*Limited evidence* (Dey et al., 2019a)	CMIP6 models project inconsistent changes in the region (Li et al., 2021)	CMIP6 models project an increase in the intensity and frequency of heavy precipitation (Li et al., 2021; 11.SM). Median increase of more than 4% in the 50-year Rx1day and Rx5day events compared to the 1°C warming level (Li et al., 2021) and more than 6% in annual Rx1day and Rx5day and 2% in annual Rx30day compared to pre-industrial (11.SM)	CMIP6 models project a robust increase in the intensity and frequency of heavy precipitation (Li et al., 2021; 11.SM). Median increase of more than 10% in the 50-year Rx1day and Rx5day events compared to the 1°C warming level (Li et al., 2021) and more than 20% in annual Rx1day and Rx5day and 10% in annual Rx30day compared to pre-industrial (11.SM)
	Medium confidence in the intensification of heavy precipitation	*Low confidence*	Intensification of heavy precipitation: *Low confidence* (compared with the recent past, 1995–2014) *Medium confidence* (compared with pre-industrial)	Intensification of heavy precipitation: *Medium confidence* (compared with the recent past, 1995–2014) *High confidence* (compared with pre-industrial)	Intensification of heavy precipitation: *Likely* (compared with the recent past, 1995–2014) *Very likely* (compared with pre-industrial)

Central Australia (CAU)	*Limited evidence* (Donat et al., 2016a; Alexander and Arblaster, 2017; Evans et al., 2017; Dey et al., 2019b; Dunn et al., 2020; Sun et al., 2021).	*Limited evidence*	CMIP6 models project inconsistent changes in the region (Li et al., 2021)	CMIP6 models project an increase in the intensity and frequency of heavy precipitation (Li et al., 2021; 11.SM). Median increase of more than 4% in the 50-year Rx1day and Rx5day events compared to the 1°C warming level (Li et al., 2021) and more than 4% in annual Rx1day and Rx5day and 2% in annual Rx30day compared to pre-industrial (11.SM)	CMIP6 models project a robust increase in the intensity and frequency of heavy precipitation (Li et al., 2021; 11.SM). Median increase of more than 10% in the 50-year Rx1day and Rx5day events compared to the 1°C warming level (Li et al., 2021) and more than 10% in annual Rx1day and Rx5day and 4% in annual Rx30day compared to pre-industrial (11.SM)
	Low confidence	*Low confidence*	Intensification of heavy precipitation: *Low confidence* (compared with the recent past, 1995–2014) *Medium confidence* (compared with pre-industrial)	Intensification of heavy precipitation: *Medium confidence* (compared with the recent past, 1995–2014) *High confidence* (compared with pre-industrial)	Intensification of heavy precipitation: *Likely* (compared with the recent past, 1995–2014) *Very likely* (compared with pre-industrial)
Eastern Australia (EAU)	Lack of agreement on the evidence of trends (Donat et al., 2016a; Alexander and Arblaster, 2017; Evans et al., 2017; Dey et al., 2019b; Dunn et al., 2020; Sun et al., 2021)	*Limited evidence*	CMIP6 models project inconsistent changes in the region (Li et al., 2021)	CMIP6 models project inconsistent changes in the region (Li et al., 2021)	CMIP6 models project an increase in the intensity and frequency of heavy precipitation (Li et al., 2021; 11.SM). Median increase of more than 10% in the 50-year Rx1day and Rx5day events compared to the 1°C warming level (Li et al., 2021) and more than 10% in annual Rx1day and Rx5day and 8% in annual Rx30day compared to pre-industrial (11.SM)
	Low confidence	*Low confidence*	Intensification of heavy precipitation: *Low confidence* (compared with the recent past, 1995–2014) *Low confidence* (compared with pre-industrial)	Intensification of heavy precipitation: *Low confidence* (compared with the recent past, 1995–2014) *Medium confidence* (compared with pre-industrial)	Intensification of heavy precipitation: *High confidence* (compared with the recent past, 1995–2014) *Likely* (compared with pre-industrial)
Region	**Observed Trends**	**Detection and Attribution; Event Attribution**	**Projections**		
			1.5°C	**2°C**	**4°C**
Southern Australia (SAU)	*Limited evidence* (Donat et al., 2016a; Alexander and Arblaster, 2017; Evans et al., 2017; Dey et al., 2019b; Dunn et al., 2020; Sun et al., 2021)	*Limited evidence*	CMIP6 models project inconsistent changes in the region (Li et al., 2021)	CMIP6 models project inconsistent changes in the region (Li et al., 2021)	CMIP6 models project an increase in the intensity and frequency of heavy precipitation (Li et al., 2021; 11.SM). Median increase of more than 10% in the 50-year Rx1day and Rx5day events compared to the 1°C warming level (Li et al., 2021) and more than 8% in annual Rx1day and Rx5day and 4% in annual Rx30day compared to pre-industrial (11.SM)
	Low confidence	*Low confidence*	Intensification of heavy precipitation: *Low confidence* (compared with the recent past, 1995–2014) *Low confidence* (compared with pre-industrial)	Intensification of heavy precipitation: *Low confidence* (compared with the recent past, 1995–2014) *Medium confidence* (compared with pre-industrial)	Intensification of heavy precipitation: *High confidence* (compared with the recent past, 1995–2014) *Likely* (compared with pre-industrial)

Table 11.12. This tables describes "Observed trends, human contribution to observed trends, and projected changes at 1.5°C, 2°C and 4°C of global warming for meteorological droughts (MET), agricultural and ecological droughts (AGR/ECOL), and hydrological droughts (HYDR) in Australasia, subdivided by AR6 regions". The colors describe the confidence in the statements, split into increasing and decreasing trends (scale is provided at the top of the first panel).

Increasing drought	*Fact*	*Virtually certain*	*Extremely likely*	*Very likely*	*Likely*	*High confidence*	*Medium confidence*
Decreasing drought	*Fact*	*Virtually certain*	*Extremely likely*	*Very likely*	*Likely*	*High confidence*	*Medium confidence*
All	*Low confidence*						

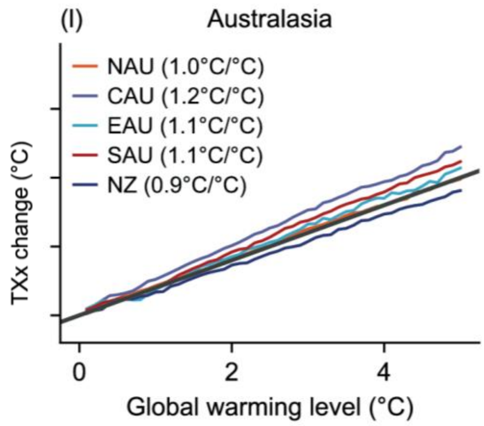
Region and Drought Type		Observed Trends	Human Contribution	Projections		
				+1.5°C	+2°C	+4°C
Northern Australia (NAU)	MET	***Medium confidence***: **Decrease** in the frequency and intensity of meteorological droughts (Gallant et al., 2013; Delworth and Zeng, 2014; Alexander and Arblaster, 2017; Knutson and Zeng, 2018; Dey et al., 2019a; Dunn et al., 2020)	***Low confidence*** in attribution (Delworth and Zeng, 2014; Knutson and Zeng, 2018; Dey et al., 2019a)	***Low confidence***: **Increases or non-robust** changes (Alexander and Arblaster, 2017; Kirono et al., 2020; Spinoni et al., 2020; 11.SM) Model disagreement in Standardized Precipitation Index (SPI) projections (Spinoni et al., 2020) Increase in Consecutive dry days (CDD)-based drought in CMIP5, but generally not significant (Alexander and Arblaster, 2017) Slight increase in CDD-based drought in CMIP6 (11.SM)	***Low confidence***: **Increases or non-robust** changes (Alexander and Arblaster, 2017; Kirono et al., 2020; Spinoni et al., 2020; 11.SM) Large inter-model spread in changes in SPI in CMIP5 projections (Kirono et al., 2020) Model disagreement in SPI projections (Spinoni et al., 2020) Increase in CDD-based drought in CMIP5, but generally not significant (Alexander and Arblaster, 2017) Slight increase in CDD-based drought CMIP6 (11.SM)	***Low confidence***: **Increases or non-robust** changes (Alexander and Arblaster, 2017; Grose et al., 2020; Kirono et al., 2020; Spinoni et al., 2020; Ukkola et al., 2020; 11.SM) Large inter-model spread in changes in SPI in CMIP5 projectons, but slight drying for median (Kirono et al., 2020) Model disagreement in SPI projections (Spinoni et al., 2020) Increase in CDD-based drought in CMIP5, but generally not significant (Alexander and Arblaster, 2017) Increase in CDD-based drought in CMIP6 (Grose et al., 2020; 11.SM) Inconsistent trends in mean precipitation in CORDEX regional climate models (RCMs), but drying trend on annual scale at northern tip of region (Evans et al., 2021)
	AGR ECOL	***Medium confidence***: **Decrease** in agricultural and ecological drought Decrease in frequency (but not intensity) of soil moisture-based droughts (Gallant et al., 2013). Inconsistent signals in changes in water-balance (Greve et al., 2014; Padrón et al., 2019). Decrease in agricultural and ecological drought based on SPEI-PM from 1950–2009 (Beguería et al., 2014; Spinoni et al., 2019) and PDSI-PM (Dai and Zhao, 2017)	***Low confidence*** ***Limited evidence*** Lack of studies although (Lewis et al., 2020) supported an anthropogenic attribution of 2018 drought associated with more extreme temperatures that exacerbated atmospheric evaporative demand (AED) and evapotranspiration, and depleting soil moisture	***Low confidence***: **Increase or non-robust change** (Naumann et al., 2018; L. Xu et al., 2019; Cook et al., 2020; Kirono et al., 2020; 11.SM) Cook et al. (2020): non-robust changes in surface and column soil moisture in both summer and winter half years (CMIP6 projections)	***Low confidence***: **Increase or non-robust** (Naumann et al., 2018; L. Xu et al., 2019; Cook et al., 2020; Kirono et al., 2020; 11.SM) Cook et al. (2020): non-robust changes in surface and column soil moisture in both summer and winter half years (CMIP6 projections) Kirono et al. (2020): Standardized soil moisture index based on surface soil moisture: drying trend for median in CMIP5 but large inter-model spread	***Low confidence***: **Increase or non-robust,** with higher increases in SPEI-PM but non-robust changes in CMIP6 soil moisture (Naumann et al., 2018; Cook et al., 2020; Kirono et al., 2020; Vicente-Serrano et al., 2020c; 11.SM) Cook et al. (2020): non-robust changes in surface and column soil moisture in both summer and winter half years (CMIP6 projections) Kirono et al. (2020): Standardized soil moisture index based on surface soil moisture: drying trend for median in CMIP5, but larger inter-model spread
	HYDR	***Low confidence*** because of **lack of data and studies**	***Low confidence***: ***Limited evidence*** because of lack of data and studies	***Low confidence***: ***Limited evidence***. One study shows lack of signals (Touma et al., 2015)	***Low confidence***: ***Limited evidence*** and generally **non-robust** change in two studies (Touma et al., 2015; Cook et al., 2020)	***Low confidence***: **Non-robust changes** or **high model disagreement** (Giuntoli et al., 2015; Touma et al., 2015; Cook et al., 2020)

Region and Drought Type		Observed Trends	Human Contribution	Projections		
				+1.5°C	+2°C	+4°C
Central Australia (CAU)	MET	***Medium confidence*:** **decrease** in the frequency/intensity of droughts (Gallant et al., 2013; Beguería et al., 2014; Delworth and Zeng, 2014; Greve et al., 2014; Alexander and Arblaster, 2017; Knutson and Zeng, 2018)	***Low confidence*** in attribution (Delworth and Zeng, 2014; Knutson and Zeng, 2018)	***Low confidence*:** **Inconsistent or non-robust** changes in meteorological droughts (Alexander and Arblaster, 2017; Kirono et al., 2020; Spinoni et al., 2020; 11.SM) Tendency to increasing SPI-based drought in CMIP6, but to decreasing SPI-based drought in CORDEX (Spinoni et al., 2020)	***Low confidence*:** **Inconsistent or non-robust** changes in meteorological droughts (Alexander and Arblaster, 2017; Kirono et al., 2020; Spinoni et al., 2020; 11.SM) Tendency to increasing SPI-based drought in CMIP6, but to decreasing SPI-based drought in CORDEX (Spinoni et al., 2020) Kirono et al. (2020): CMIP6 models project increased in SPI in much of region for 2006–2100 under RCP8.5	***Low confidence*:** **Inconsistent or non-robust** changes in meteorological droughts (Alexander and Arblaster, 2017; Grose et al., 2020; Kirono et al., 2020; Spinoni et al., 2020; Ukkola et al., 2020; 11.SM) Tendency to increasing SPI-based drought in CMIP6, but to decreasing SPI-based drought in CORDEX (Spinoni et al., 2020) Kirono et al. (2020): CMIP6 models project increased in SPI in much of region for 2006–2100 under RCP8.5
	AGR ECOL	***Low confidence*:** **Inconsistent** changes in frequency/intensity of droughts (Gallant et al., 2013; Beguería et al., 2014; Delworth and Zeng, 2014; Greve et al., 2014; Dai and Zhao, 2017; Knutson and Zeng, 2018; Padrón et al., 2019; Spinoni et al., 2019)	***Low confidence*** because of **lack of studies**	***Low confidence*:** **Inconsistent changes** in soil moisture and SPEI-PM (Naumann et al., 2018; L. Xu et al., 2019; Cook et al., 2020; Kirono et al., 2020; 11.SM)	***Low confidence*:** **Inconsistent changes** in soil moisture and SPEI-PM (Naumann et al., 2018; L. Xu et al., 2019; Cook et al., 2020; Kirono et al., 2020; 11.SM)	***Medium confidence*:** **Increased drying** for some metrics or part of domain for soil moisture and SPEI-PM with stronger changes for SPEI-PM (Naumann et al., 2018; Cook et al., 2020; Kirono et al., 2020; Vicente-Serrano et al., 2020c; 11.SM)
	HYDR	***Low confidence*** because of **lack of data and studies**	***Low confidence*** ***Limited evidence,*** because of lack of studies	***Low confidence*:** ***Limited evidence.*** One study shows lack of signals (Touma et al., 2015)	***Low confidence*:** ***Limited evidence*** and generally **non-robust** change in two studies (Touma et al., 2015; Cook et al., 2020)	***Low confidence*:** **Non-robust changes** or **high model disagreement** (Giuntoli et al., 2015; Touma et al., 2015; Cook et al., 2020)
Eastern Australia (EAU)	MET	***Low confidence*:** **Inconsistent trends** (Gallant et al., 2013; Delworth and Zeng, 2014; Alexander and Arblaster, 2017; Knutson and Zeng, 2018; Spinoni et al., 2019) Gallant et al. (2013): Inconsistent trends, wetting on average in MDB Delworth and Zeng (2014): no trend Knutson and Zeng (2018): no trend Alexander and Arblaster (2017); Dunn et al. (2020): no trends in CDD Spinoni et al. (2019): Inconsistent trends, some increased severity in part of the region	***Low confidence*** in attribution (Delworth and Zeng, 2014; King et al., 2014; Knutson and Zeng, 2018)	***Low confidence*:** **Increase** in meteorological droughts based on CDD (11.SM) and SPI (Kirono et al., 2020), but weak signals and lack of other studies at this GWL	***Medium confidence*:** **Increases** in meteorological droughts (Alexander and Arblaster, 2017; Kirono et al., 2020; Spinoni et al., 2020; 11.SM)	***Medium confidence*:** **Increases** in meteorological droughts (Alexander and Arblaster, 2017; Grose et al., 2020; Kirono et al., 2020; Spinoni et al., 2020; Ukkola et al., 2020; 11.SM)

Region and Drought Type		Observed Trends	Human Contribution	Projections		
				+1.5°C	+2°C	+4°C
Eastern Australia (EAU) *continued*	AGR ECOL	***Low confidence***: **Inconsistent trends** (Gallant et al., 2013; Beguería et al., 2014; Greve et al., 2014; Dai and Zhao, 2017; Spinoni et al., 2019; Padrón et al., 2020)	***Low confidence*** because of lack of studies, although enhanced AED-driven by extreme temperatures increased the severity of the 2019 drought (van Oldenborgh et al., 2021)	***Low confidence***: **Inconsistent changes** in soil moisture and SPEI-PM, but tendency to **increase** (Naumann et al., 2018; L. Xu et al., 2019; Cook et al., 2020; Kirono et al., 2020; 11.SM)	***Medium confidence***: **Increase** in drought based on soil moisture and SPEI-PM, but partly inconsistent changes for some studies (Naumann et al., 2018; L. Xu et al., 2019; Cook et al., 2020; Kirono et al., 2020; 11.SM)	***High confidence***: **Increased drying** for some metrics or part of domain for soil moisture and SPEI-PM with stronger changes for SPEI-PM (Naumann et al., 2018; Cook et al., 2020; Kirono et al., 2020; Vicente-Serrano et al., 2020c; 11.SM)
	HYDR	***Low confidence***: ***Limited evidence*** because of **lack of data and studies** (X.S. Zhang et al., 2016)	***Low confidence***: ***Limited evidence***, because of lack of studies	***Low confidence***: ***Limited evidence***. One study shows lack of signals (Touma et al., 2015)	***Low confidence***: **Lack of studies** and generally **non-robust** change in two studies (Touma et al., 2015; Cook et al., 2020)	***Low confidence***: **Non-robust changes** or **high model disagreement** (Giuntoli et al., 2015; Touma et al., 2015; Cook et al., 2020)
Southern Australia (SAU)	MET	***Low confidence***: **Mixed signals** depending on subregion, index and season (Gallant et al., 2013; Delworth and Zeng, 2014; Alexander and Arblaster, 2017; Dai and Zhao, 2017; Spinoni et al., 2019; Dunn et al., 2020; Rauniyar and Power, 2020) Gallant et al. (2013): Wetting in eastern part, drying in eastern part Rauniyar and Power (2020): Recovery from Millenium drought Delworth and Zeng (2014): Only drying in the western part, not in the eastern part Alexander and Arblaster (2017); Dunn et al. (2020): Overall decreasing CDD trends Spinoni et al. (2019): Decreasing droughts in most of domain	***Low confidence***: Mixed signals in observations Increase in the frequency/ intensity of meteorological droughts can be attributed to anthropogenic forcing (greenhouse gases, ozone and aerosols) (Cai et al., 2014a; Delworth and Zeng, 2014; Karoly et al., 2016; Knutson and Zeng, 2018)	***Medium confidence***: **Increase** overall in meteorological droughts based on CDD (11.SM) and SPI (Kirono et al., 2020); but weak signals and lack of other studies at this GWL	***Medium confidence***: **Increases** in meteorological droughts (Alexander and Arblaster, 2017; Kirono et al., 2020; Spinoni et al., 2020; 11.SM)	***Medium confidence***: **Increases** in meteorological droughts (Alexander and Arblaster, 2017; Grose et al., 2020; Kirono et al., 2020; Spinoni et al., 2020; Ukkola et al., 2020; 11.SM)
	AGR ECOL	***Medium confidence***: **Increase.** Dominant increasing drying signal but some inconsistent trends depending on subregion and index; strongest drying trend in Western SAU. (Gallant et al., 2013; Beguería et al., 2014; Greve et al., 2018; Spinoni et al., 2019; Padrón et al., 2020)	***Low confidence***: ***Limited evidence***, Enhanced AED driven by extreme temperatures increased the severity of the 2019 drought (van Oldenborgh et al., 2021)	***Medium confidence***: **Increase** in soil moisture and SPEI-PM, but partly inconsistent changes for some studies (Naumann et al., 2018; L. Xu et al., 2019; Kirono et al., 2020; 11.SM)	***Medium confidence***: **Increase** in drought based on soil moisture and SPEI-PM, but partly inconsistent changes for some studies (Naumann et al., 2018; L. Xu et al., 2019; Cook et al., 2020; Kirono et al., 2020; 11.SM)	***High confidence***: **Increased drying** for some metrics or part of domain for soil moisture and SPEI-PM with stronger changes for SPEI-PM (Naumann et al., 2018; Cook et al., 2020; Kirono et al., 2020; Vicente-Serrano et al., 2020c; 11.SM)

Region and Drought Type		Observed Trends	Human Contribution	Projections		
				+1.5°C	+2°C	+4°C
Southern Australia (SAU) *continued*	HYDR	***Medium confidence***: **Increasing drying signal in the southeast and particularly the southwest. Some dependence on time frame** in available studies (X.S. Zhang et al., 2016; Gudmundsson et al., 2019, 2021)	***Low confidence***: ***Limited evidence*** because of lack of studies (Cai and Cowan, 2008)	***Low confidence***: ***Limited evidence***. One study shows lack of signal (Touma et al., 2015)	***Medium confidence***: **Increase in drought**, but some inconsistent and non-robust change, including subregional/ seasonal differences (Touma et al., 2015; Zheng et al., 2019; Cook et al., 2020)	***Medium confidence***: **Increase in drought**, but some inconsistent changes depending on season or study (Giuntoli et al., 2015; Touma et al., 2015; Cook et al., 2020)

Section 11.1.4. Effects of Greenhouse Gas and Other External Forcings on Extremes.
"increases in the intensity of temperature extremes scale robustly, and in general linearly, with global warming across different geographical regions in projections up to 2100, with minimal dependence on emissions scenarios".



"Regional mean changes in annual hottest daily maximum temperature (TXx) for Australasia against changes in global mean surface air temperature (GSAT) as simulated by Coupled Model Intercomparison Project Phase 6 (CMIP6) models under different Shared Socio-economic Pathway (SSP) forcing scenarios, SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7. 0, and SSP5-8.5. Changes in TXx and GSAT are relative to the 1850–1900 baseline, and changes in GSAT are expressed as global warming level." This panel l shows the "multi-model median for the pooled data for Australasia" by sub-region. "Numbers in parentheses indicate the linear scaling between regional TXx and GSAT. The black line indicates the 1:1 reference scaling between TXx and GSAT". Sub-regions: Northern Australia (NAU), Central Australia (CAU), Eastern Australia (EAU), Southern Australia (SAU) and New Zealand (NZ). [panel l of Figure 11.3 from IPCC WG1 Chapter 11]

3.1.2 Chapter 12: Climate Change Information for Regional Impact and for Risk Assessment

Section 12.4.3 Australasia

12.4.3.1 Heat and Cold
Describing Mean air Temperature: "Mean temperature in Australasia is projected to continue to rise through the 21st century (virtually certain) (Atlas.6.4). Projections for Australia indicate that the average temperature will increase by +1.1°C (0.84–1.52°C 10–90th percentile range) by 2041–2060 (mid-century), and by +1.9°C (1.29–2.58°C) by 2081–2100 (end-century), relative to the baseline period of 1995–2014, under SSP2-4.5 (Interactive Atlas). For SSP5-8.5, the projected changes are up to +1.5°C (1.17–1.96°C) and +3.7°C (2.75–4.91°C) for mid- and end-century respectively. For SSP1-2.6, mean temperature is projected to rise by +0.9°C (0.55–1.26°C) and +1.0°C (0.55–1.54°C) relative to 1995–2014 by mid- and end-century respectively (Interactive Atlas)."

Describing extreme heat: "More frequent hot extremes and heatwaves are expected over the 21st century in Australia (virtually certain) (Table 11.10). Heat thresholds potentially affecting agriculture and health, such as 35°C or 40°C, are projected to be exceeded more frequently over the 21st century in Australia under all RCPs (high confidence). By 2090 under RCP4.5, the average number of days per year with maximum temperatures above 35°C is highly spatially variable and is expected to increase by 50–100%, while the number of days per year with maximum temperatures above 40°C is expected to increase by 200%, relative to 1985–2005 (CSIRO and BOM, 2015). Under RCP8.5 the corresponding projected increases are even greater, with a greater than 100% increase in most of Australia, and far greater increases in Central and Northern Australia (up to a 20-fold increase in Darwin)."

"The projected frequency of exceeding dangerous humid heat thresholds is increasing in Australia, with a strong increase in Northern Australia for RCP8.5 (high confidence) (Zhao et al., 2015; Mora et al., 2017; Brouillet and Joussaume, 2019), consistently across CMIP5, CMIP6 and CORDEX simulations (Figure 12.4d–f and Figure 12.SM.2). Using the HI index, by end-century, the average number of days exceeding 41°C is projected to increase in NAU by about 100 days and by about 25 days under SSP5-8.5 and SSP1-2.6, respectively."

Describing cold spell and frost: "Less frequent cold extremes are virtually certain in Australasia (Table 11.10) while a decrease of frost days is projected with high confidence for the region. Projections, relative to 1986–2005, for the number of frost days per year in Australia indicate declines of 0.9 days by mid-century and 1.1 days by end-century for RCP4.5, while for RCP8.5, the projected declines are 1.0 days and 1.3 days by mid- and end-century respectively (Alexander and Arblaster, 2017; Herold et al., 2018)."

Conclusion: "In general, there is high confidence that most heat hazards in Australasia will increase and that cold hazards will decrease over the 21st century. The mean temperature in Australasia is virtually certain to continue to rise through the 21st century, accompanied by less frequent cold extremes (virtually certain) and frost days (high confidence), and more frequent hot extremes (virtually certain). Heat stress is projected to increase in Australia (high confidence)."

12.4.3.2 Wet and Dry

Describing mean precipitation: "Annual mean precipitation is projected to increase in Central and north-east Australia (low confidence) and in the south and west of New Zealand (medium confidence) (Atlas.6.4). Liu et al. (2018a) show that under 1.5°C warming, Central and north-east Australia will become wetter."

Describing river flood: "While median annual runoff is projected to decrease in most of Australia (Chiew et al., 2017), consistent with projected decreases in average rainfall (CSIRO and BOM, 2015; Alexander and Arblaster, 2017), river floods are projected to increase due to more intense extreme rainfall events and associated increase in runoff (medium confidence). Asadieh and Krakauer (2017) found a decrease in the value of the 95% percentile of mean streamflow with RCP8.5 by the end of the century in all of Australia, except in a small part in centre of the country. In terms of relative increases, flooding is expected to increase more in Northern Australia (driven by convective rainfall systems) than in Southern Australia (where more intense extreme rainfall may be compensated by drier antecedent moisture conditions; Alexander and Arblaster, 2017; Dey et al., 2019) with flood frequency increasing in Northern Australia and along parts of the east coast and decreasing in south-western Western Australia (Hirabayashi et al., 2013). Gu et al. (2020) project larger flood magnitude and volumes under both RCP2.6 and RCP8.5 in Northern Australia, and smaller flood magnitudes and volumes in Southern Australia under the same RCPs. These findings are in general agreement with the patterns in peak flow, corresponding to the 1-in-100-year return period streamflow, shown in Figure 12.7a,c for mid-21st century under RCP8.5."

Describing Heavy precipitation and pluvial flood: "There is high confidence that Rx1day and Rx5day precipitation extremes will increase for 2°C or lower warming for the region as a whole, but on a sub-regional basis there is only medium confidence of increases in NAU and CAU and low confidence of increases on EAU, SAU and NZ. For warming levels exceeding 2°C, these extremes are very likely to increase in NAU and CAU and they are likely to increase elsewhere in the region (Section 11.9)."

Describing aridity: "Aridity is projected to increase, especially during winter and spring, with medium confidence in SAU but with high confidence in south-west Western Australia (Table 11.11 and Atlas.6.4). In EAU […], aridity is projected to increase with medium confidence […]. Although there is only low confidence in the projected decrease of mean annual precipitation in south-western and eastern Australia […], there is high confidence of reduced winter and spring precipitation in Australia in future, mostly in south-western and eastern Australia (Atlas.6.4). Liu et al. (2018b) show that under 2°C warming, most of Australia is projected to become drier based on the Palmer Drought Severity Index (PDSI), with the exception of the tropical north-east. Ferguson et al. (2018) project that between 1976–2005 and 2070–2099, winters will become drier (mainly in Southern Australia) under RCP8.5."

Describing hydrological drought: "Future projections indicate medium confidence in further hydrological drought increases for Southern Australia for warming levels of 2°C or higher (Section 11.9). Mean annual runoff in far south-east and far south-west Australia are projected to decline by median values of 20 and 50% respectively, by mid-century under RCP8.5 (Chiew et al., 2017). Prudhomme et al. (2014) assess changes in the Drought Index (DI), defined as areal runoff less than the 10th percentile over the reference period 1976–2005, and project DI increases for both Australia and New Zealand by 10–20% by 2070–2099 under RCP8.5, with the greatest effects being in the southern parts of the Australian continent. These projections are consistent with the trends shown in Figure 12.4g–i (Figure 12.SM.3). The SPI drought frequency is projected to increase in SAU and particularly in south-west Western Australia by mid-century, while by the end of the century SPI drought frequency is projected to increase all over Australia, and particularly strongly in south-west Western Australia as well as southern Victoria (see Figure 12.4g–i). For the Murray–Darling basin, Ferguson et al. (2018) project effectively no change (–1%) in mean precipitation, a 27% decrease in P–E, and 30% increase in runoff in 2070–2099 relative to 1976–2005 with RCP8.5."

Describing agricultural and ecological drought: "Future evaporative demand is projected to lead to medium confidence increases in agricultural and ecological droughts for 2°C of global warming in SAU and EAU and low confidence for changes in CAU, NAU and NZ, although there is medium confidence of increases in CAU with 4°C of global warming (Section 11.9). There is medium confidence for more time in agricultural and ecological drought in SAU by mid-21st century (Coppola et al., 2021b) as well as by the end of the 21st century (Herold et al., 2018). […] There is consensus among the different model ensembles (CORDEX-CORE, CMIP5 and CMIP6) that the drought frequency (DF), one of several proxies for agricultural and ecological drought, will increase in all four Australian regions for both mid-century (NAU 0.2–2 DF increase, CAU 0.5–2 DF increase, SAU 1–3 DF increase and EAU 0.8–3 DF increase) and end-century (0.8–2.7 DF increase for NAU, 1.2–2 DF increase for CAU, 2.2–3.8 for SAU and 0.2–3 for EAU) for both RCP8.5 and SSP5-8.5, with CMIP6 showing the lowest increase (Figure 12.4g–l and Figure 12.SM.4; Coppola et al., 2021b)."

Describing fire weather: "Fire weather indices are projected to increase in most of Australia (high confidence) and many parts of New Zealand (medium confidence), in particular with respect to extreme fire and induced pyroconvection (Dowdy et al., 2019b). Increasing mean temperature, cool season rainfall decline, and changes in tropical climate variability all contribute to a future increase in extreme fire risk in Australia (Abram et al., 2021). Projections indicate that the annual cumulative FFDI will increase by 31–33% in Southern and Eastern Australia, and by 17–25% in Northern Australia and the Rangelands by 2090 (relative to 1995) under RCP8.5 (CSIRO and BOM, 2015). Using a CMIP5 ensemble of 17 models, Abatzoglou et al. (2019) found a statistically significant positive trend for fire weather intensity and fire season length for future mid-century conditions under RCP8.5, including a detectable anthropogenic influence on fire risk magnitude and fire season length by 2040 in Western Australia and along the Queensland coastline. Using the C-Haines and FFDI indices with A2 and RCP8.5 respectively, Di Virgilio et al. (2019) and Clarke et al. (2019) have shown that extreme fire weather frequency will increase in south-eastern Australia by the end of the 21st century. Most of these projections indicate that the biggest increases in fire weather conditions will be in late spring, effectively resulting in longer (stronger) fire seasons in areas where spring is the shoulder (peak) season."

In summary: "Annual mean precipitation is projected to increase in Central and north-east Australia (low confidence) […] while it is projected to decrease in Southern Australia (medium confidence), albeit with high confidence in south-west Western Australia, in Eastern Australia (medium confidence) […]. Heavy precipitation and pluvial flooding are projected to increase with medium confidence in Northern Australia and Central Australia. There is medium confidence that river flooding will increase in […] Australia, with higher increases in Northern Australia. Aridity is projected to increase with medium confidence in Southern Australia (high confidence in south-west Western Australia), Eastern Australia (medium confidence) [..]. Hydrological droughts are projected to increase in Southern Australia (medium confidence), while agricultural and ecological droughts are projected to increase with medium confidence in Southern Australia and Eastern Australia. Fire weather is projected to increase throughout Australia (high confidence) […]."

12.4.3.4 Snow and Ice

Describing snow: "Projections for Southern Australia […] show a continuing reduction in snowfall during the 21st century (high confidence). The magnitude of decrease varies with the altitude of the region and the emissions scenario. At elevations lower than 1500 m, years without snowfall are projected from 2030 in some models. By 2090, and under RCP8.5, such years are projected to become common (CSIRO and BOM, 2015)."

12.4.3.5 Coastal and Oceanic

Describing relative sea level rise: "Relative sea level is virtually certain to increase throughout the region over the 21st century (Section 9.6.3, Figure 9.28). Regional mean RSLR projections for the oceans around Australasia range from 0.4–0.5 m under SSP1-2.6 to 0.7–0.9 m under SSP5-8.5 for 2081–2100 relative to 1995–2014 (median values), which means local RSL change falls within the range of mean projected GMSL change (Section 9.6.3.1). However these RSLR projections may be underestimated due to potential partial representation of land subsidence (Section 9.6.3.2)."

Describing coastal floods: "Extreme total water level magnitude and occurrence frequency are expected to increase throughout the region (high confidence) (Figure 12.4p–r and Figure 12.SM.6). Across the region, the 5–95th percentile range of the 1-in-100-year ETWL is projected increase (relative to 1980–2014) by 5–35 cm and by 10–40 cm by 2050 under RCP4.5 and RCP8.5 respectively (Figure 12.4q). By 2100 (Figure 12.4p,r), this range is projected to be 25–80 cm and 50–190 cm under RCP4.5 and RCP8.5 respectively (Vousdoukas et al., 2018; Kirezci et al., 2020). Furthermore, the present-day 1-in-100-year ETWL is projected to have median return periods of around 1-in-20-years by 2050 and 1-in-1-year by 2100 in SAU and NZ and return periods of around 1-in-50-years by 2050 and 1-in-20-years by 2100 in NAU under RCP4.5 (Vousdoukas et al., 2018), while the present-day 1-in-50-year ETWL is projected to occur around three times a year by 2100 with a SLR of 1 m around Australasia (Vitousek et al., 2017)."

Describing coastal erosion: "Projections indicate that a majority of sandy coasts in the region will experience shoreline retreat, throughout the 21st century (high confidence) (Figure 12.7b,d). Median shoreline change projections (CMIP5) under both RCP4.5 and RCP8.5 presented by Vousdoukas et al. (2020b) show that, by mid-century, sandy shorelines will retreat (relative to 2010) by between 50 and 80 m all around Australasia, except in SAU and NZ where the projected retreat (relative to 2010) is between 35 and 50 m. By 2100, median shoreline retreats exceeding 100 m (relative to 2010) are projected along the sandy coasts of NAU (about 150 m), CAU (about 160 m), and EAU (about 110 m) under RCP4.5m, while projections for SAU […] are around 80–90 m. Under RCP8.5, shoreline retreat exceeding 100 m is projected all around the region by 2100 (relative to 2010) with retreats as high as 220 m in NAU and CAU (about 170 m in EAU and about 130 m in SAU and NZ; Figure 12.7b,d). The total length of sandy coasts in Australasia that is projected to retreat by more than a median of 100 m by 2100 under RCP4.5 and RCP8.5 is about 12,500 and 16,000 km respectively, an increase of approximately 30%."

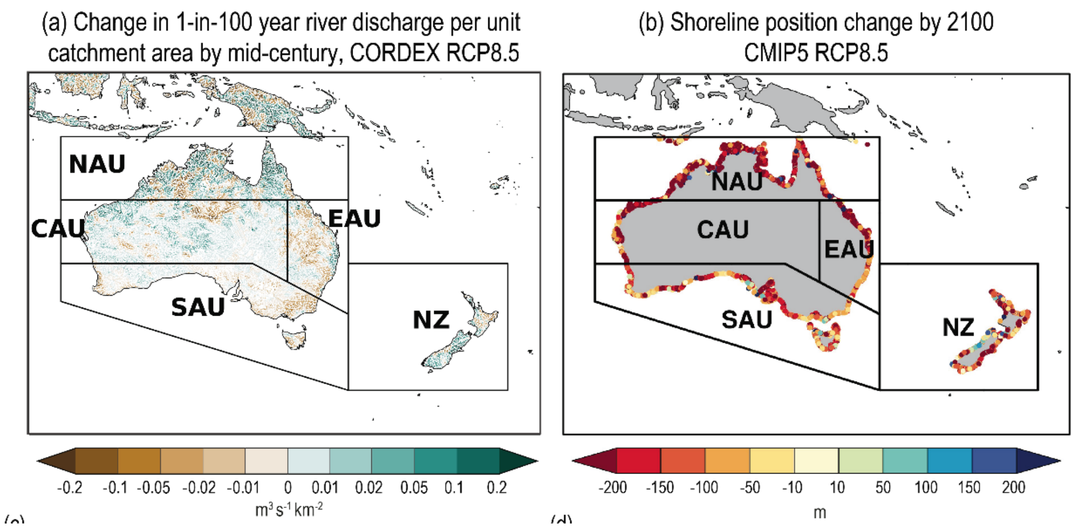
"Distinct from long-term coastline recession, storms and storm surges also result in episodic coastal erosion. In general, the historically measured maximum episodic coastal erosion (either eroded volume or coastline retreat distance) or that due to a 1-in-100-year return period storm wave height is used as a design criterion for coastal zone management and planning in Australia (Wainwright et al., 2014; Mortlock et al., 2017)."

"While there is wide recognition in Australia that the combined effect of SLR, changing storm surge and wave climates will directly affect future episodic coastal erosion (McInnes et al., 2016; Ranasinghe, 2016; Harley et al., 2017) only a few projections of how this hazard may evolve are available for Australia. In one such study, Jongejan et al. (2016) provide projections of how the full exceedance probability curve of the maximum erosion per year may evolve over the 21st century (due to the combined action of SLR, storm surge and storm waves). Their results show that, for example, the 0.01 exceedance probability maximum coastline retreat in 2025 will have an exceedance probability of 0.015 by 2050 and 0.07 by 2100."

Describing marine heatwaves: "There is high confidence that MHWs will increase around most of Australasia. Under RCP4.5 and RCP8.5 respectively, mean SST is projected to increase by 1°C and 2°C around Australia by 2100, with a hotspot of around 2°C for RCP4.5 and of 4°C for RCP8.5 along the south-east coast between Sydney and Tasmania (Interactive Atlas). Under all RCPs, the mean SST around Australia is expected to increase in the future, with median values of around 0.4°C–1.0°C by 2030 under RCP4.5, and 2°C–4°C by 2090 under RCP8.5 (CSIRO and BOM, 2015). Warming is expected to be largest along the north-west coast of Australia, southern Western Australia, and along the east coast of Tasmania (CSIRO and BOM, 2018). More frequent, extensive, intense and longer lasting MHWs are projected around Australia and New Zealand for GWLs of 1.5°C, 2°C and 3.5°C relative to the modelled reference value for 1861–1880 (Frölicher et al., 2018). Projections for SSP1-2.6 and SSP5-8.5 both show an increase in MHWs around Australasia by 2081–2100, relative to 1985–2014 (Box 9.2, Figure 1)."

In summary: "In general, there is high confidence that most coastal/ocean-related hazards in Australasia will increase over the 21st century. Relative sea level rise is virtually certain to continue in the oceans around Australasia, contributing to increased coastal flooding in low-lying areas (high confidence) and shoreline retreat along most sandy coasts (high confidence). Marine heatwaves are also expected to increase around the region over the 21st century (high confidence)."

Figure 12.7. This figure 12.7 illustrates "projected changes in two selected climatic impact-driver indices for Australasia". We only reproduce here below the top two panels: "*(a) Mean change in 1-in-100-year river discharge per unit catchment area (Q100, $m^3s^{-1}km^{-2}$) from CORDEX-Australasia models for 2041–2060 relative to 1995–2014 for RCP8.5. (b) Shoreline position change along sandy coasts by the year 2100 relative to 2010 for RCP8.5 (metres; negative values indicate shoreline retreat) from the CMIP5-based dataset presented by [Vousdoukas et al. (2020b)](#)*."



3.1.3 Interactive Atlas: Regional information (advanced)

We reproduce in this section projections of key climate variables for Australia, as provided in the Working Group 1 Interactive Atlas, for two warming levels and their associated emission pathways:

- Warming of 3°C under SSP3-7.0
- Warming of 4°C under SSP5-8.5

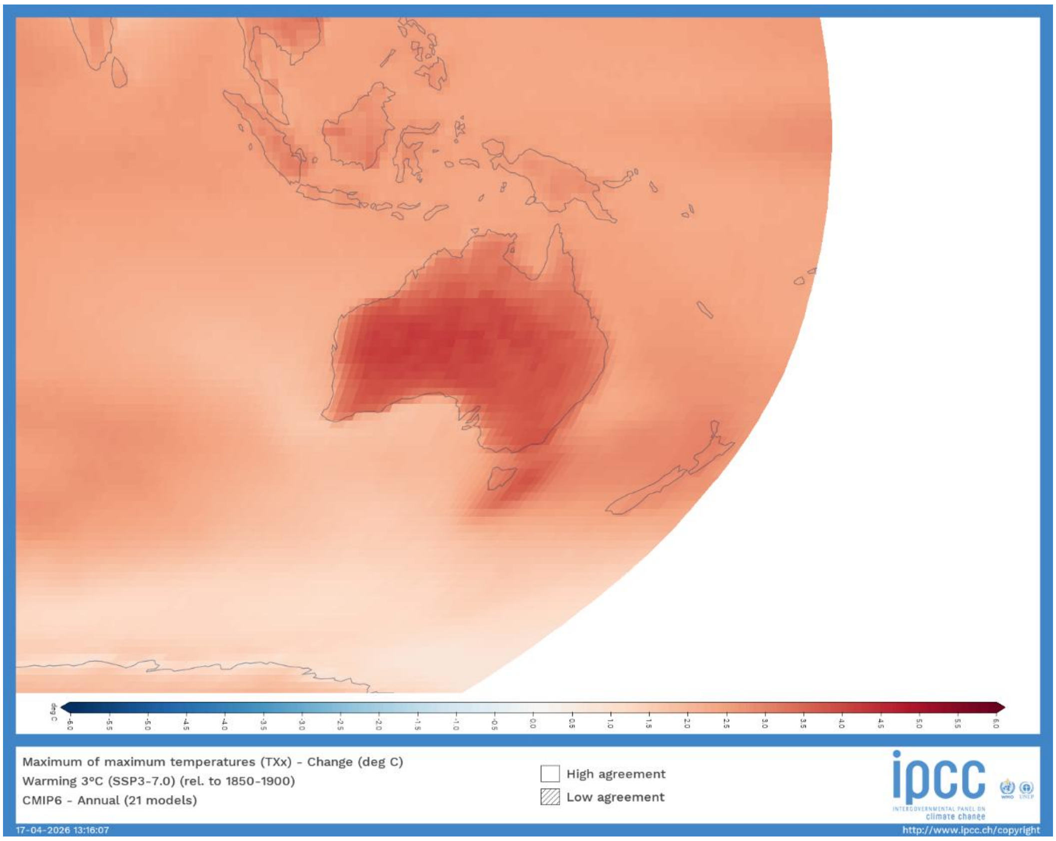
Each map shows the percentage change in the chosen variable relative to the pre-industrial average (1850-1900), with projections provided from the Coupled Model Intercomparison Project 6 (CMIP6) modelling experiments. The Interactive Atlas (regional information – advanced) can be further queried here.

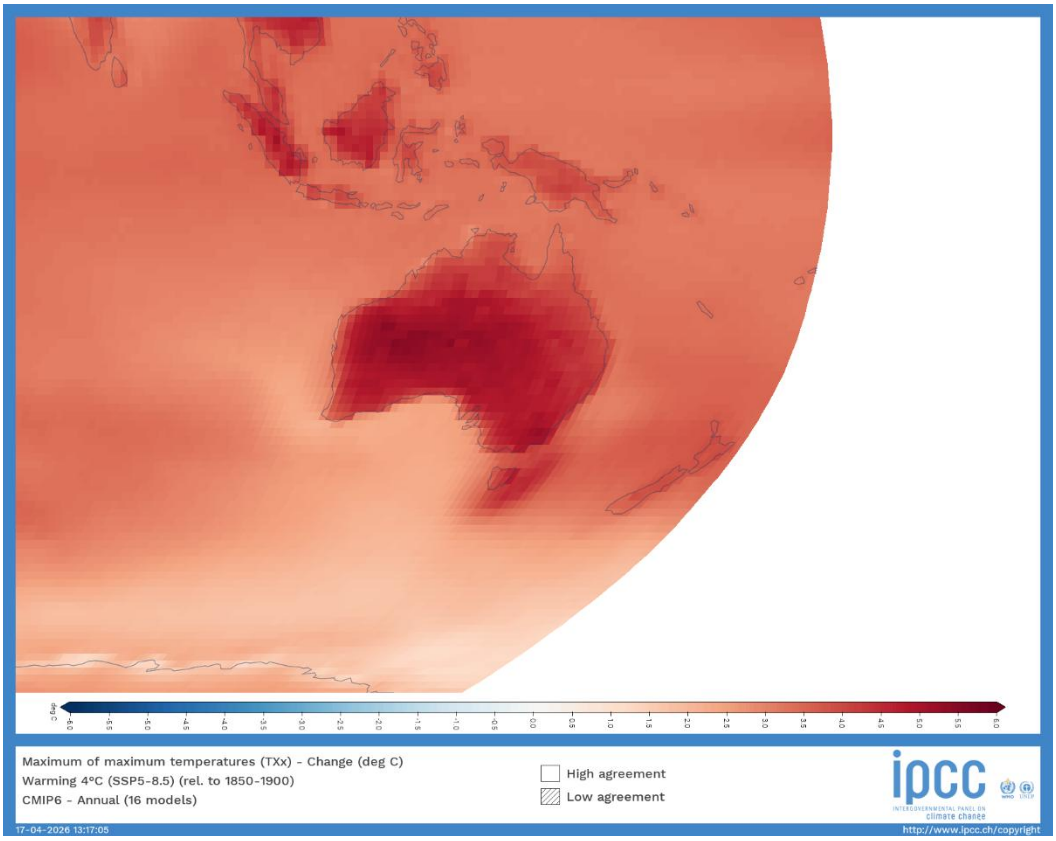
The text panel at the bottom of each figure provides metadata regarding: (i) the variable displayed, (ii) the warming scenario, (iii) the model(s) used, (iv) the timescale examined (annual in all cases), (v) the number of model simulations (outputs) that have been averaged to produce the map shown. No stippling indicates a high agreement between the distinct model simulations; stippling indicates a low agreement between the simulations. The occurrence of stippled areas of the maps therefore indicates areas for which we are more uncertain about the projected change for that specific variable and warming level. We note that stippling only occurs over and around Australia for the river flood and drought indicator, highlighting the strong agreement among climate projections with different Earth system models for all other variables considered: heat, marine heatwaves, coastal flooding and ocean acidification.

Each climate indicator is further defined in Annex VI of WG1.

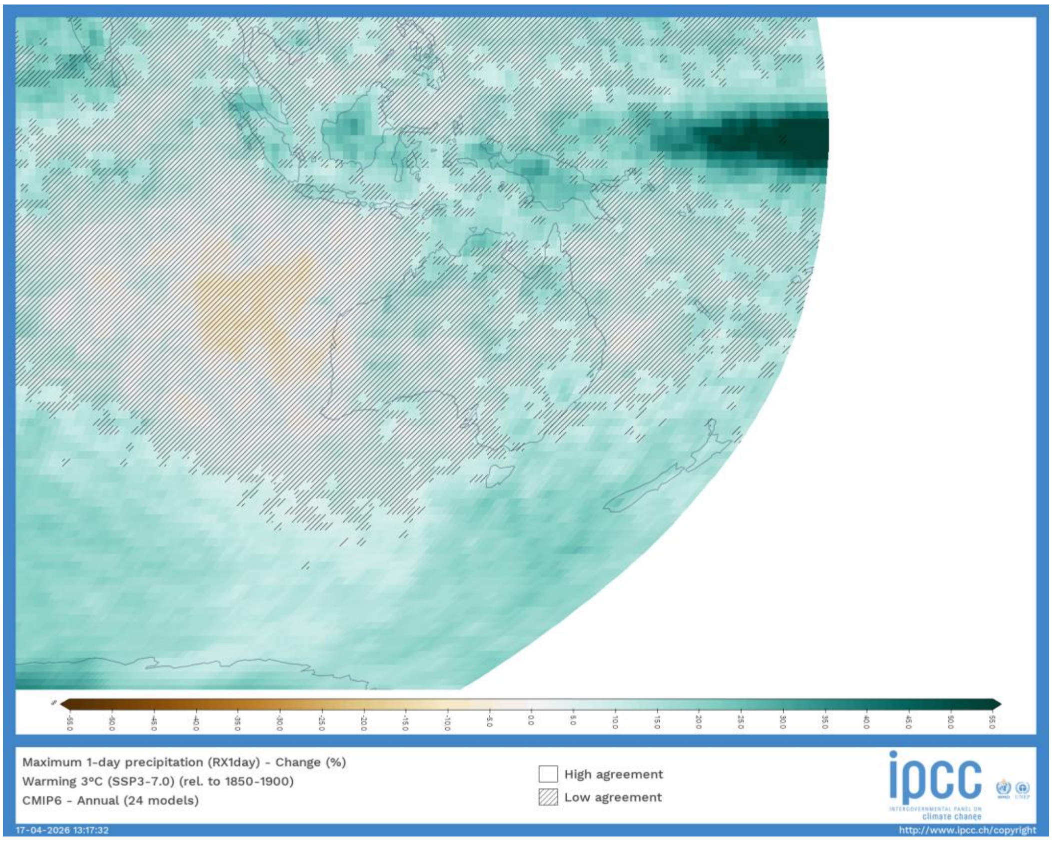
We always display the 3°C warming scenario (top panel), then the 4°C warming scenario (bottom panel).

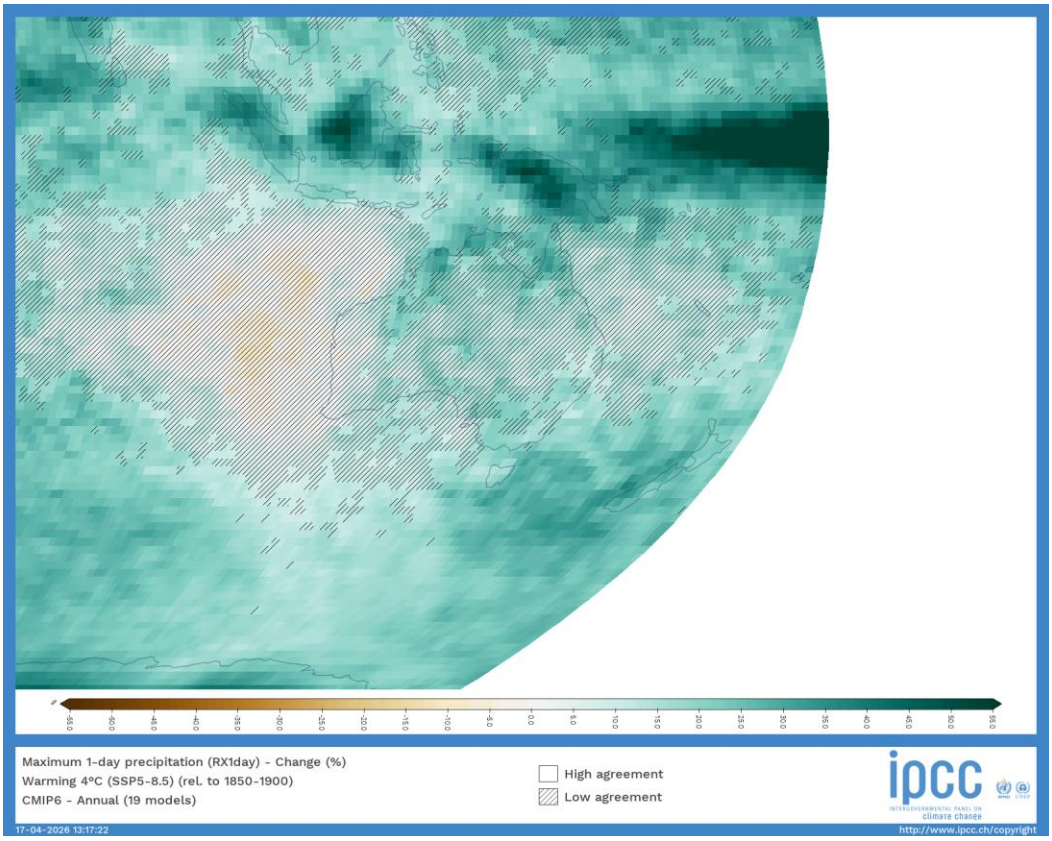
Heat indicator: Maximum of maximum temperatures (TXx, as defined in Annex VI of WG1)
TXx is the annual maximum of daily maximum temperature, in degrees Celsius.



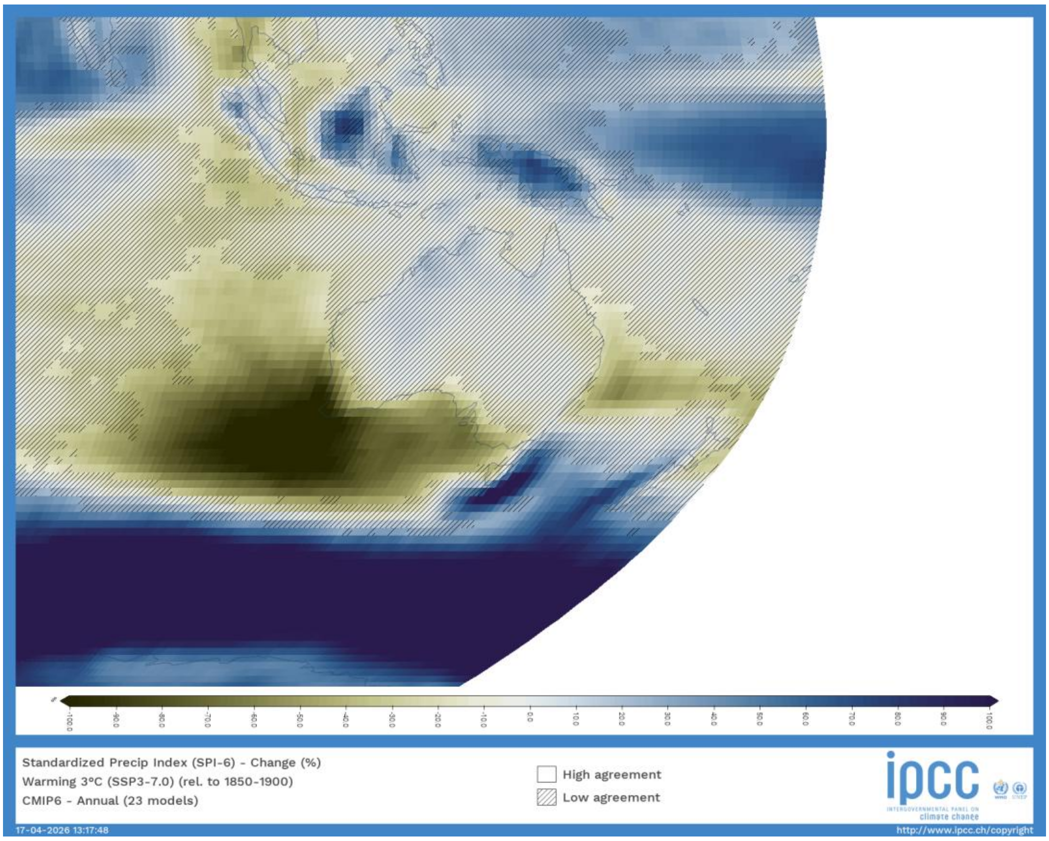


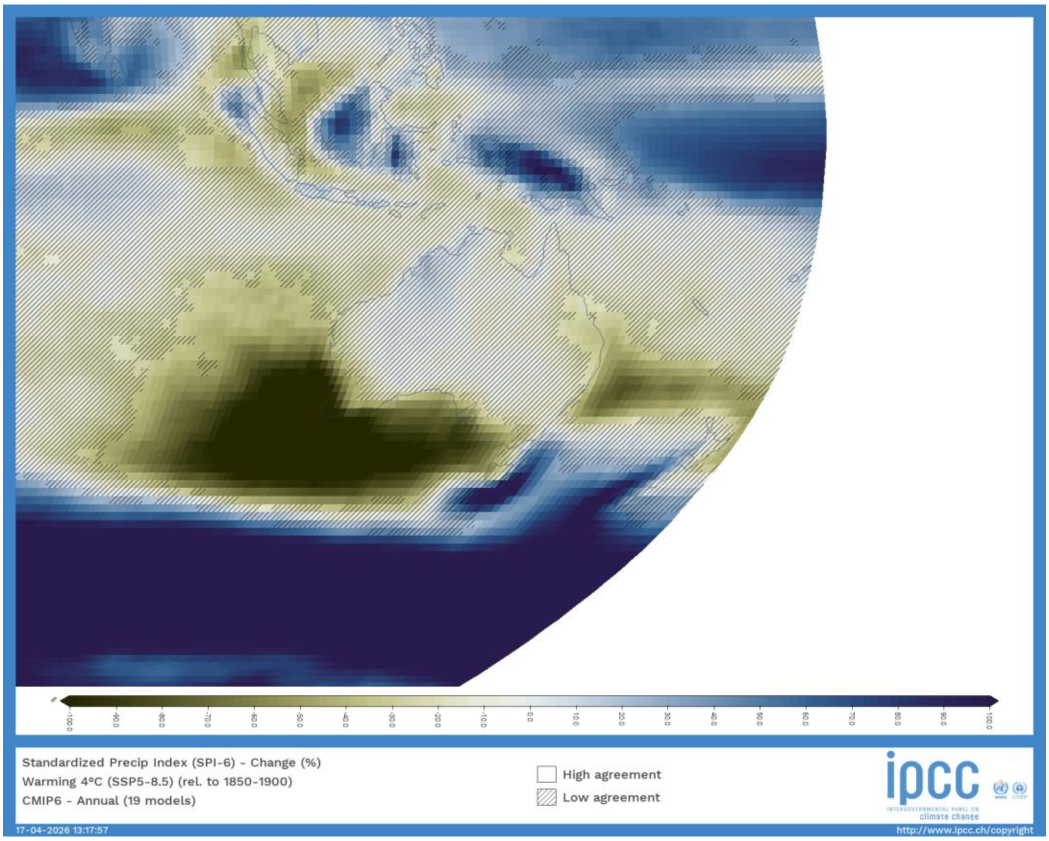
<u>River flood indicator:</u> Maximum 1-day precipitation (RX1day)
RX1day is the annual maximum 1-day precipitation amount in mm.



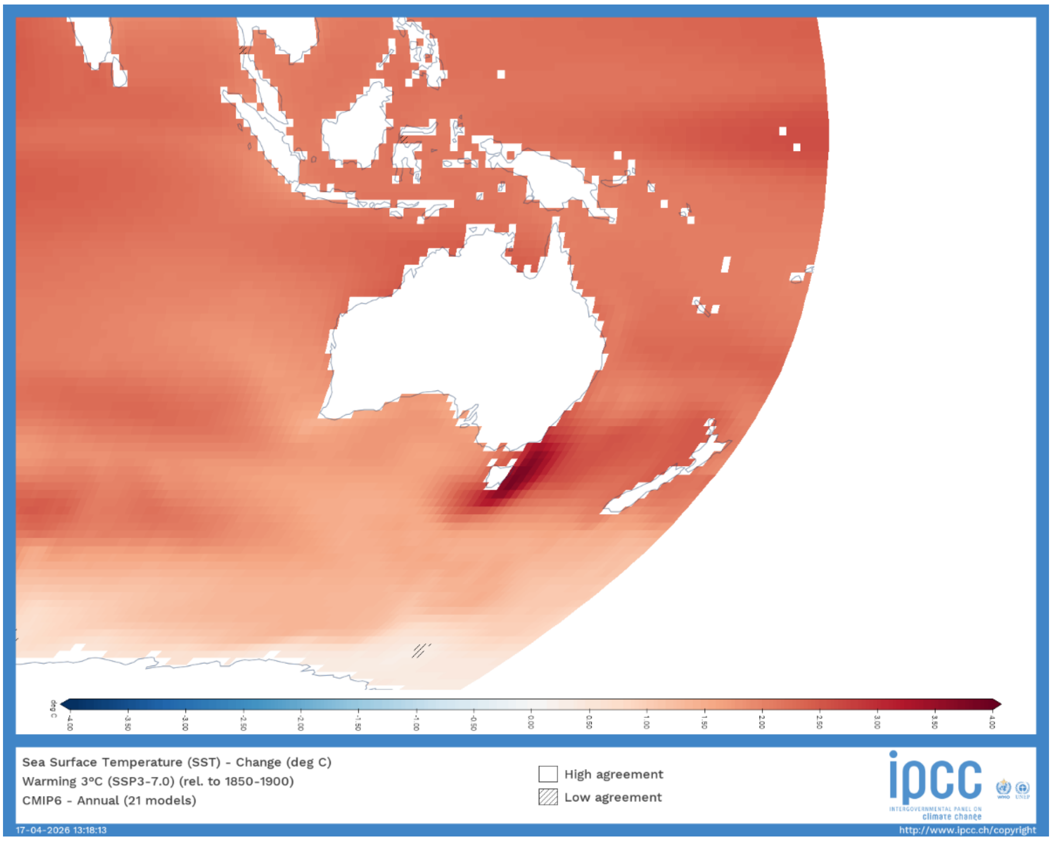


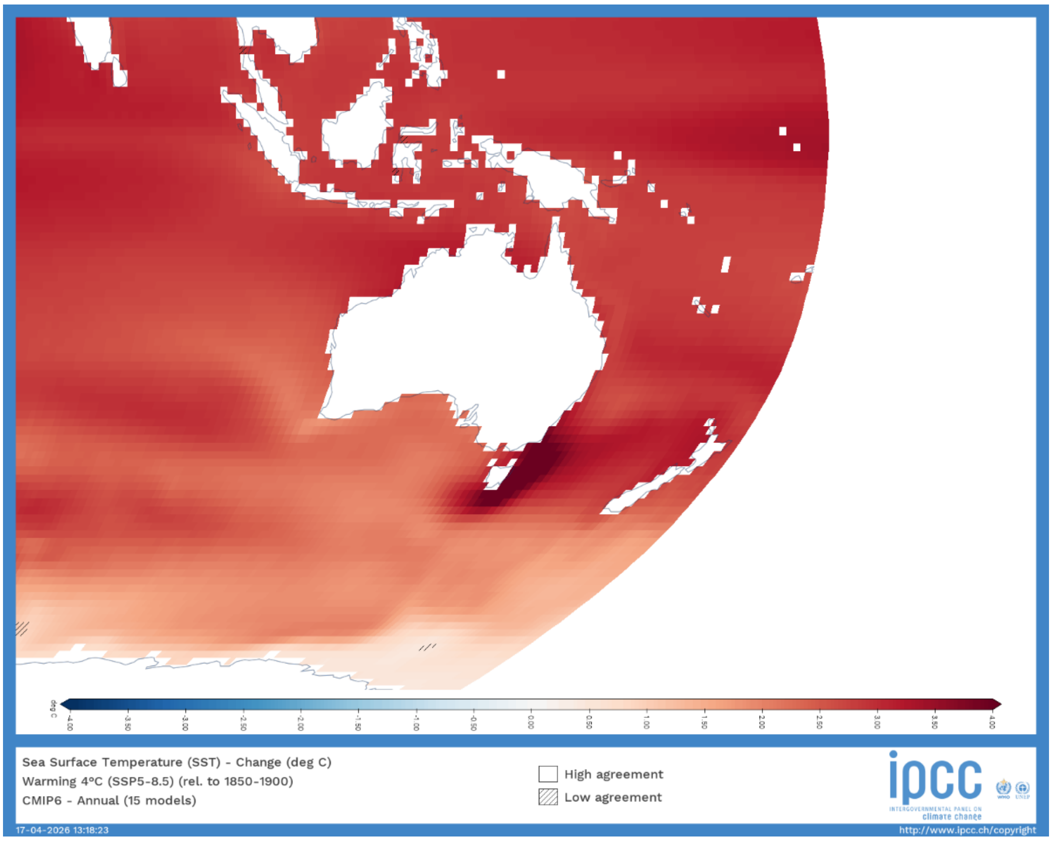
Drought indicator: Standardized Precipitation Index (SPI-6).
SPI-6 is an index that compares cumulated precipitation for 6 months with the long-term precipitation distribution for the same location and cumulation period. It does not have a unit.



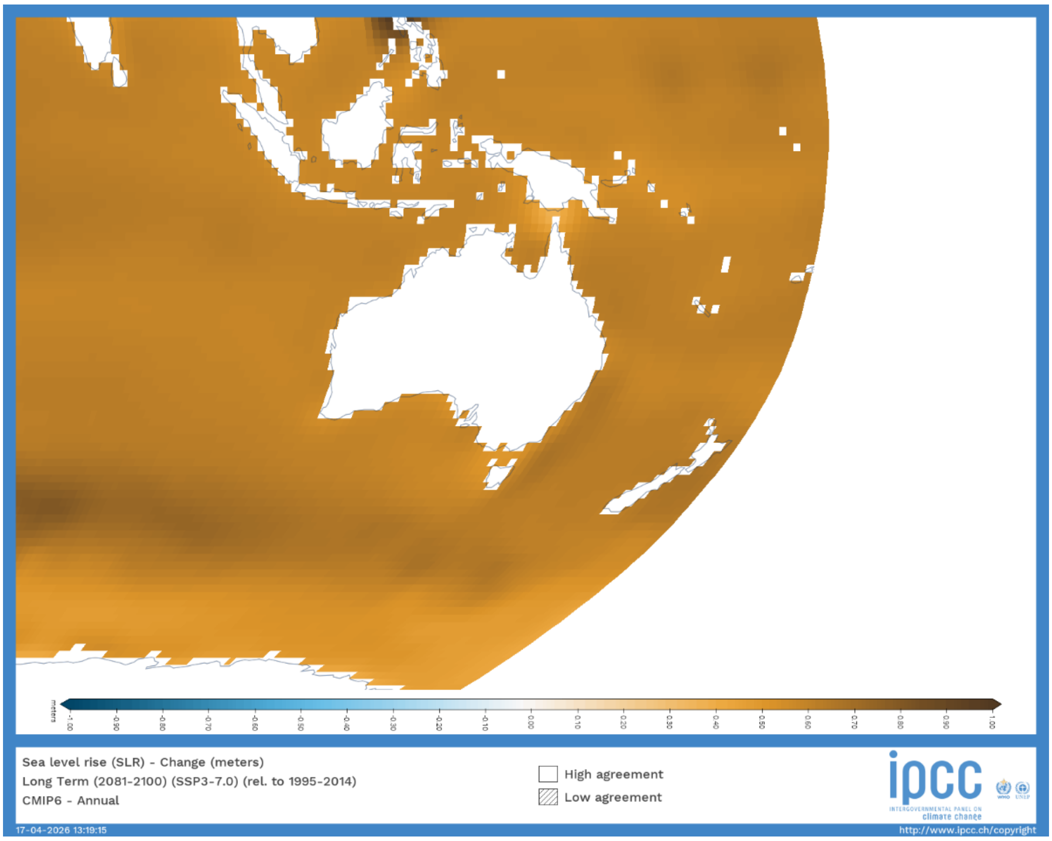


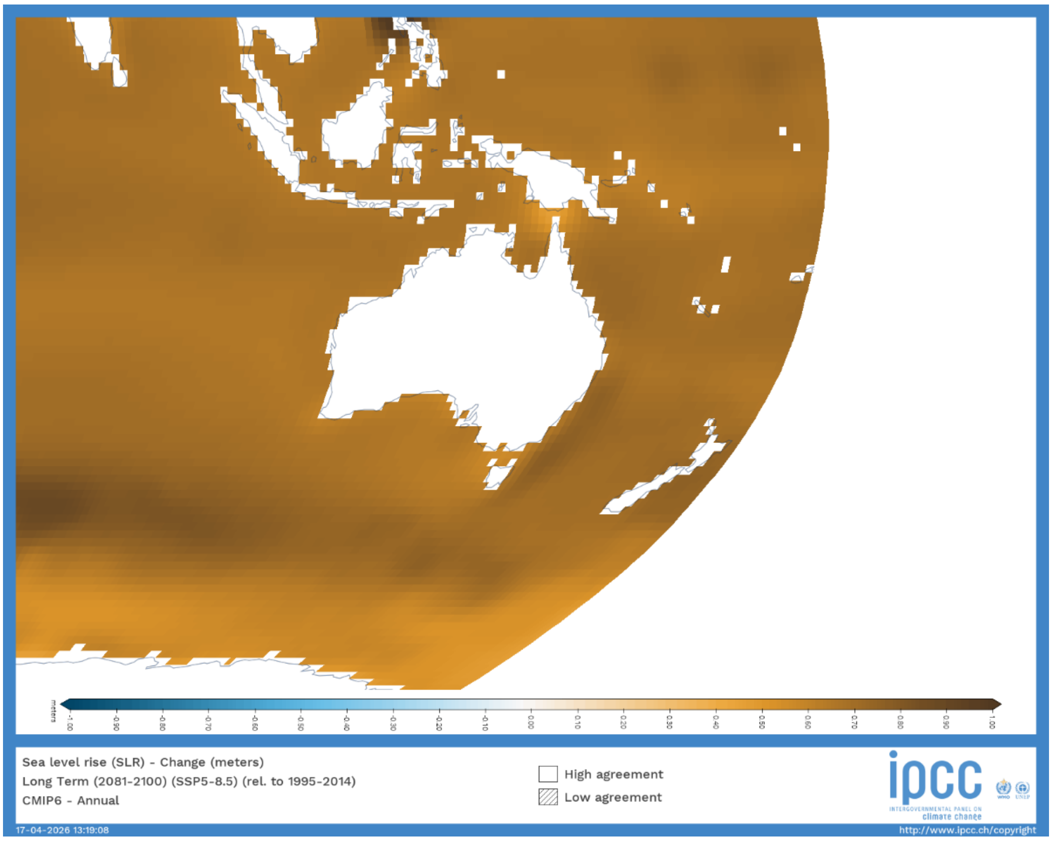
Marine heatwave indicator: Sea Surface Temperature (SST).
SSTs is the temperature of the sea at surface level, in units of degrees Celsius.



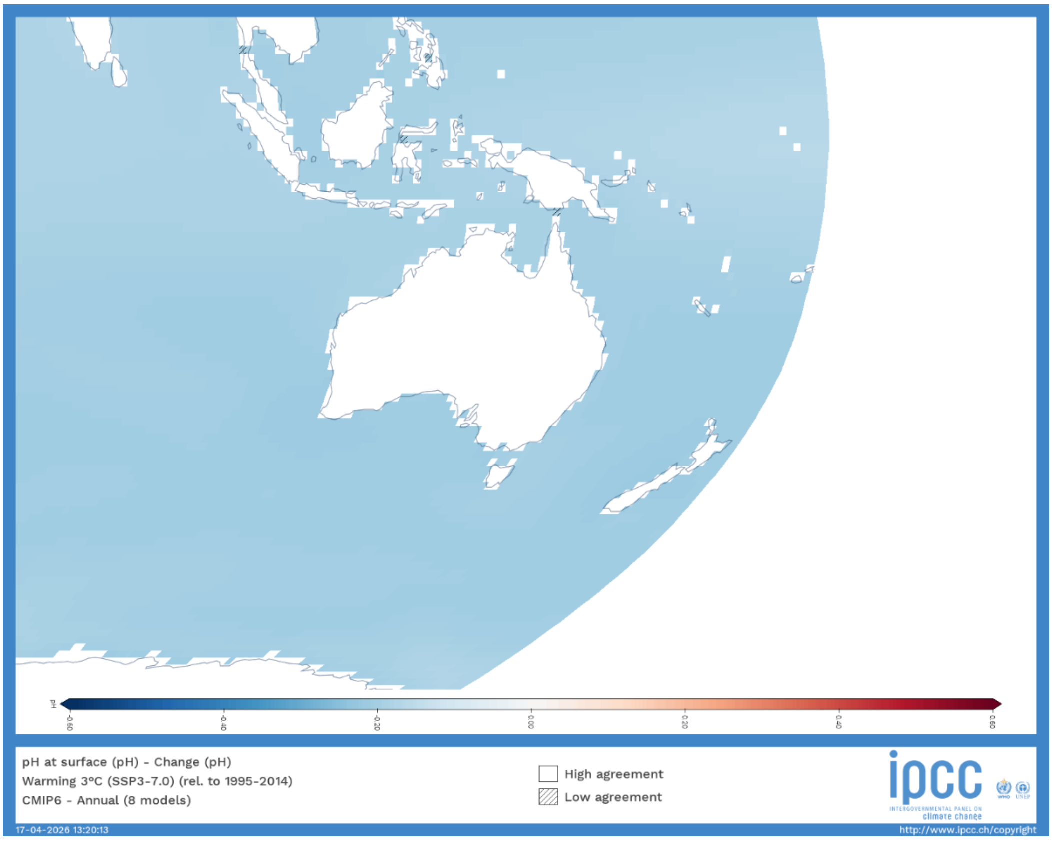


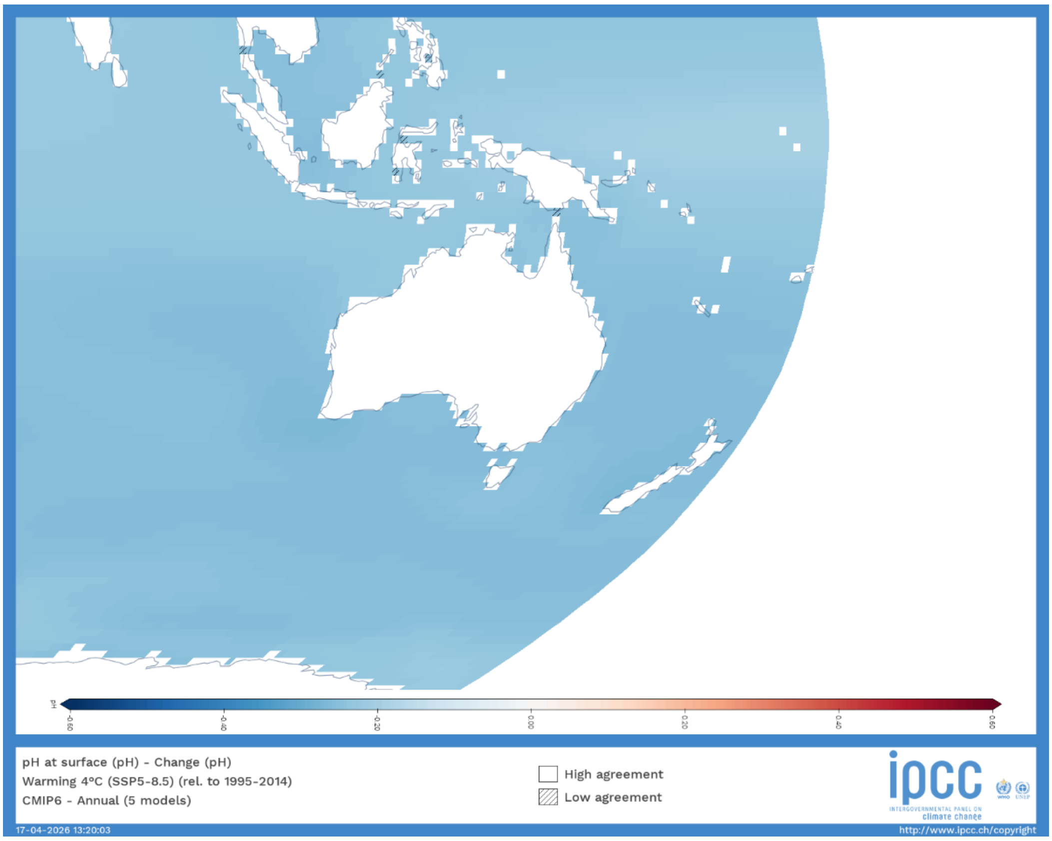
Coastal flood indicator: Sea level rise (SLR).
SLR is total sea level rise, in meters above sea level.





<u>Ocean acidification indicator:</u> pH at surface (pH).
pH is the pH at the surface of the ocean, pH units.





3.2 Working Group 2 contribution to the Sixth Assessment Report (AR6)

3.2.1 Chapter 2: Terrestrial and freshwater ecosystems and their services

Executive summary: "Biodiversity loss is projected for more regions with increasing warming, and will be worst in northern South America, southern Africa, <u>most of Australia</u> and at northern high latitudes (medium confidence) {2.5.1.3; Figure 2.6}." (own emphasis)

2.3.1 Observed Changes to Hazards and Extreme Events: "While the major climate hazards at the global level are generally well described with high confidence, there is less understanding about the importance of hazards on ecosystems when they are superimposed […] and the outcomes are difficult to quantify in future projections (Handmer et al., 2012). Simultaneous or sequential events (coincident or compounding events) can lead to an extreme event or impact, even if each event is not in themselves extreme (Denny et al., 2009; Hinojosa et al., 2019). […] On land, changing rainfall patterns and repeated heat waves may interact with biological factors such as altered plant growth and nutrient allocation under elevated CO_2, affecting herbivore rates and insect outbreaks leading to the widespread dieback of some forests (e.g., in Australian eucalypt forests) (Gherlenda et al., 2016; Hoffmann et al., 2019a)."

2.5.1.3.3 Global projections of extinction risk: "About one-third of land area risks more than 50% of species becoming "endangered" by 4.0° GSAT warming (Figure 2.6). […] Species' losses are projected to be worst in northern South America, southern Africa, most of Australia and at northern high latitudes (medium confidence) (Figure 2.6)."

2.5.2.3 Risk to Arid Regions: "Warm season (C4) grass expansion into arid shrublands risks sudden ecosystem transformation due to introduced wildfire (Bradley et al., 2016), a risk anticipated for grass-invaded desert ecosystems of Australia and the southwestern USA (Horn and St. Clair, 2017)."

2.5.2.6 Risk to Tropical Forests: "[sea level rise] as the result of climate change is likely to influence mangroves in all regions, with greater impact on North and Central America, Asia, Australia and East Africa than on West Africa and South America (robust evidence, high agreement)."

2.5.3.2.2 Future projections of wildfire in high-risk areas: "Regions identified by multiple global analyses as being at a high risk of increased burned area, fire frequency and fire weather include: […] Western Australia (Gonzalez et al., 2010; Burton et al., 2018; Abatzoglou et al., 2019) […]. Higher-resolution spatial projections indicate high risks of increased wildfire in the Amazon, Australia, boreal ecosystems, Mediterranean Europe and the USA with climate change (medium evidence, medium agreement)."

2.5.3.2.2 Future projections of wildfire in high-risk areas: "In Australia, climate change under RCP8.5 increases the risk of pyro-convective fire by 20–40 days in rangelands of Western Australia, South Australia and the Northern Territory (Dowdy et al., 2019). Pyro-convective fire conditions could reach more frequently into the more populated areas of New South Wales, particularly at the start of the austral summer (Di Virgilio et al., 2019). […] Increases in heat and potential increases in wildfire threaten the existence of temperature montane rainforest in Tasmania, Australia (Mariani et al., 2019)."

3.2.2 Chapter 4: Water

4.4.5 Projected Changes in Droughts: "Agricultural drought likelihood also increases by 100–250% at 4°C global warming in southwestern North America, southwest Africa, southern Asia and Australia."
"[…] On the other hand, van Vliet et al. (2016b) projected an increase in global hydropower production between +2.4% to +6.3% under RCP4.5 and RCP8.5, respectively, by the 2080s, as compared to a baseline period of 1971–2000, but with significant regional variations (high confidence)."

4.5.2 Projected Risks to Energy and Industrial Water Use: "[…] On the other hand, southern Europe, northern Africa, southern USA and parts of South America, southern Africa and southern Australia are projected to experience more than 20% decreases in gross hydropower potential."

4.5.8 Projected Risks to the Cultural Water Uses of Indigenous Peoples, Local Communities and Traditional Peoples: "In Australia, Yuibera and Koinmerburra Traditional Owners fear the saltwater inundation of culturally significant sites and waterholes (Lyons et al., 2019)."

3.2.3 Chapter 5: Food, Fibre and Other Ecosystem Products

5.10.3 Projected Impacts: "In the Western Australian wheat belt, Thamo (2017) assessed climate-change-induced shifts in farm profitability to the 2050s. For most options, the adverse effects on profitability were greater than the advantageous effects, profit margins being much more sensitive to climate change than production levels."

3.2.4 Chapter 11: Australia

Executive summary - Projected impacts and key risks: "Further climate change is inevitable, with the rate and magnitude largely dependent on the emission pathway (very high confidence). 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. More extreme fire weather is projected in southern and eastern Australia (high 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}"
"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}"

Table 11.3a below provides "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 11.5 describes a "selection of projected climate-change impacts on terrestrial and freshwater ecosystems and species in Australia".

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)

11.3.1.2 Projected Impacts: "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).[…] 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."

11.3.1 Terrestrial and Freshwater Ecosystems - Box 11.1. Escalating Impacts and Risks of Wildfire: This box describes how fire activity has been increasing in Australia and discusses future projections: "Fire weather is projected to increase in frequency, severity and duration for southern and eastern Australia (high 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)."

11.3.2 Coastal and Ocean Ecosystems - 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 to decline with continued warming. […] Climate-change-related temperature and acidification may affect species sex ratios and, thus, population viability (medium 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)."

11.3.2 Coastal and Ocean Ecosystems - Box 11.2. The Great Barrier Reef in Crisis: This box describes the impacts of climate changes on the Great Barrier Reef and particularly how it induces coral bleaching: "Bleaching is expected to continue for the [Great Barrier Reef] 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."

11.3.3 Freshwater Resources - 11.3.3.2. **Projected Impacts**: This section discusses how climate change impacts freshwater resources, with projections described: "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) […] 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)."

Box 11.3. Drought, Climate Change and Water Reform in the Murray-Darling Basin: This box describes the Murray-Darling Basin (MDB), Australia's largest and key river system economically and politically. Projections indicate that: **"**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 11.4. Changing Flood Risk: "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) […]. 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" & "Australian flood estimation guidelines recommend a 5% increase in design rainfall intensity per degree global average warming (Bates et al., 2015)."

11.3.4 Food, Fibre, Ecosystem Products - 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)."

11.3.4.2 Livestock – 11.3.4.2.2. Projected Impacts: "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)."

11.3.4.3 Forestry - 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 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)."

11.3.5 Cities, Settlements and Infrastructure- 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 1.1-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). […] 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. 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)."

Table Box 11.6.2. This tables provides "observed relative sea-level rise with uncertainty range (standard deviation) and projected impacts on infrastructure and population of 1.1 m in Australia".

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)

11.3.6 Health and Well-being - 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)."

11.3.7 Tourism - 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). […] 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)."

11.3.8 Finance - 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)."

11.3.10 Energy - 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 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."

11.5.1 Cascading, Compounding and Aggregate Impacts - 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).[…] 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)."

Table 11.13. This table shows the "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)

11.5.2 Implications for National Economies - 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)."

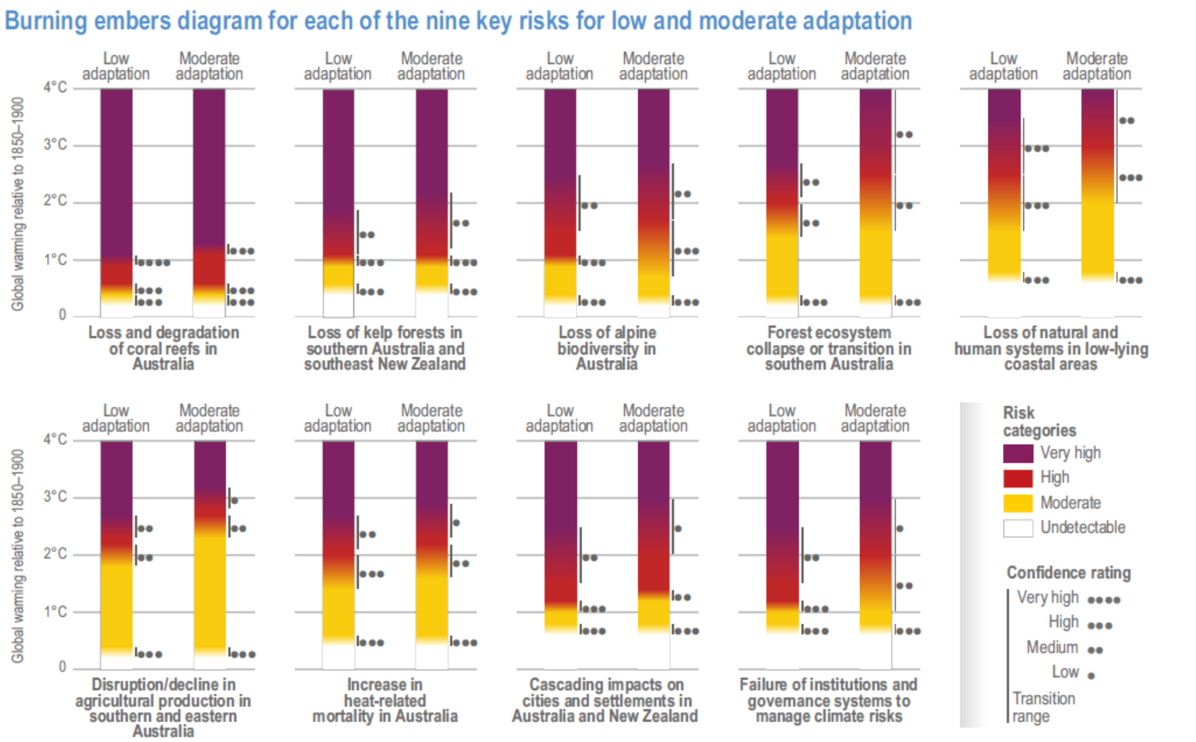


Figure 11.6. This figure shows the "burning embers diagram for each of the nine key risks for low and moderate adaptation [for Australia]. The risk categories are undetectable, moderate, high and very high. While there is no risk category beyond very high, risks obviously get worse with further global 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."**

4 Percentage of Australia's surface area affected by heat waves per year under different pathways

In the remainder of this report, we present results from our own calculations, in contrast to the previous sections which were summarizing results from the scientific literature and IPCC reports.

Figure 3 illustrates the temporal evolution of the percentage of Australia's surface area that is affected each year by heat waves[4]. Three projections are presented, corresponding to three distinct warming pathways. The first pathway limits global warming to a global mean temperature anomaly of 1.5°C relative to the pre-industrial period by the end of the century (yellow colours). The second pathway results in a warming of 2.0°C by the end of the century (orange colours), while the third leads to a warming of 2.8°C, corresponding to a scenario in which countries continue with their current climate policies (red colours) (this can be interpreted as: under current climate policies, we have 67% probability of staying below 2.8°C and 33% probability of exceeding it)[5].

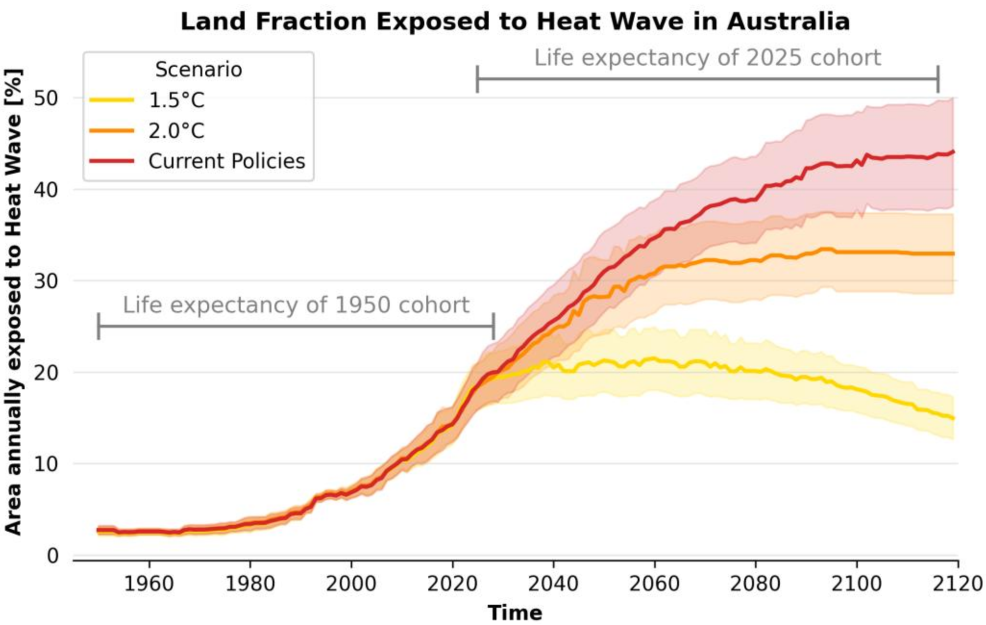


Figure 3. Land fraction exposed annually to heat waves in Australia under warming pathways aligned with 1.5°C, 2.0°C, and Current Policies (2.8°C). Lines represent multi-model means of a heat wave metric calculated from four global climate models. Uncertainty bands span 1 standard deviation across the model ensemble.

In 2025, on average, 18% of Australia's surface area is annually experiencing a heat wave under our heat wave definition[1], up from around 2% in the early historical period. From 2025 onward, differences in the land fraction exposed become discernible, reflecting the initial divergence between the warming pathways in the global climate model projections. By 2050, approximately 21% of

[4] The definition of heat waves that we use is provided in the Methods section at the end of the report.
[5] The 66[th] percentile value of global temperature anomaly in 2100 following the emission pathway indicated by countries' current policies is annually updated, with the best estimate at the time of writing (March 2026) being 2.8°C. For more information see: https://www.unep.org/resources/emissions-gap-report-2025

Australia's surface area is annually affected by heat waves under the lowest warming pathway. Under a pathway leading to 2.0°C of warming, this proportion increases to 28%, and under the Current Policies-aligned warming pathway, on average 30% of Australia is projected to be annually affected by an extreme heat wave by mid-century. As expected, the differences between scenarios become most pronounced toward the end of the century, when the divergence in reachable global warming levels is greatest. By 2100, the annually exposed land fraction reaches 18%, 33%, and 43% under the 1.5°C, 2.0°C, and Current Policies warming pathways, respectively.

5 Heat waves faced by young generations born in Australia under different pathways

By combining the above projections of heat wave occurrence in Australia with demographic data, it is possible to project how many heat waves each birth cohort is expected to experience over their lifetime under a given scenario. Figure 4 presents these trajectories for birth cohorts ranging from individuals born in 1950 to children born in 2025.

For individuals born in 1950, the different warming pathways have no significant effect on lifetime heat wave exposure. Based on the life expectancy of this cohort in Australia, these individuals are not expected to live long enough for the divergence between the warming scenarios to substantially modify their life experience. On average, a person born in Australia in 1950 is therefore expected to experience approximately 1.8 heat waves over their lifetime. In contrast, the choice of warming pathway rapidly leads to diverging impacts for younger generations. For the 1990 birth cohort, individuals in Australia are projected to experience, on average, 4.0 heat waves over their lifetime under the 1.5°C pathway, compared with 5.2 heat waves under the 2.0°C pathway and 5.5 heat waves under the current policies-aligned pathway. The differences in climate change impacts are largest for the youngest cohorts considered. For children born in 2025, lifetime exposure increases to an average of 4.9, 8.0, and up to 9.4 heat waves under warming levels of 1.5°C, 2.0°C, and the Current Policies pathway, respectively.

In Figure 4, the authors' birth cohorts are highlighted using a color scale ranging from older to younger individuals. Table 1 reports the numerical values associated with projections of lifetime exposure to heat waves in Australia for each author. Two main patterns emerge. First, higher greenhouse gas emission scenarios, and thus higher levels of global warming, lead to greater lifetime exposure to heat waves within the same birth cohort. Second, for a given warming scenario, a marked increase in lifetime exposure is observed for younger generations.

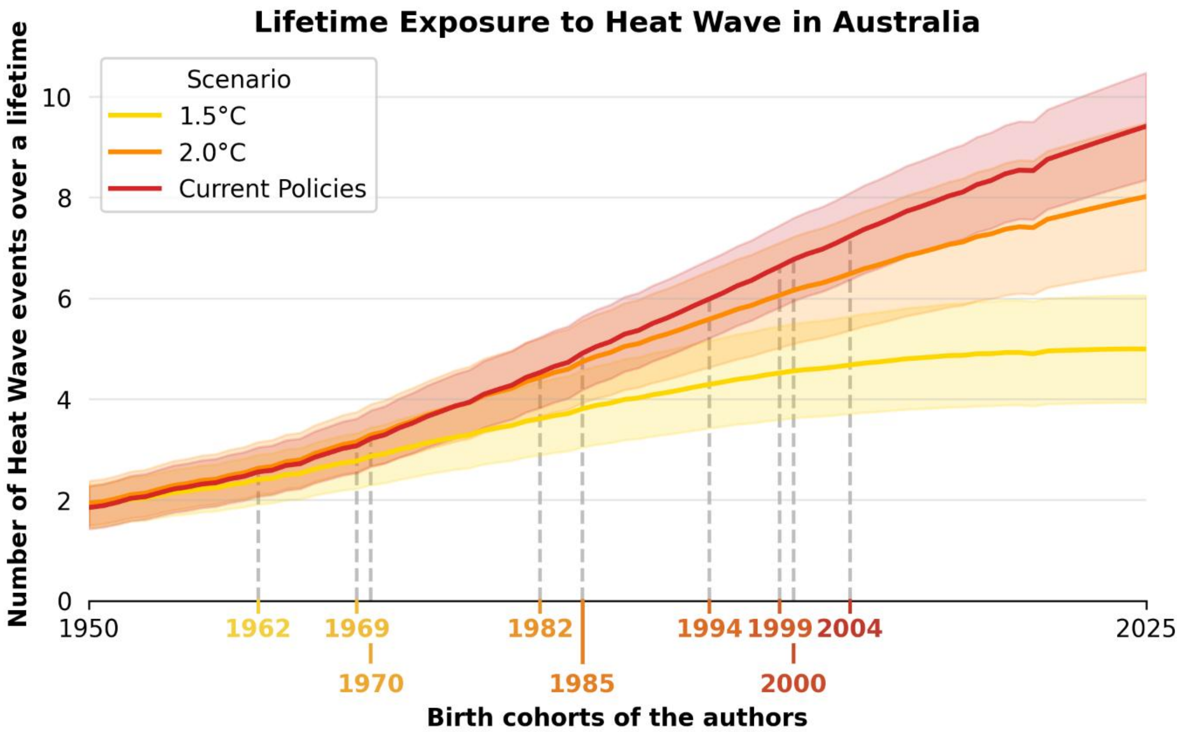


Figure 4. Lifetime exposure to heat waves in Australia for birth cohorts from 1950 to 2025. The birth years of the authors are highlighted using a colour scale ranging from older to younger individuals. Solid lines represent the multi-model mean for each of the three warming pathways (1.5°C, 2.0°C, and Current Policies). Shaded bands indicate ±1 standard deviation across the model ensemble.

Lifetime Exposure to Heat Waves — Australia

Author	Birth cohort	1.5°C	2.0°C	Current Policies
Barry	1962	2.41 ± 0.49	2.63 ± 0.52	2.56 ± 0.49
Jack	1969	2.77 ± 0.55	3.15 ± 0.59	3.07 ± 0.54
Anne	1970	2.87 ± 0.57	3.29 ± 0.61	3.22 ± 0.56
Fiona	1970	2.87 ± 0.57	3.29 ± 0.61	3.22 ± 0.56
Rikki	1985	3.81 ± 0.76	4.74 ± 0.82	4.91 ± 0.73
Brendon	1994	4.29 ± 0.87	5.58 ± 0.95	5.98 ± 0.78
Cat	1999	4.52 ± 0.93	6.06 ± 1.04	6.63 ± 0.81
Melissa	1982	3.61 ± 0.72	4.43 ± 0.78	4.53 ± 0.70
Pam	2000	4.56 ± 0.94	6.16 ± 1.06	6.77 ± 0.82
Latisha	2000	4.56 ± 0.94	6.16 ± 1.06	6.77 ± 0.82
Sama	2004	4.68 ± 0.97	6.49 ± 1.12	7.23 ± 0.86

Table 1. Projected absolute number of heat waves faced by the different authors in Australia under the three warming pathways (1.5°C, 2.0°C and Current Policies). Note that the lifetime exposure numbers are computed using the country-average heatwave projections.

6 Lifetime heat wave exposure for young generations compared to the 1950 birth cohort

To highlight the intergenerational inequity of climate warming, Figure 5 presents the Exposure Multiplication Factor (EMF). This metric is defined as the number of heat waves that the 2025 birth cohort is expected to experience over its lifetime divided by the number experienced by the 1950 birth cohort. In other words, the Exposure Multiplication Factor (EMF) indicates how many *more* heat waves a particular generation will experience compared to a reference generation (here taken as people born in Australia in 1950). The results are shown for the three warming pathways, leading to 1.5°C, 2.0°C, and 2.8°C (Current Policies) of warming relative to the pre-industrial period.

The height of each bar represents the absolute number of heat waves experienced during the lifetime of the 1950 and 2025 birth cohorts. The numerical values displayed above the bars for the 2025 cohort indicate the corresponding Exposure Multiplication Factors. Under the 1.5°C warming pathway, children born in 2025 in Australia are on average projected to experience 2.7 times more heat waves over their lifetime than people born in 1950. This factor increases to 4.1 times under the 2.0°C pathway and reaches 5.1 times under the Current Policies pathway.

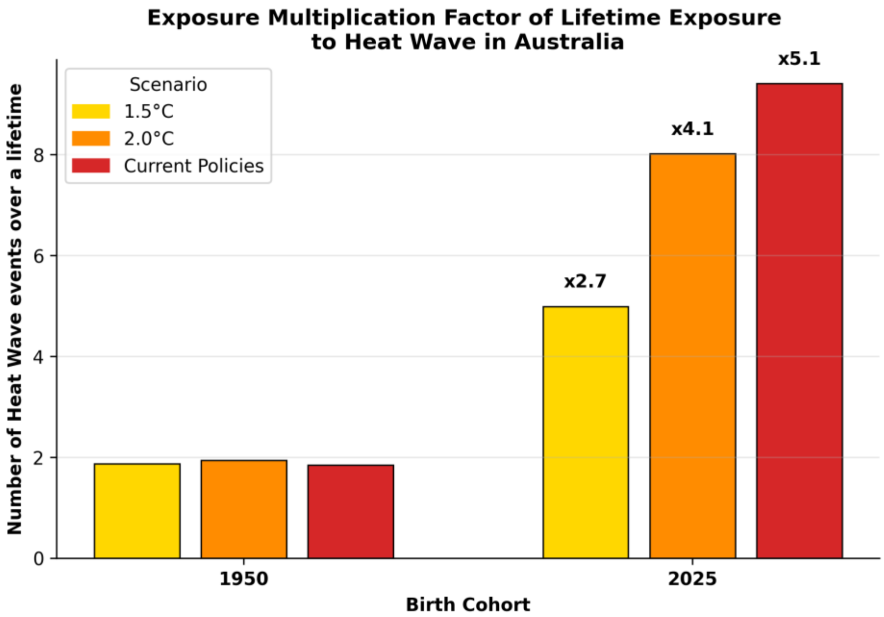


Figure 5. Number of heat waves events experienced over a lifetime for the 1950 and 2025 birth cohorts, and value of the Exposure Multiplication Factor (EMF) in Australia relative to the 1950 birth cohort, for each of the three warming pathways under study. The bar height represents the absolute number of heat wave events experienced during the birth cohort's lifetime, and numbers displayed above the bars indicate the EMF.

Figure 6 shows the evolution of the EMF across all birth cohorts, with the authors' birth years highlighted using a colour scale ranging from older to younger individuals. Specific results are reported in Table 2. For example, Barry, the oldest author, does not experience a substantial change in lifetime exposure to heatwaves across the different emission scenarios considered. In contrast, for Sama, who is born in 2004, we project that she will experience 3.91 times more heatwaves over her lifetime compared to individuals born in 1950 under the Current Policies scenario. This value decreases to 2.5 times more heatwaves over her lifetime relative to the 1950 cohort under the 1.5°C warming pathway.

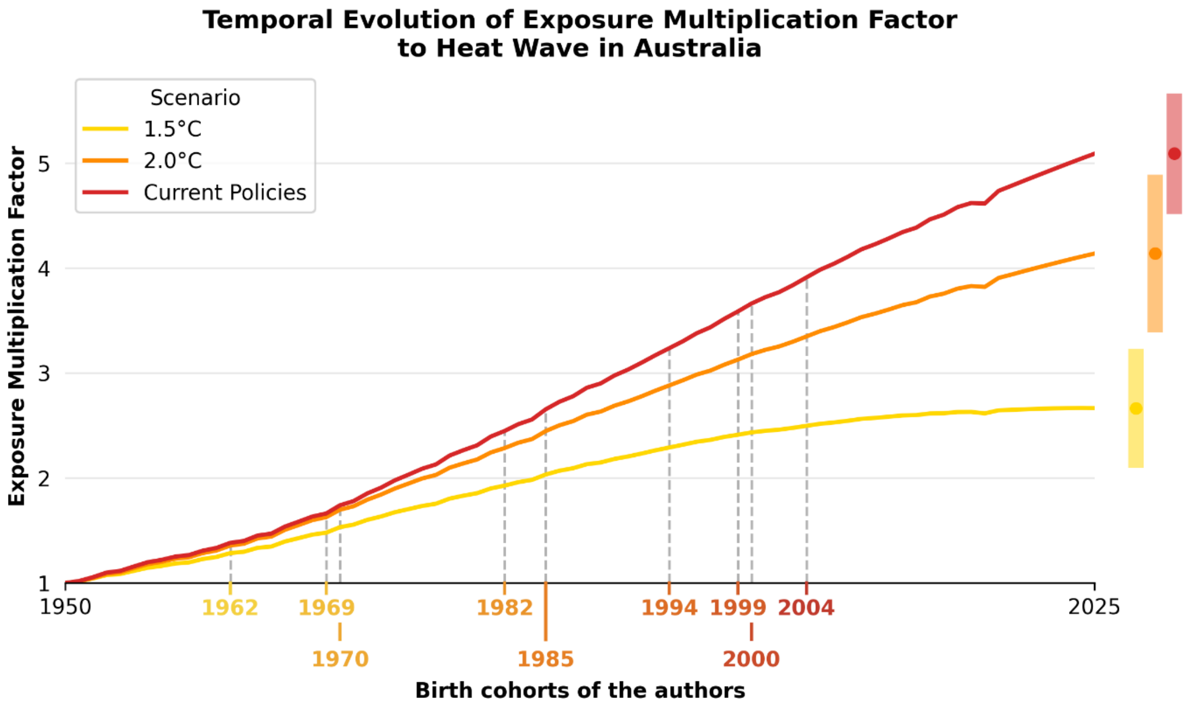


Figure 6. Evolution of the Exposure Multiplication Factor (EMF) to heat waves in Australia across all birth cohorts from 1950 to 2025 with the birth years of the authors highlighted by using a colour scale ranging from older to younger individuals. The lines show the ensemble mean of the climate models used, with different colours representing the three warming pathways under study. On the right of the plot, the dark-coloured markers indicate the best estimate of the EMF for the last birth cohort (ensemble mean), while the bars represent the uncertainty around this estimate. Uncertainty bands span 1 standard deviation across the model ensemble.

EMF for Heat Waves — Australia (reference cohort: 1950)

Author	Birth cohort	1.5°C	2.0°C	Current Policies
Barry	1962	1.28 ± 0.26	1.36 ± 0.27	1.38 ± 0.26
Jack	1969	1.48 ± 0.29	1.63 ± 0.31	1.66 ± 0.29
Anne	1970	1.53 ± 0.30	1.70 ± 0.32	1.74 ± 0.30
Fiona	1970	1.53 ± 0.30	1.70 ± 0.32	1.74 ± 0.30
Rikki	1985	2.03 ± 0.41	2.45 ± 0.42	2.65 ± 0.39
Brendon	1994	2.29 ± 0.46	2.88 ± 0.49	3.24 ± 0.42
Cat	1999	2.41 ± 0.49	3.13 ± 0.54	3.59 ± 0.44
Melissa	1982	1.93 ± 0.39	2.28 ± 0.40	2.45 ± 0.38
Pam	2000	2.43 ± 0.50	3.18 ± 0.55	3.66 ± 0.45
Latisha	2000	2.43 ± 0.50	3.18 ± 0.55	3.66 ± 0.45
Sama	2004	2.50 ± 0.52	3.35 ± 0.58	3.91 ± 0.47

Table 2. Exposure Multiplication Factor (EMF) to heat waves in Australia for different authors under three warming pathways (1.5°C, 2.0°C, and Current Policies). The reference cohort used for comparison of lifetime exposure is the 1950 birth cohort.

7 Number of young people born in Australia between 1990 and 2020 facing unprecedented lifetime exposure to heat waves

Unprecedented lifetime exposure to heat waves for a specific birth cohort in Australia is defined to occur whenever the number of heat wave events experienced over a lifetime exceeds a level that would have been statistically virtually impossible in a pre-industrial climate, i.e., without the influence of anthropogenic climate change. Mathematically, this threshold is defined as the 99.99th percentile of a large sample of lifetime exposures in a pre-industrial control climate. In other words, there is less than a 1 in 10,000 chance of experiencing this number of heat waves over a lifetime in the absence of climate change.

Table 3 presents the absolute number of people (in thousands) in each birth cohort in Australia who are projected to experience an unprecedented lifetime exposure to heat waves. The figures in parentheses indicate the percentage of the cohort this represents relative to the total cohort size in Australia. These results are taken directly from the study by Grant et al. (2025) published in *Nature*[6]. We note that the warming pathways in the latter study differ from those used in this report, leading to 1.5°C, 2.5°C and 3.5°C of global warming by the year 2100, respectively.

Similarly to the results presented in the questions 3-5, the warming pathway does not have a substantial impact on the proportion of the 1960 birth cohort in Australia experiencing an unprecedented lifetime exposure to heat waves. This older generation will not live long enough to experience the different levels of warming that will occur under the various greenhouse gas emissions pathways. Nonetheless, 9% of the 1960 birth cohort is already committed to experiencing an unprecedented lifetime exposure to heat waves in Australia.

	Birth year			
Pathway	**1990**	**2000**	**2010**	**2020**
1.5°C	44 (19)	50 (21)	58 (22)	65 (22)
2.5°C	64 (28)	98 (42)	128 (49)	158 (54)
3.5°C	83 (36)	131 (55)	181 (70)	220 (75)

Table 3. Absolute population (in thousands) of cohorts facing unprecedented lifetime exposure to heat waves in Australia and cohort fraction (in % between brackets) per birth year for three warming pathways. Note that the high warming pathway in this table differs from the Current Policies pathway used in the remainder of the report.

For the 1990 birth cohort, the impact of different warming pathways becomes clearly visible. Under the 1.5°C trajectory, 44 000 Australian people born in 1990 (19% of this cohort) are projected to experience an unprecedented lifetime exposure to heat waves. Under the 2.5°C trajectory, 64 000 Australian people born in 1990 (28% of this cohort) face an unprecedented lifetime exposure to heat waves. Finally, under the 3.5°C pathway, this number rises to 83 000 people (36% of this cohort).

[6] Grant, L. *et al.* Global emergence of unprecedented lifetime exposure to climate extremes. *Nature* **641**, 374–379 (2025).

The younger birth cohorts face the highest exposure. For instance, under the 1.5°C trajectory, 65 000 Australian people born in 2020 (22% of this cohort) are projected to experience an unprecedented lifetime exposure to heat waves. Under the 2.5°C trajectory, 158 000 Australian people born in 2020 (54% of this cohort) face an unprecedented lifetime exposure to heat waves. Under the 3.5°C pathway, 220 000 people (75% of this cohort) are set to live an unprecedented life in terms of heatwave exposure. In absolute terms this is over 11 times higher than for the 1960 cohort. These results also imply that limiting global warming to 1.5°C instead of 3.5°C would spare 155 000 Australian 6-years old children from facing an unprecedented life in terms of heatwave exposure, with similar numbers for each recent birth year.

From these results, it can be concluded that recent birth cohorts are disproportionally affected by any current and future emissions. Globally, this is the combined effect of two factors: the younger cohorts are larger (that is, more people were born in the recent period), and the younger cohorts will spend a larger part of their life under a climate affected by future global warming. In areas with relatively limited population growth, the overall change is dominated by the climate change signal.

8 Methods

To address Questions 3 through 6, the methodology follows that initially described in Thiery et al. (2021) published in *Science*[7]. However, certain methodological updates have been implemented since that study, to reflect the best available science:

1. Demographic data have been updated to use the latest available data. Life expectancy data and cohort size data were updated from UNWPP2019 to UNWPP2024[8].
2. Gridded population data were updated to use the best available data, replacing data previously used, obtained from ISIMIP2, with data produced within the European Project COMPASS[9].
3. Warming pathways were extended beyond 2100 using a more realistic approach. In Thiery et al. (2021), post-2100 years were generated by keeping the mean value of the last ten available years (i.e. 2090–2100) constant, thus underestimating warming beyond the end of the century. In the present analysis, global mean temperature trajectories for the period 2100–2119 are extrapolated using the linear trend over the years 2090–2100, representing a more realistic projection.
4. To better isolate the forced signal of change from natural variability of the climate system, a 21-year rolling mean is applied to both global mean temperature pathways, as well as the heat wave data. This approach is better aligned with best available science and recent scientific methods[10].
5. Climate impact simulations for heat waves were taken from ISIMIP3b, an updated version of ISIMIP2b used in Thiery et al. (2021), which provides more precise results with reduced uncertainty.

To address Questions 3 through 6, we use the same definition of heat waves as initially described in Thiery et al. (2021). In a grid cell of the climate model used, we define a heat wave as an event in which the annual Heat Wave Magnitude Index Daily (HWMId) exceeds the 99th percentile of the annual maximum HWMId distribution under pre-industrial (1850-1900) climate conditions for that grid cell. This corresponds to a 1-in-100-year heat wave event under pre-industrial climatic conditions. The HWMId is defined as the maximum magnitude of all hot periods occurring within a year, where a hot period is a sequence of at least three consecutive days during which the daily maximum temperature exceeds a threshold value, T_c. This threshold is defined as the 90th percentile of daily maximum temperatures under pre-industrial climate conditions, calculated using a centred 31-day moving window.

To address Question 6, the method and the results are identical as in Grant et al. (2025) published in *Nature*[11]. The numbers in Table 1 are directly available in Supplementary Materials, Tables 1 to 3.

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[7] Thiery, W. *et al.* Intergenerational inequities in exposure to climate extremes. *Science* **374**, 158–160 (2021).
[8] UNDESA. *World Population Prospects 2024, Online Edition.* https://population.un.org/wpp/ (2024).
[9] Paprotny, D. Exposure Datasets at Multiple Scales. Horizon Europe Project COMPASS. Deliverable D3.1. (2025).
[10] Byers, E. *et al.* Fast climate impact emulation for global temperature scenarios with the rapid impact model emulator (RIME). *Environ. Res.: Climate* **4**, 035011 (2025)
[11] Grant, L. *et al.* Global emergence of unprecedented lifetime exposure to climate extremes. *Nature* **641**, 374–379 (2025).

9 Statutory declaration

We hereby confirm that we have made these reviews and calculations in full scientific independence, and that we have not received any remuneration for this work, nor for any previous work related to this case.

Sincerely yours,

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10 About the authors

Prof. Dr. Wim Thiery is a climate scientist focused on modelling extreme events in a changing climate. After obtaining MScs at KU Leuven in Philosophy (2008) and Terrestrial Ecosystems and Global Change (2011), he was an FWO PhD fellow investigating the interaction between climate and the African Great Lakes with a regional climate model (2011–2015). From 2015 to 2018, he was a Postdoctoral Fellow at ETH Zurich, where he investigated the historical and future impacts of irrigation on climate extremes at the global scale. In 2017 (age 29), he was appointed as research professor at the Vrije Universiteit Brussel, where he established the bclimate Group. In 2026, he became full professor (age 38). With over 1100 media contributions since 2014, he is one of Belgium's leading climate science communicators. During his research, he undertook research exchanges to Montréal, Berlin, and Zurich, and conducted field campaigns to Uganda, Rwanda, and DR Congo to install automatic weather stations on Lake Kivu and Lake Victoria. Thiery is contributing author of the IPCC Special Report on Climate Change and Land (2019) and the Sixth Assessment Report (2021). His expertise includes climate change, climate extremes, regional and global climate modelling, global-scale climate impact modelling, impact attribution, land-atmosphere interactions, land management, storm early warnings, and energy meteorology. Overall, he (co-)authored 148 peer-reviewed scientific articles, including 28 in the flagship Science and Nature-Family journals. In 2017, Forbes magazine elected him as a member of the "Forbes 30 under 30 Europe", bringing together "the brightest young entrepreneurs, innovators and game changers in Europe". Prof. Thiery is currently leading a 2-million-euro European research grant awarded by the European Research Council (ERC Consolidator Grant) on impact attribution. In 2023, he received one of the Arne Richter Awards for Outstanding Early Career Scientists from the European Geosciences Union. This is de facto the highest scientific recognition an early career researcher in climate science can receive in Europe. In 2024, he received the Scientific Award Climate Research, awarded by the Research Foundation – Flanders (FWO). In 2024, he received the price Laureate of the Royal Flemish Academy of Belgium for Science and the Arts (KVAB - Class Natural Sciences). Since 2023, he is recognised by Stanford University as a member of the top 2% of scientists worldwide across all scientific disciplines.

Full CV can be found here.
Full publication list can be found here.

Dr. Marie Cavitte is a climate scientist with a focus on polar regions and our warming climate. She holds a Bachelor's and Master's degree in Earth Sciences from the University of Cambridge (2007-2010) and a PhD in Glaciology from the University of Texas at Austin (2011-2017) where she specialized in using radar technology to study Antarctic paleoclimate and has contributed to the European Oldest Ice Beyond EPICA project to recover 1.5-million-year-old ice. From 2019-2024, she was a postdoc then a FRS-FNRS research fellow at the Earth and Life Institute at UCLouvain where she researched Antarctic snowfall evolution, bringing together ice core and model data sets through analysis and offline assimilation, including an Antarctic field mission over 2021-2022 winter. Cavitte has held many leadership roles: Editor-in-Chief of the EGU Cryosphere Blog for 2 years, Co-President of the Association for Polar Early Career Scientists Belgium (APECS Belgium) for 4 years, founder and co-chair of the Ice Core Young Scientists (ICYS) network. She also collaborates with artists to communicate science through the prism of art and participates in expert panels (Jubel.be, Avocats.be, Citizen

Service, Louvain Finance School). Additionally, she gives interviews on climate change and polar regions on written, audio and TV press (RTBF, BX1, RTL, Le Soir, VRT, NOS, BBC, Daily Science, Liberation). She is the valorisation manager for the bclimate Group where her responsibilities include building networks across disciplines, in particular on climate impacts and attribution science, communication of climate change and project fund raising. Cavitte is engaged at the science for policy interface at the EU level: she was Bluebook trainees in 2024 at DG Climate Action (European Commission) and is currently Policy Officer for the European Geosciences Union (EGU) Cryosphere Division and member of the Climate Hazards and Risks Task Force.

Full publication list can be found here.

Amaury Laridon is a climate scientist whose research focuses on climate change impacts and Earth system tipping points, with a particular emphasis on the attribution of climate impacts to fossil fuel projects. He obtained a Bachelor of Science in Physics (2018–2021) at UCLouvain, followed by a University Certificate in Philosophy (2021–2022) focusing on the philosophy of science, and a Master of Science in Physics (2022–2024), specialising in climate physics, also at UCLouvain. His MSc thesis developed a tipping element emulator for the Atlantic Meridional Overturning Circulation (AMOC) and the Greenland Ice Sheet, integrated into a reduced-complexity climate model. Amaury is currently pursuing a PhD under Prof. W. Thiery at Vrije Universiteit Brussel, co-supervised by Prof. M. Crucifix at UCLouvain. His doctoral project aims to produce original climate projections for the 22nd century, assessing the impacts of continued global warming and the potential transgression of major Earth system tipping points, including the AMOC and the Amazon rainforest. In the first year of his PhD, he published his first peer-reviewed article in Open Research Europe, building on his MSc research, and initiated the Source2Suffering project to strengthen a framework for attributing climate impacts to emissions from specific fossil fuel projects. In addition, Amaury was nominated by BELSPO as an author to the forthcoming JPI Climate and JPI Ocean report AMOC in Focus. He is actively engaged in science communication, through conferences, courses, science festivals, and summer schools, and has authored two articles in a journal of critical social analysis.

Full CV can be found here.
Full publication list can be found here.