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).

By employing the fraction of attributable risk (FAR) framework (Allen 2003), Lewis and Karoly (2013) demonstrated that the likelihood of the extreme Australian heat during the 2012/13 summer had increased by between 2.5 and 5 times due to human activity. However, this assessment was on the seasonal average temperature anomaly and did not include specific heat wave measures. Here we also undertake an analysis of the summer of 2012/13 but with a metric of two heat wave characteristics (Perkins and Alexander 2013). While focusing specifically on seasonal heat wave measures, such an analysis also allows for the assessment of whether changes in risk are consistent for heat wave magnitude and frequency, thus providing important information for adaptation and impacts groups.

Data and methods. We calculate heat waves using the Excess Heat Factor (EHF) definition (Nairn and Fawcett 2013; Perkins and Alexander 2013) for November–March, where the daily average of minimum and maximum temperature must exceed a separate climatological and monthly threshold for at least three consecutive days. Here the climatological threshold is the calendar day 90th percentile, calculated from a 15-day moving window for 1961–90. Note that EHF units are °C^2 (see Nairn and Fawcett 2013).

In order to investigate the effects of human activity on heat waves, the preindustrial control (289 years long), historical, and RCP8.5 experiments (Taylor et al. 2012) from the Community Earth System Model (CESM; Fischer et al. 2013) were employed. Here we use a 21-member ensemble of CESM (1.875° × 2.5° resolution; for further model details, see Fischer et al. 2013). The ensemble is generated through perturbations on the order of 10–13 applied to atmospheric temperature initial conditions. We use 1955–2005 of the historical period and merge it with 2006–13 from RCP8.5. A caveat to this study is its dependence on a single model (CESM). However, collectively, the CESM ensemble simulates reasonable changes and variability in observed heat waves over Australia (Perkins and Fischer 2013). Observed heat wave metrics were calculated for austral summers commencing in 1955–2012 using the Australian Water Availability Project (AWAP) temperature dataset (Jones et al. 2009) interpolated onto a two-degree grid. Using AWAP, the observed 2012/13 anomalies of heat wave measures were calculated.

In this study, we investigate the extreme heat of the 2012/13 summer by analyzing two heat wave characteristics (Perkins and Alexander 2013). These are the total number of heat waves and the peak amplitude (hottest heat wave day). The number of heat waves represents the frequency, and peak heat wave amplitude represents the intensity of the 2012/13 extended summer season (November–March). For each model run and the observations, the characteristics were calculated at the grid box level and expressed as anomalies against the relative 1961–90 average, with the control simulation relative to model years 111–140. The control base period was chosen to be the same length as the historical; however, the start year (111) was selected at random since no significant difference between 30-year windows from the control was detected. All anomalies were area-averaged, and all 21 CESM members were concatenated to form a longer single sample.

We employ the FAR framework to analyze changes in the risk of heat wave attributes due to increases in anthropogenic greenhouse gases. This requires conditions where no anthropogenic emissions are present (the control run) and where greenhouse gas concentrations are prescribed to observed levels to 2005 and projected to 2013, accounting for anthropogenic emissions (the historical/RCP8.5 runs). Three periods are analyzed for summers commencing in 1955–83, 1955–2012, and 1984–2012 to investigate how the risk of each characteristic changes with increasing anthropogenic forcings during the observational period. Per period, we generate 1000 bootstrapped samples, consisting of 50% of the control and historical/RCP8.5 data per heat wave characteristic (i.e., the bootstrapped sample sizes of the control and forced runs are half of the original). Selected years are in two-year blocks to account for time dependence, and using 50% of data accounts for sample size sensitivity. Bootstrapping is employed since a true estimate of FAR cannot be obtained from the original control and forced simulations. Our bootstrapping technique allows the uncertainty in FAR to be estimated. The probability of the respective observed anomaly is calculated, and 1000 FAR values are calculated by:

$$FAR = 1 - \left(\frac{P_{cntrl}}{P_{forced}}\right) \quad (1)$$

We also compute the corresponding changes in risk of the characteristics by:

$$Risk = \frac{1}{(1 - FAR)} \quad (2)$$

Lastly, using the FAR values for each heat wave characteristic, we compare the waiting time of the frequency and intensity of the 2012/13 summer in each of the three periods and the control. This determines how historical return intervals of the hot 2012/13 summer compare to a world without anthropogenic influence.

Results. Figures 10.1a and 10.1b present the area-averaged probability density functions (PDFs) of anomalies of seasonal heat wave frequency and intensity, respectively. The summer of 2012/13 experienced an unprecedented number of heat waves; however, the peak intensity was not particularly unusual (see Table 10.1). Throughout the periods of the simulations, the right tail of the PDF increases—with greater anthropogenic forcing, more extreme summers, as characterized by heat wave frequency and intensity, are expected (relative to 1961–90).

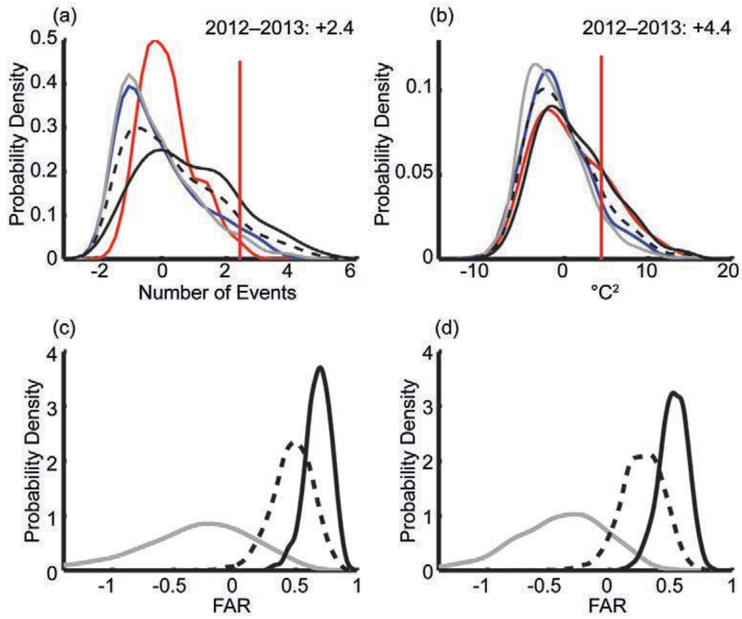

Fig. 10.1. (a), (b) Respective probability density functions (PDFs) of heat wave frequency (number of heat waves) and intensity (peak magnitude) anomalies. Vertical lines reflect the respective anomalies for the 2012/13 Austral summer. (c), (d) Respective PDFs of FAR values from 1000 bootstrapped samples. Red is for the observations, blue is for the control, gray is for 1955–83, black dashed is for 1955–2012, and black solid is for 1984–2012.

Figures 10.1c and 10.1d present PDFs of the FAR values per period for heat wave frequency and intensity, respectively. FAR values for intensity (Fig. 10.1b) and frequency (Fig. 10.1a) are very similar. This includes negative median FAR values for 1955–83 (−0.22 and −0.32 for frequency and intensity, respectively). A Kolmogorov–Smirnov test at the 5% level indicates that the 1955–83 and control simulations are not significantly different, indicating that these values hold little meaning and that the impact of human activity on Australian summer intensity and frequency had not yet emerged from natural variability. In the case of this study, this result occurs only when the first 30 years of the historical period (1955–83) is included, that is, when anthropogenic forcings were considerably lower than 2012/13.

It is very likely (>90%) that FAR values are greater than 0.26 and 0.1, respectively, during 1955–2012 (medians 0.49 and 0.27) and very likely that FAR values are greater than 0.55 and 0.37 (medians 0.69 and 0.53), respectively, for 1984–2012. The all-positive FAR values in 1984–2012 indicate that the risk of the intensity and frequency of the 2012/13 summer is always larger due to human activity during the latter decades of the 20th century. Kolmogorov–Smirnov tests on 1955–2012 and 1984–2012 against the control indicate statistical significance for both heat wave frequency and intensity.

Based on the median FAR values, Table 10.1 presents the best estimate changes in the risk of the 2012/13 summer heat wave frequency and intensity during the three time intervals and the

Table 10.1. Changes in the risk of Australian 2012/13 heat wave frequency (number of heat waves) and intensity (peak magnitude) anomalies due to anthropogenic forcings throughout summers commencing in 1955–83, 1955–2012, and 1984–2012, as well as return periods relative to observations for 1955–2012. Note that 1955–83 values are calculated from non-significant FARs.

Characteristic	1955–83		1955–2012		1984–2012		Control	
	Risk	Return period	Risk	Return period	Risk	Return period	Risk	Return period
Frequency	0.78	145.22	1.94	58.00	2.94	32.94	NA	112.64
Intensity	0.73	8.45	1.37	4.46	2.31	2.97	NA	6.12

corresponding return periods. The risk due to human activity is similar for both characteristics during 1955–1983 and is less than zero. However as discussed above, 1955–83 summer heat wave frequencies and intensities are not distinguishable from the control (i.e., cannot be separated from no human influence).

A striking result is that during 1955–2012 and 1984–2012, the risk of the summer of 2012/13 having such a high heat wave frequency anomaly increases faster than heat wave intensity. During the latter period, the risk of experiencing a summer heat wave number (intensity) greater than that of 2012/13 increases by almost three-fold (two-fold) compared to a world with no anthropogenic forcing. This corresponds to a reduction in return periods to ~33 and 3 years, respectively, compared to 1955–2012. It is also an interesting and important result that even though the 2012/13 summer heat wave intensity was much less "extreme" than heat wave frequency (see corresponding return periods in Table 10.1), human activity has clearly increased the risk of both characteristics occurring. Thus, there is a calculable human influence on the hot Australian summer of 2012/13.

Conclusions. Using a 21-member ensemble of the CESM model, we analyzed changes in the risk of the hot Australian 2012/13 summer with respect to heat wave frequency and intensity. Our study found that the risk of both simulated heat wave characteristics has increased due to human activity. The risk of summer heat wave frequency increases faster than heat wave intensity. When isolating 1984–2012, the 2012/13 heat wave frequency increased three-fold due to human activity, while heat wave intensity increased two-fold, compared to a climate with no anthropogenic forcings.

This infers a reduction in return periods when comparing 1955–2012 to 1984–2012—from 58 years to 33 years for frequency and from 4 years to 3 years for intensity. Lastly, even though heat wave intensity of 2012/13 was not the most severe Australia experienced, there is still a calculable influence on this heat wave characteristic on a seasonal scale. Overall, our study shows that the risk of the hot 2012/13 Australian summer with respect to simulated heat wave frequency and intensity increased due to human influences on climate.

11. UNDERSTANDING AUSTRALIA'S HOTTEST SEPTEMBER ON RECORD

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Record high September maximum temperatures over Australia arose from a combination of a strongly anomalous atmospheric circulation pattern, background warming, and dry and warm antecedent land-surface conditions.

Introduction. 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. Lewis and Karoly ("The role of anthropogenic forcing in the record 2013 Australia-wide annual and spring temperatures" in this report) determine that the attributable risk of such extreme heat in September has increased five-fold due to anthropogenic climate change. Here we take a different attribution approach and use multiple linear regression and experiments with a seasonal forecast system to explain and understand the magnitude of the September 2013 temperatures.