9. THE ROLE OF ANTHROPOGENIC FORCING IN THE RECORD 2013 AUSTRALIA-WIDE ANNUAL AND SPRING TEMPERATURES

Sophie C. Lewis and David J. Karoly

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.

Introduction. 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 (ΔT_{ANN1}), with the previous record anomaly of 1.36°C recorded in 2005 (ΔT_{ANN2}).

In 2013, new Australian area-average mean temperature (Tmean) records were also set for spring (ΔT_{SON1} = 1.83°C) and the month of September (ΔT_{SEP1} = 3.01°C), when the largest anomaly was recorded for any month since at least 1910 (Bureau of Meteorology 2014).

In this study, we investigate the roles of anthropogenic climate change and natural variability in contributing to the observed 2013 record-breaking temperatures. These contributing factors are assessed using multiple simulations from nine global climate models that participated in phase five of the Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2012), and they were selected using the criteria from Lewis and Karoly (2013) based on data availability and representation of observed Australian temperature variability (see Supplementary Table S9.1 for model list). We consider the observed 2013 annual, spring, and September Australian area-average Tmean anomalies, as these were large record-setting events that have not been investigated previously. We then estimate anthropogenic contributions to 2013 record temperatures using a suite of CMIP5 experiments for the period 1850–2020 with different climate forcing factors imposed [see Supplementary Table S9.2 for experiment description and Lewis and Karoly (2013) for further information].

Data and methods. We investigate changes in area-average Australian annual (January–December, ANN), spring (September–November, SON), and September (SEP) Tmean distributions from observational and CMIP5 model datasets. We use observed Australian area-average annual Tmean from the high-quality ACORN-SAT dataset for 1911–2013 (Trewin 2012) and then consider 65 realizations of the CMIP5 historical experiment for the period 1911–2005, forced by observed time-evolving changes in anthropogenic (well-mixed greenhouse gases, aerosols, and ozone) and natural forcings (solar irradiance and volcanic aerosols). We also use 35 realizations of the RCP8.5 experiment (representative concentration pathway with high emissions for the 21st century) for 2006–20, centered on 2013, as this is representative of global greenhouse gas emissions from 2005 to present (Peters et al. 2012). Full details of experiment forcings are provided by Taylor et al. (2012).

The probabilities of Australian annual, spring, and September temperatures were calculated for experiments incorporating anthropogenic and natural forcings, and they were compared to a parallel set of experiments including only natural forcings. The long control runs with no changes in external forcing factors (piControl) completed for each participating CMIP5 model provide an estimate of the unforced variability of the climate. The piControl experiment allows a large number of model years to be analyzed (13 realizations from selected models) but provides only an approximation of natural climate variability. Hence, we also utilize 36 realizations of the historicalNat experiment as an additional "natural" climate reference state in which time-evolving solar and volcanic forcings are imposed for the period 1850–2005.

We calculate historical, historicalNat, and RCP8.5 Tmean anomalies relative to the 1911–40 climatology and piControl anomalies relative to the long-term mean. We investigate the frequency of anomalies exceeding the ΔT_{ANN2} threshold observed in 2005. The historical simulations from the nine models used agree well with the distribution of observed Australian annual average temperatures over the period 1911–2005 (Fig. 9.1b) estimated using a kernel smoothing function, with a two-sided Kolmogrov-Smirnov test indicating that the distributions are statistically indistinguishable ($p = 0.05$).

Results. We compare the occurrence of extreme Australia-wide annual temperatures ($> \Delta T_{ANN2}$) in the CMIP5 experiments (Fig. 9.1c). When anthropogenic forcings are included, there is a clear increase in the likelihood of extreme annual temperatures. The Australia-wide ΔT_{ANN2} temperature anomaly occurs once in six years on average in the RCP8.5 experiments over the period 2006–20 (Fig. 9.1d). Conversely, none of the 5572 historicalNat model years analyzed here exceeds the observed 2005 temperature threshold; it is virtually impossible to reach such a temperature record due to naturally forced climate variability alone in these model simulations. Furthermore, in the unforced piControl simulations, only one of the 6795 model years analyzed here exceeds the ΔT_{ANN2} threshold set in 2005.

Previous studies investigating anthropogenic contributions to observed extremes have quantified the relative influences on the occurrence of an event using a fraction of attributable risk (FAR) approach (Stott et al. 2004; Stone and Allen 2005) as a quantitative estimate of the fraction of risk of exceeding a particular climatic threshold that can be attributed to a cause. Using CMIP5 experiments, we previously estimated that the probability of extreme Australian summer temperatures, such as observed in 1998 and 2013, very likely increased by at least five-fold (FAR = 0.82) due to anthropogenic forcings (Lewis and Karoly 2013). However, when quantifying anthro-

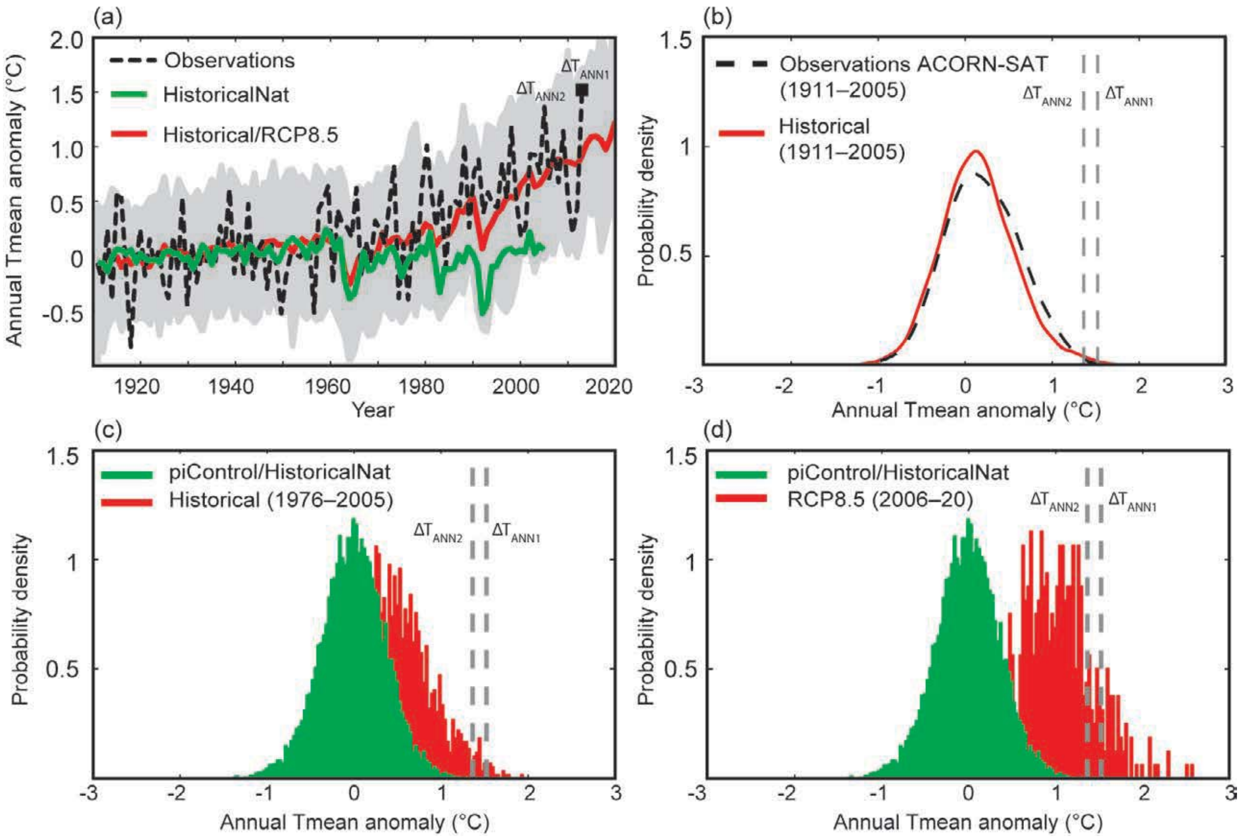

Fig. 9.1. (a) Australian annual average Tmean anomalies (relative to 1911–40) for observations (dashed black) and historicalNat (green) simulations. The historical and RPC8.5 multimodel mean is also shown (red), and gray plumes indicate the 5th and 95th percentile values across the ensemble members. (b) Probability density functions for Australian annual average Tmean anomalies (relative to 1911–40) for observations (dashed black) compared with historical (red) for 1911–2005. (c) Histograms for Australian annual average Tmean anomalies (relative to 1911–40) of historical (red, years 1976–2005) and piControl and historicalNat (green, all years shown). (d) Same as panel (c), but instead showing RCP8.5 Tmean anomalies (red, years 2006–20). In all probability plots, vertical dashed lines show the observed 2013 anomaly ($\Delta T_{ANN1} = 1.53°C$) and threshold of the second hottest year on record ($\Delta T_{ANN2} = 1.36°C$).

pogenic influences on the occurrence of Australian annual average temperatures exceeding ΔT_{ANN2}, the FAR value is effectively equal to one as there is only a single instance in over 12 300 combined model years in which this threshold was exceeded without anthropogenic forcings.

Christidis et al. (2013) investigated the record 2010 Moscow temperatures and found the probability of such an event occurring was near zero in climate simulations without anthropogenic influences. However, as the observed anomalies lie in the far warm tail of both the natural and anthropogenically influenced temperature distributions, this event likely resulted from internal variability. Unlike the Moscow record, 2013 Australian temperature anomalies occur frequently in simulations with anthropogenic factors. A FAR value of one is also obtained by shifting the observed temperature distribution by the modeled mean RCP8.5 temperature changes, demonstrating that the increased likelihood of the Australian annual temperature of 2013 can be explained by the mean warming trend of Australian annual average Tmean having increased by ~0.9°C since 1910 (Bureau of Meteorology 2012). Similarly, although ENSO temperature anomalies are a major driver of Australian temperature variability, the 2013 ENSO conditions were predominantly neutral (observed NINO3.4 anomaly −0.16°C relative to 1981–2010; http://www.ncdc.noaa.gov/sotc/global/2013/13, which is typically associated with cooler Australian temperatures (Power et al. 2006; Arblaster and Alexander 2012). ENSO variations alone are also unlikely to explain the record 2013 Australian summer temperature (Lewis and Karoly 2013).

We next compare the probability of spring and September Tmean anomalies in the CMIP5 experiments, using a kernel smoothing function (Fig. 9.2). There is a warm shift in these distributions when anthropogenic forcings are included. As spring and September temperatures exceeding the respective ΔT_2 thresholds occur in natural-only forced simulations, we calculate FAR values by comparing the probability of extreme ($>\Delta T_2$) mean temperatures in the various model simulations, as determined by the number of times ΔT_2 was exceeded, relative to the total sample size. Using subsamples of only 50% of available data bootstrap resampled 1000 times, a distribution of possible FAR values was calculated. Conservative estimates of the FAR values, which are exceeded by 90% of the values in the FAR distribution determined by bootstrapping, are reported here. The FAR value for Australian SON Tmean anomalies is 0.97 (relative to the historicalNat) for the RCP8.5 experiment for the period 2006–20, indicating a greater than 50-fold in-

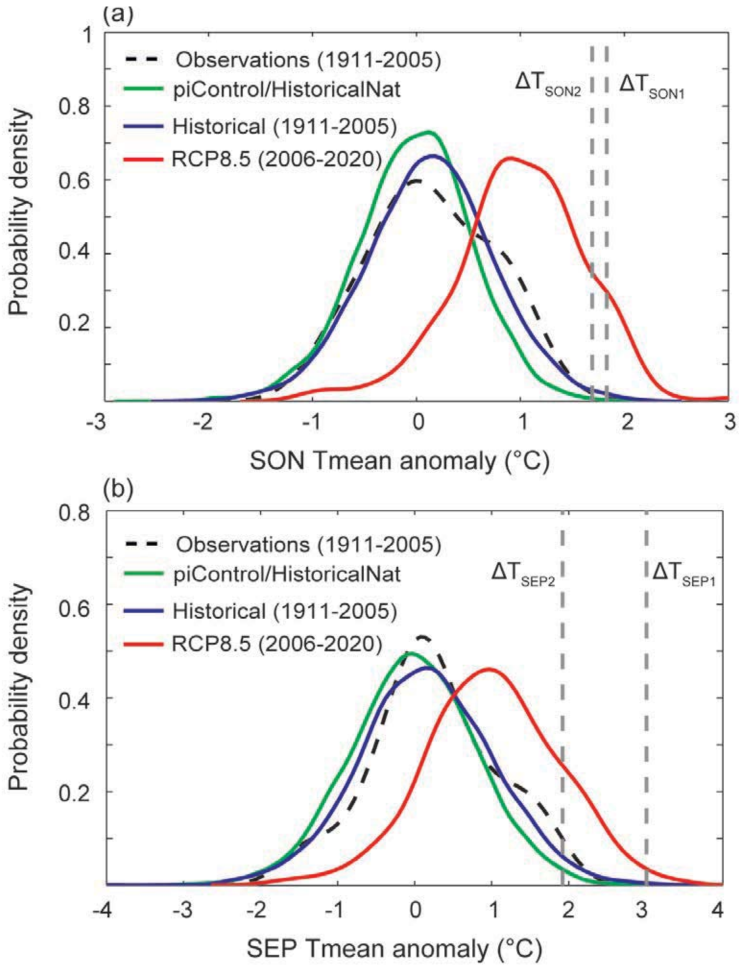

Fig. 9.2. (a) Probability density functions for Australian SON average Tmean anomalies (relative to 1911–40) for observations (dashed black, all years shown) compared with historical (blue, 1911–2005), RCP8.5 (red, years 2006–20), and piControl and historicalNat (green, all years shown), estimated using a kernel smoothing function. Vertical dashed lines show the observed 2013 anomaly (ΔT_{SON1} = 1.83°C) and threshold of the second hottest spring on record (ΔT_{SON2} = 1.62°C). (b) Same as panel (a), but showing Australian September average Tmean anomalies for historical (blue), RCP8.5 (red), and piControl and historicalNat (green), with ΔT_{SEP1} (3.01°C) and ΔT_{SEP2} (1.92°C) thresholds indicated.

crease in risk of hot spring temperatures in Australia that can be attributed to anthropogenic forcings. The equivalent FAR value for September Tmean anomalies for Australia is 0.82 (five-fold increase in risk) for the RCP8.5 experiment.

Conclusions. We examined anthropogenic and natural contributions to the record-breaking 2013 Australia-wide annual, spring, and September temperature anomalies. There are substantial increases in the likelihood of hot temperatures occurring ($>\Delta T_2$) that can be attributed to anthropogenic forcings for spring (FAR = 0.97) and September (FAR = 0.82) area-average Australian Tmean anomalies. Annual Tmean anomalies greater than the second hottest year observed for Australia (ΔT_{ANN2}) occur once in six years in the RCP8.5 years investigated here. In the piControl simulations including only natural forcings, only a single year of the 6795 model years analyzed exceeds ΔT_{ANN2}. The ΔT_{ANN2} anomaly falls entirely outside the bounds of natural climate variability simulated in the historicalNat experiment. Hence, temperature anomalies as extreme as those observed in 2005 occur only once in over 12 300 years of model simulations without anthropogenic forcings, and the resulting FAR value is essentially equal to one.

These results are derived from a subset of CMIP5 data and encompass only the range of natural variability simulated therein. Model years as warm as or warmer than ΔT_{ANN2} could occur in realizations that were not included. This analysis necessarily assumes that the statistics of the modeled temperature distributions are equivalent to the statistics of observations on long timescales. Additionally, the calculation of meaningful FAR values depends on the validity of the forced response of the models relative to the observed forced response. Nonetheless, it is unlikely that alternative CMIP5 model inclusions or the use of alternative attribution model datasets would result in the attribution of the 2013 Tmean anomalies to a cause other than the anthropogenic factors identified here. Indeed, further analysis of Australia's 2013 record annual Tmean also demonstrates anomalies were largely outside the modeled natural variability, with the attributable risk to anthropogenic forcing essentially 100% (see "Multimodel assessment of extreme annual-mean warm anomalies during 2013 over regions of Australia and the western tropical Pacific" and "Climate change turns Australia's 2013 big dry into a year of record-breaking heat" in this report).

10. INCREASED SIMULATED RISK OF THE HOT AUSTRALIAN SUMMER OF 2012/13 DUE TO ANTHROPOGENIC ACTIVITY AS MEASURED BY HEAT WAVE FREQUENCY AND INTENSITY

Sarah E. Perkins, Sophie. C. Lewis, Andrew D. King, and Lisa V. Alexander

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.

Introduction. 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. Rainfall was below average for much of the country since July 2012. Along with the late onset of the Australian monsoon, such conditions primed the continent for extremely hot summer weather, including heat waves. Heat waves require detailed focus due to their large impacts (Karoly 2009; Coumou and Rahmstorf 2012), particularly on human health and morbidity (Nitschke et al. 2007). Much of inland Australia experienced extreme temperatures for over three consecutive weeks (Bureau of Meteorology 2013a).