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Australian climate extremes at 1.5 °C and 2 °C of global warming

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To avoid more severe impacts from climate change, there is international agreement to strive to limit warming to below 1.5 °C. However, there is a lack of literature assessing climate change at 1.5 °C and the potential benefits in terms of reduced frequency of extreme events[1–3]. Here, we demonstrate that existing model simulations provide a basis for rapid and rigorous analysis of the effects of different levels of warming on large-scale climate extremes, using Australia as a case study. We show that limiting warming to 1.5 °C, relative to 2 °C, would perceptibly reduce the frequency of extreme heat events in Australia. The Australian continent experiences a variety of high-impact climate extremes that result in loss of life, and economic and environmental damage. Events similar to the record-hot summer of 2012–2013 and warm seas associated with bleaching of the Great Barrier Reef in 2016 would be substantially less likely, by about 25% in both cases, if warming is kept to lower levels. The benefits of limiting warming on hydrometeorological extremes are less clear. This study provides a framework for analysing climate extremes at 1.5 °C global warming.

The Paris Agreement reached in December 2015 committed signatories to 'Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change'. The 1.5 °C target has not been the focus of much research previously[1–3] compared with higher warming levels such as 2 °C (ref. 4), but the Intergovernmental Panel on Climate Change has accepted an invitation to produce a report on the impacts of global warming of 1.5 °C in 2018. Thus, a wide-ranging and rapid set of analyses on the effects of limiting global warming to 1.5 °C is required. As a collection, these studies should detail not only changes in mean climate states, but also extremes, and the impacts of these climatic changes using multiple methods, so we have a comprehensive understanding to inform decision-making. For example, an initial study on changes in some daily-scale extremes has been performed previously[5], but many more analyses are required.

In this study we use existing climate model simulations to assess changes in large-scale Australian climate extremes at global warming levels of 1.5 °C and 2 °C above pre-industrial. We explore the potential benefits of limiting warming to 1.5 °C compared with a higher level of warming at 2 °C. We select model simulated years of 1.5 °C and 2 °C global warming from the four representative concentration pathway (RCP) scenarios for the twenty-first century used in the fifth phase of the Coupled Model Intercomparison project (CMIP5; ref. 6). Our methodology utilizes the ensemble of coupled models and all of the RCP scenarios so that large ensembles can be generated representing the 1.5 °C and 2 °C warmer worlds (Supplementary Fig. 1) relative to a natural baseline. Our 1.5 °C and 2 °C worlds are represented by 3,143 and 3,618 model years respectively, allowing for robust estimation of the differences in climate between these two warmer worlds (Supplementary Fig. 2). We compare extreme events in these worlds with simulations representing a natural climate that includes no human influences (3,990 model years), and simulations of the climate of the modern world centred on 2016 (798 model years). For the analysis of each extreme event we selected the models that performed best with regard to observations of the variables relevant to the specific extreme event (temperature or precipitation; Methods). Accurately simulating precipitation extremes is more difficult than temperature extremes, so our confidence in statements on temperature extremes is higher.

We investigate changes in Australian climate extremes by applying an event attribution framework to four different climate scenarios: a pre-industrial, or natural, world without human influences; the current world; a 1.5 °C world; and a 2 °C world.

Analyses of specific types of extreme event in our current climate compared with a world without anthropogenic influences have been used previously to quantify and communicate the effects of climate change[7,8]. Here we present analysis for a set of climate extremes in Australia, including the heat extreme relevant to the major coral bleaching event of early 2016. Australia has experienced many climatic extremes recently, some of which have had detectable anthropogenic influences[9] and others not[10]. Also, Australia has high-quality observational data sets allowing for robust estimations of changes in extremes using climate models that have been evaluated against observation-based data (see Methods). Given that Australia suffers from a broad range of high-impact climate extremes and has the availability of high-quality observational data, the continent provides an excellent test-bed for the quantification of climate change effects on extreme events at 1.5 °C and 2 °C of global warming. The events we analyse cover a diverse range of climate extremes—extreme heat over Australia (summer 2012–2013), marine heat (early 2016), large-scale heavy precipitation (December 2010), and severe drought (2006). These events had wide-ranging impacts, including deaths, severe ecosystem damage and high economic costs. It is vital that we understand how frequent similar high-impact extreme events would be if we are to pursue limiting global warming to 1.5 °C or 2 °C.

Overall, the Australian continent is projected to warm in the future (Supplementary Fig. 3). The 2 °C world is, on average, more than 0.5 °C warmer over inland areas compared with the 1.5 °C world and less than 0.5 °C warmer at the coast (Supplementary Fig. 4). Areas of the south of the continent are expected to dry under higher levels of global warming in both summer and winter while other regions show some seasonal dependence in rainfall changes with weak levels of model agreement (Supplementary Fig. 4).

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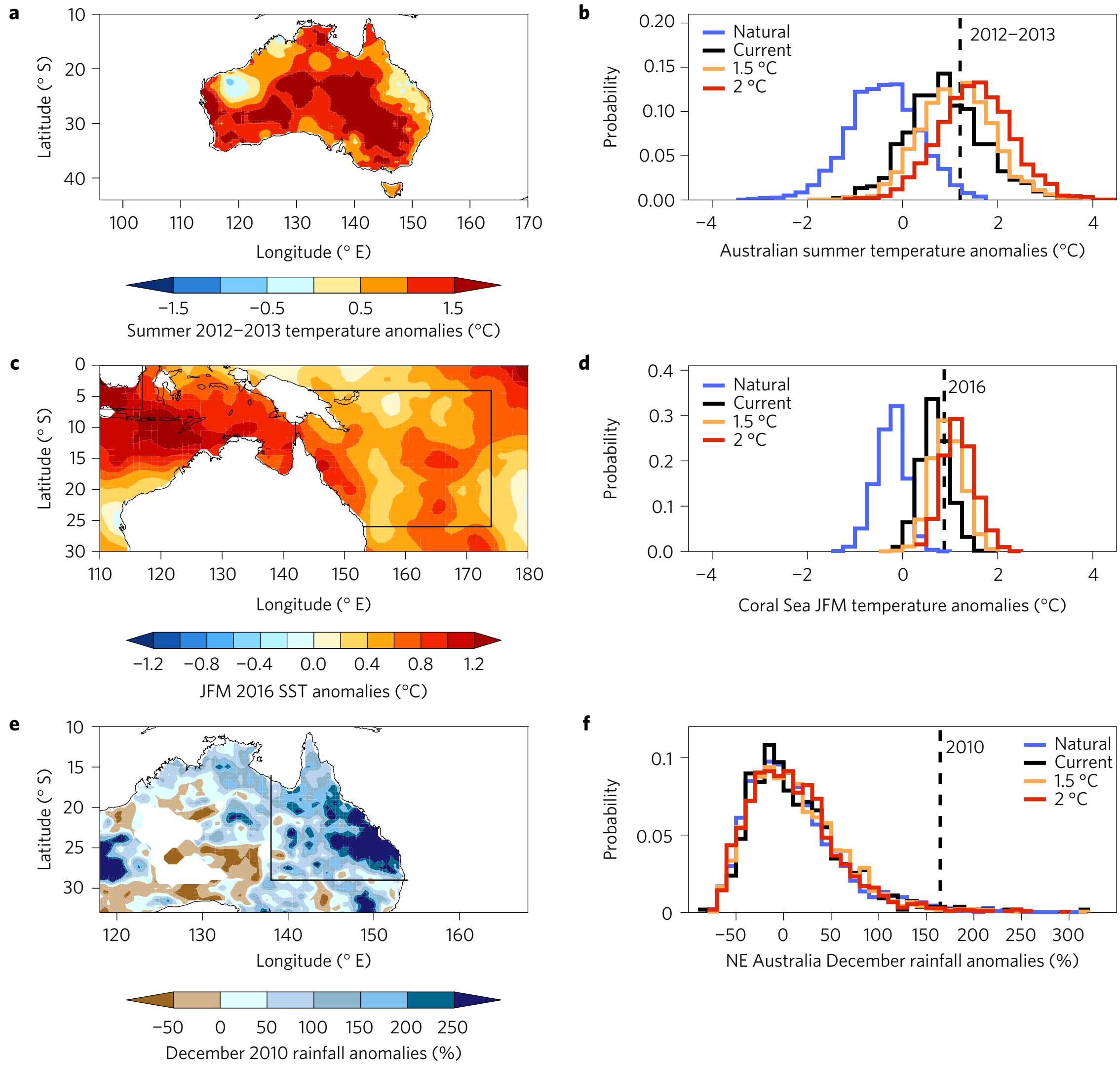

Figure 1 | Australian climate under varying levels of human-induced climate change. a–f, Maps of observed anomalies (**a**,**c**,**e**) and associated probability distributions (**b**,**d**,**f**) of model-simulated anomalies for the 'angry summer' of 2012–2013 (**a**) and Australian summer temperature (**b**), the Coral Sea heat of January–March 2016 (**c**) and Coral Sea January–March temperature (**d**), and the heavy rains of December 2010 (**e**) and northeast Australia December precipitation (**f**). All anomalies are from a 1961–1990 climatology and are shown under natural climate influences (blue), the current world (black), 1.5 °C (orange) and 2 °C (red) of human-induced global warming. The observed extreme event anomalies are shown as dashed lines. The black boxes on the maps denote the area being looked at in the accompanying panel.

The record-hot summer of 2012–2013, dubbed the 'angry summer' (Fig. 1a), was made at least five times more likely due to the human climate influence[9]. Under increased levels of global warming, Australian summers also get warmer and the likelihood of extreme hot summers and record heat increases (Fig. 1b)[11,12]. A similar pattern of change can be seen in high Coral Sea temperatures in January–March, such as those associated with the Great Barrier Reef coral bleaching event of 2016[13] (Fig. 1c). Under either the 1.5 °C or 2 °C global warming scenario, there is significant warming of sea surface temperatures in the Coral Sea (Fig. 1d) relative to today's climate. The relatively low interannual variability in sea surface temperatures results in a clear and detectable anthropogenic signal. There are no events in our natural ensemble as warm as the observed 2016 Coral Sea anomaly (this is not the case for any of the other observed events studied here).

In contrast to the results for temperatures, we do not see the same changes in precipitation. December rainfall in northeastern Australia, which was exceptionally high in 2010 (Fig. 1e) and associated with damaging floods, is similar across the four scenarios indicating a weak climate change influence in the model simulations (Fig. 1f).

Australian climate is strongly related to the El Niño–Southern Oscillation (ENSO), which itself may change under future warming scenarios, although the nature of any such change is uncertain[14]. Australian hot summers are typically coincident with El Niño conditions, although the 'angry summer' of 2012–2013 occurred in an ENSO-neutral season. Hot summers primarily occur during El Niño events in a natural world (Fig. 2), with only 1% of events similar to the 'angry summer' occurring in La Niña conditions, compared with 53% in El Niño seasons. In warmer climate scenarios similar hot summers will be more common and can occur frequently even under La Niña conditions, although they remain more likely in El Niño summers. No significant change in the nature of the ENSO–Australian summer temperature relationship is simulated here (Fig. 2e–h). However, with background warming, historically hot Australian summers such as the 'angry summer', are more likely to occur in general, regardless of ENSO phase (Fig. 2i–l). Unprecedented hot summers in a warmer world are more common under El Niño conditions (Fig. 2g,h).

In addition to the aforementioned climate extremes, Australia is also often affected by severe drought (Fig. 3). Droughts are

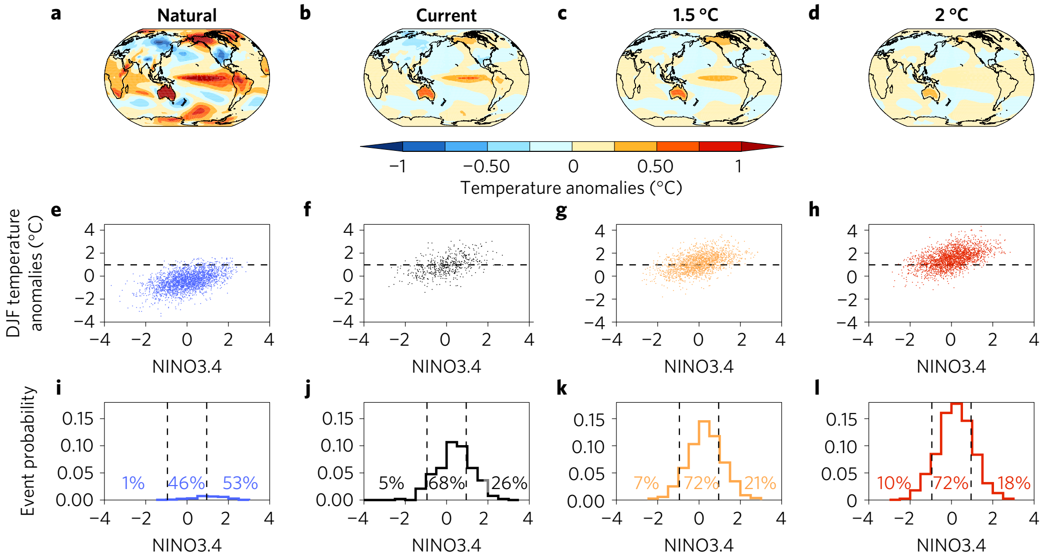

Figure 2 | ENSO conditions associated with historically hot Australian summers. a–d, Austral summer temperature anomalies (from 21-year moving windows within each scenario) associated with hot Australian summers similar to 2012–2013 in a natural climate (**a**), the current world (**b**), 1.5 °C (**c**) and 2 °C (**d**) of human-induced global warming. **e–h**, Scatter plots of Niño-3.4 index against Australian summer temperature anomalies (1961–1990 historical simulation averages) under each scenario. **i–l**, The probability of a hot Australian summer dependent on the Niño-3.4 index. The percentages of hot Australian summers under El Niño, La Niña and ENSO-neutral conditions are shown.

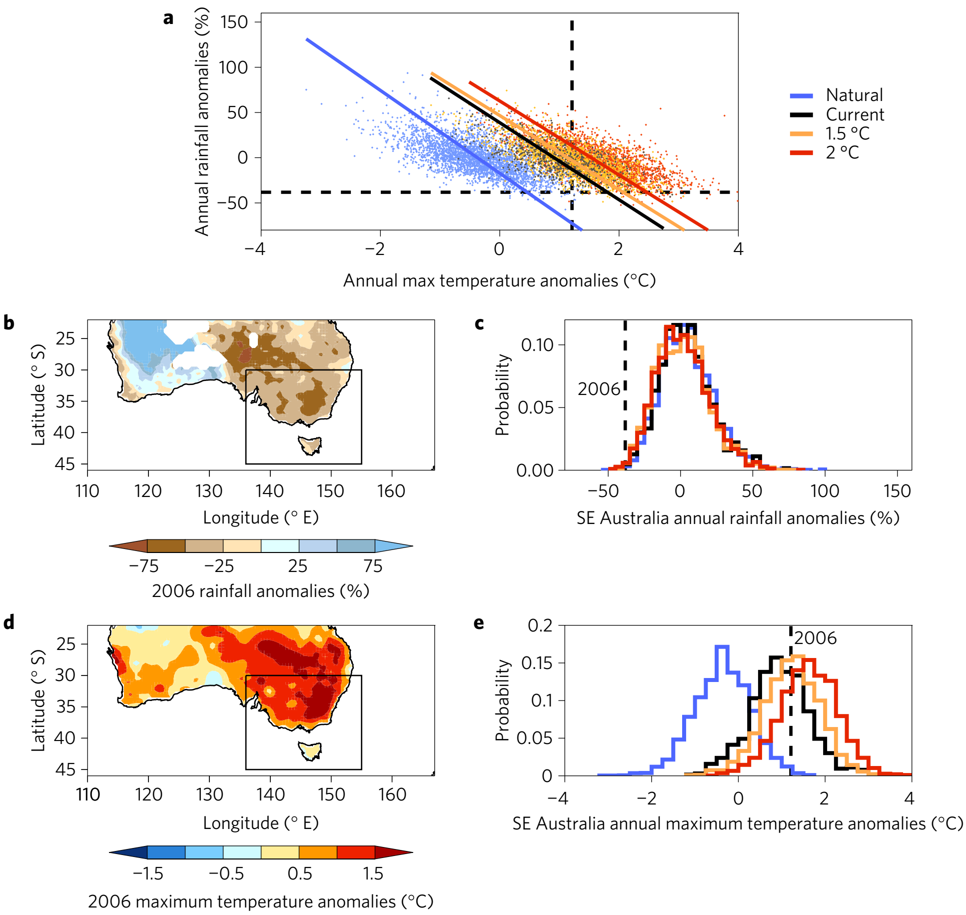

Figure 3 | Changing Australian one-year drought under varying levels of human-induced climate change. a, Scatter plot of southeast Australian annual-average maximum temperature anomalies against annual precipitation anomalies (1961–1990 climatology) under natural world (blue), current world (black), 1.5 °C global warming and 2 °C global warming scenarios with regression lines (total least squares) shown. **b–e**, Maps of observed anomalies (**b**,**d**) and associated probability distributions (**c**,**e**) of model-simulated anomalies respectively for annual precipitation anomalies in 2006 (**b**) and southeast Australia annual precipitation anomalies (**c**), and annual maximum temperature anomalies in 2006 (**d**) and southeast Australia annual maximum temperature anomalies (**e**). All anomalies are from a 1961–1990 climatology and are shown under the four scenarios (**c**,**e**). The observed 2006 extreme event anomalies are shown as dashed lines. The black boxes on the maps denote the area being looked at in the accompanying panel.

Event		Associated impacts	Natural	Current	1.5 °C	2 °C
Angry summer 2012–2013		Severe heatwaves, Power blackouts, Bushfires	**3%** (1–5%)	**44%** (36–52%)	**57%** (50–65%)	**77%** (70–84%)
Coral Sea heat JFM 2016		Worst coral bleaching event on record	**0%** (0%)	**31%** (22–40%)	**64%** (53–76%)	**87%** (79–93%)
NE Australia rain December 2010		Widespread floods, Dozens of deaths	**1%** (0–2%)	**2%** (0–2%)	**1%** (1–1%)	**1%** (1–2%)
SE Australia drought 2006	Low rainfall	Water restrictions, Reduced crop yields	**1%** (1–2%)	**2%** (1–3%)	**3%** (1–4%)	**3%** (1–4%)
	High temperatures		**1%** (0–1%)	**35%** (28–42%)	**52%** (45–59%)	**74%** (67–81%)

Figure 4 | The changing likelihood of Australian extreme events. Examples of the likelihoods in a given year of similar events to four recent Australian extremes in a natural world, the current world, a 1.5 °C world and a 2 °C world. For the Australian drought case, changes in the likelihood of both precipitation deficits and high temperatures are considered due to their relevance. The best estimate is shown with the 5th–95th percentile confidence intervals in parentheses. Several of the impacts of each extreme event are highlighted.

multi-faceted and can be measured in different ways including rainfall deficits and indices that combine several hydrometeorological variables. A clear inverse relationship exists between average daily maximum temperatures and precipitation in regions of Australia[15], including the southeast of the continent[16] (Fig. 3a). Both heat and rainfall deficits are associated with drought in Australia and can be used as drought indicators[16,17]. This has an additional advantage as temperature and precipitation are both well-observed variables in comparison with other drought-relevant quantities, such as evaporation and soil moisture. Over the southeast of Australia, although there is a signal for only a small reduction in projected annual precipitation totals (Fig. 3a,c), average maximum temperatures would rise substantially in a 1.5 °C or a 2 °C world (Fig. 3a,e).

By applying event attribution techniques[9] we compare the probability of climate extremes between the current and future worlds. Events similar to the 'angry summer' of 2012–2013 would be very likely at least 26% more frequent in a 2 °C world than a 1.5 °C world and at least 50% more frequent in a 2 °C world than the world of today. Similarly, events such as the early 2016 Coral Sea heat would be very likely at least 22% more frequent in a 2 °C world than a 1.5 °C world and at least twice as frequent in a 2 °C world than they are at present. Given the severe bleaching associated with the warmth of the Coral Sea[12] in early 2016, the viability of parts of the Great Barrier Reef would be threatened in either warmer world.

Comparing the four climate scenarios (natural, current world, 1.5 °C and 2 °C), we find that extreme heat events such as the 'angry summer'[9] of 2012–2013 and the record-hot temperatures in the Coral Sea in early 2016[13] would become more common in either a 1.5 °C or a 2 °C world relative to the present (Fig. 4). In these events the human-induced climate change signal is already clear as they are much less likely to occur in a natural world than in the climate of today. However, such extreme heat events would be commonplace in either the 1.5 °C or 2 °C warmer world and are significantly more frequent in a 2 °C world than a 1.5 °C world.

In contrast, the difference in hydrometeorological extremes between a 1.5 °C and 2 °C world is less clear. Extremely wet Decembers such as 2010 in Queensland are projected to remain rare in a warmer world. Studies of heavy precipitation extremes in Australia have previously found that climate variability related to ENSO plays a greater role than climate change in determining the likelihood of such extremes occurring[10,18] and this is projected to continue even as anthropogenic global warming continues.

Precipitation deficits such as those of 2006 in southeast Australia, which were part of the longer Millennium Drought, would become slightly more frequent, but remain unusual (occurring less than 1-in-20 years on average). Both the high annual-average temperatures and the precipitation deficits associated with drought in southeast Australia would become more frequent under 1.5 °C or 2 °C global warming. The increasing probability of hot and dry conditions associated with annual drought in Australia has previously been attributed to anthropogenic influences,[15,17] but here we find that climate change influences both variables individually. Using drought indices, analyses have projected an increase in the intensity of drought conditions in southeast Australia[19] and our findings are consistent with that conclusion.

In Australia, extreme heat events are projected to become significantly and substantially more common in a 2 °C warmer world than in a 1.5 °C world. Precipitation extremes, such as the heavy rains of December 2010 in Queensland, are likely to see comparatively less change. We note that we are considering precipitation extremes that are 'more extreme' in the current climate than the temperature extremes, although the entire statistical distributions show less change for rainfall than temperature (Figs 1f and 2c). The benefits of limiting warming to 1.5 °C are clearer through the significant and substantial reduction in frequency of heat extremes[20] as opposed to precipitation extremes. Under either warming scenario, the dependence of an El Niño event coinciding with contemporary extreme heat events such as the 'angry summer' weakens significantly relative to the world of today.

This study illustrates some of the differences in Australian climate extremes that could be expected in a 1.5 °C or 2 °C world. We show that existing climate model simulations can be used to investigate the difference in frequency of extreme events between 1.5 °C and 2 °C. Our analysis is designed to highlight the utility of readily available model data and to complement the work being undertaken in the Half a degree Additional warming, Prognosis and Projected Impacts project (HAPPI; ref. 2) using high-resolution ensembles of atmosphere-only model experiments. We also use more simulations in our analysis than has been utilized previously[6,21] by making full use of the CMIP5 model projections. This gives the results more statistical power, with thousands of model years contributing to each ensemble. We highlight the benefit of less frequent heat extremes in a 1.5 °C world than a 2 °C world by analysing Australian hot summers and warm seas that lead to coral bleaching in the Great Barrier Reef. Extending this type of analysis to other regions of the world, where high-quality observational data also exist, would be beneficial.

Methods

Methods, including statements of data availability and any associated accession codes and references, are available in the online version of this paper.

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Author contributions

A.D.K. conceived the study and performed the analysis. All authors developed the methodology, discussed the results, and contributed to the preparation of the manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Publisher's note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations. Correspondence and requests for materials should be addressed to A.D.K.

Competing financial interests

The authors declare no competing financial interests.

Methods

Model and observational data. Simulations from 16 models in the CMIP5[5] archive (listed in Supplementary Table 1) representing 1861–2005 under both natural and anthropogenic forcings (historical), 1861–2005 under natural forcings only, and 2006–2100 under four RCP scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5) were analysed. The surface air temperature 'tas', average daily maximum temperature 'tasmax', surface ocean temperature 'tos', and precipitation 'pr' variables were used.

The simulated global temperature series were compared with the observed series from HadCRUT4 (ref. 22). Models were evaluated for analysis on the Australian extremes using observational series derived from the Australian Water Availability Project (AWAP; ref. 23) for the land-based extremes (available for 1900–present for precipitation and 1911–present for temperature) and the Extended Reconstructed Sea Surface Temperature v4 (ERSSTv4; refs 24–26) for the warm Coral Sea event (analysed from 1951–present).

All data were interpolated onto a regular 2° grid for further analysis.

Definition of a natural baseline, current, 1.5 °C and 2 °C worlds. There are different ways in which a natural baseline climate can be defined. Here we use the 1901–2005 average temperature from the historicalNat model simulations. This gives a baseline based on a century-long average, so influences from decadal-scale variability are small, during a period with relatively few major volcanic eruptions. Other analyses have used a late-nineteenth-century baseline period that includes a small anthropogenic signal and major eruptions such as Krakatoa, but has the advantage of being directly comparable with observational series from this time.

A comparison of simulated global average temperature differences between the end of the historical simulations (1996–2005) and these two possible baseline periods (that is, 1901–2005 in the historicalNat simulations and 1861–1900 in the historical simulations) shows small differences (Supplementary Fig. 5) and a Kolmogorov–Smirnov test on the distributions of these temperature differences shows a statistical similarity.

The 1.5 °C and 2 °C worlds can also be defined in multiple ways. Here we define our 1.5 °C world as all years within decades in the 2006–2100 scenario simulations when decadal-average temperatures are between 1.3–1.7 °C warmer than the equivalent model run natural baseline. The 2 °C world is defined in the same way but for decadal-averaged temperatures at 1.8–2.2 °C above the corresponding natural baseline. These definitions resulted in a large proportion of model years being selected for each ensemble (Supplementary Fig. 1). Although individual years may contribute to both the 1.5 °C and 2 °C ensembles, none of the analysis assumes independence between the two worlds. Using a narrower range reduced the sample sizes but made little difference to the results.

The current climate was simply defined as the 2006–2026 period (that is, a 21-year window centred on 2016) in the high-emissions RCP8.5 scenario. The natural climate is estimated using the 1901–2005 period from the ensemble of historicalNat simulations.

Analysis of 1.5°C and 2°C worlds. Model years within the natural baseline period, the current world, and the warmer 1.5 °C and 2 °C worlds were defined as above and used in subsequent analysis. Differences in median average annual and seasonal temperature at each model gridbox between the four different worlds were calculated.

Globally the simulated warming and precipitation changes at 1.5 °C and 2 °C are similar to those produced in other analyses[4,27] and show the expected patterns of Arctic amplification and greater land warming (Supplementary Fig. 3).

The use of transient and quasi-equilibrium model runs was investigated by simply subsetting the RCP8.5 high-emissions years (that is, 'most' transient) and the RCP2.6 low-emissions years (that is, quasi-equilibrium) and comparing differences between the 1.5 °C and 2 °C worlds with the natural baseline in each case. The RCP8.5 scenario represents a rapidly warming world under high emissions in which simulations rapidly pass through the 1.5 °C and 2 °C levels and RCP2.6 represents a slower rate of warming reaching a quasi-equilibrium state close to 1.5 °C and 2 °C. A comparison of the 1.5 °C and 2 °C worlds under the very different scenarios represented by the different RCPs finds little difference in warming or precipitation patterns over most of the world (Supplementary Figs 6 and 7) highlighting the strength of this approach. In the equatorial central and eastern Pacific region there is an intensification in precipitation under more rapid warming[28]. The lack of a pattern dependence on warming rates and precipitation changes over most areas suggests that simulations from different RCPs can be used in combination over our study region of Australia. Given that the analysis of extreme events requires large sample sizes, the use of simulations across the four scenarios together provides increased statistical power.

Extreme event analysis. A comparison of the frequency of four types of extreme climate event, similar to those that have occurred in Australia in recent years, was made between the four different worlds. Australia was chosen as a test-bed because of the availability of high-quality observational data for model validation and the broad range of extremes that have occurred there recently. The variables analysed were the Australia-average summer-mean temperature (112° E–155° E, 10° S–45° S), the Coral Sea January–March temperature (142° E–174° E, 4° S–26° S), northeast Australia December precipitation (138° E–157° E, 10° S–29° S), and the southeast Australian annual-average maximum temperature and precipitation (136° E–155° E, 30° S–45° S). These regions and indices are chosen as representative variables for recent extreme Australian climate events: the record-hot 'angry summer' of 2012–2013, the warmth associated with coral bleaching of the Great Barrier Reef in early 2016, the extreme rainfall over Queensland in late 2010, and the drought year of 2006 in southeast Australia, respectively.

The first step was to evaluate the models as to whether they capture the observed historical variability in the variable of interest in each of the four regions (Supplementary Table 2) by using a Kolmogorov–Smirnov test (the *P* value for similarity with the observation-based series must be greater than 0.05 in at least two-thirds of the available model simulations; similar to ref. 29) applied to the relevant area-averaged time series (for example, Australian-averaged summer temperatures). This evaluation is conducted over the common 1951–2005 period between the observation-based series and the historical model simulations, and this removes the worst-performing models resulting in statistical distributions for the current world that closely match those in the recent observational series (that is, 1986–2015). Using a subset of models, the frequencies of extreme events in the four worlds were calculated with best estimates (based on all model years in each ensemble) and 5th–95th percentile confidence intervals estimated from 10,000 bootstrapped subsamples of data from half of the ensemble of complete model runs (for example, if there are 30 model simulations from models that pass the evaluation test in the histNat ensemble, 15 runs are randomly sampled with replacement and this is done 10,000 times).

In the case of the 2006 drought, the extreme event was defined by a high annual-average daily maximum temperature and low annual precipitation, and model evaluation was conducted using both variables and only models that adequately captured the variability in both were analysed. The precipitation deficit and high temperatures were investigated separately. This allowed us to examine the changes in both well-observed meteorological parameters, which are understood to be important factors in Australian drought[17]. Other indices are often used to represent drought, including the self-calibrated Palmer Drought Severity Index and Standardized Precipitation Evapotranspiration Index, and these allow for estimations of the evapotranspirative effect as a function of temperature. These are not employed here due to uncertainties in the method to estimate the evapotranspiration and, as a consequence, drought intensity. We instead highlight the evolving nature of single-year droughts through the changing likelihood of two significant components of Australian drought events: well-above-average maximum temperatures and precipitation deficits.

Extreme events and ENSO relationships. As Australian climate is strongly related to ENSO variability, a brief analysis of the changing event dependence on ENSO conditions under the warming scenarios was conducted. The austral summer Niño-3.4 region temperature index and gridbox temperature anomalies were calculated for each simulation relative to a centred 21-year moving window. The average temperature anomalies and Niño-3.4 index values associated with each event were calculated and the nature of the ENSO relationship with each relevant variable (for example, Australian summertime average temperatures) across the four scenarios was compared. Events were separated by their ENSO background conditions using a threshold derived by observational Niño3.4 variability. The threshold was defined as the standard deviation of austral summer Niño-3.4 over the detrended 1951–2005 period in HadISST[30], which is 0.95 °C.

Data availability. The model data supporting this study are available in a public repository, for example at http://cmip-pcmdi.llnl.gov/cmip5. The Australian observational temperature and precipitation data are publicly available from http://www.bom.gov.au/jsp/awap and are available in netCDF format on request from the Bureau of Meteorology. The Coral Sea temperature data are available from http://www.bom.gov.au/cgi-bin/climate/change/timeseries.cgi?graph=sst&area=cor.

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