DECONSTRUCTING FACTORS CONTRIBUTING TO THE 2018 FIRE WEATHER IN QUEENSLAND, AUSTRALIA

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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.

EVENT DESCRIPTION AND STUDY APPROACH. 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.

The McArthur Forest Fire Danger Index (FFDI) is used to assess dangerous bushfire weather conditions in Australia (Noble et al. 1980). The FFDI increased considerably in the last week of November and was the highest on record (from 1950) in some areas. During 24–29 November, daily FFDI values were "extreme" (FFDI ≥ 75) for large parts of Queensland and "catastrophic" (FFDI ≥ 100) in some locations. The FFDI includes a measure of fuel moisture content calculated from antecedent rainfall and temperature, daily temperature, relative humidity (RH), and wind speed (V). The 99th percentile FFDI (number of days > 99th percentile) is discussed here as indicative of the extreme end of the fire risk spectrum based on these weather conditions.

The 2018 fire occurred during a period of synoptic- and large-scale extremes. This is typical of a compound extreme event (Zscheischler et al. 2018) and makes definition and analysis of the event as a single variable limited. Prior research cautions that direct attribution of the FFDI to specific forcings (e.g., anthropogenic greenhouse gases) is complicated by the index's integration of multiple dependent variables (Black 2017). Model bias correction of one variable (e.g., temperature) requires its relationship with others (e.g., humidity) to be preserved. While explicit examination of the FFDI may be possible with multivariate bias correction (e.g., Cannon 2018), we adopt an alternative approach and instead examine FFDI components separately. As individual variables have different weightings in the FFDI calculation and are affected by climate change differently (Black 2017), it is valuable to examine each separately in order to determine the factors contributing to the extreme fire and heatwave period. We deconstruct the observed key synoptic features during November and the conditioning heatwave event (defined as 24 to 29 November 2018, hereafter "the event") and large-scale 2018 conditions [antecedent conditions in spring (September–November) and in November only, and large-scale modes of variability). Using two climate model attribution [CMIP5 (Taylor et al. 2012) and weather@home (Black et al. 2016)] frameworks, we examine whether aspects of these observed

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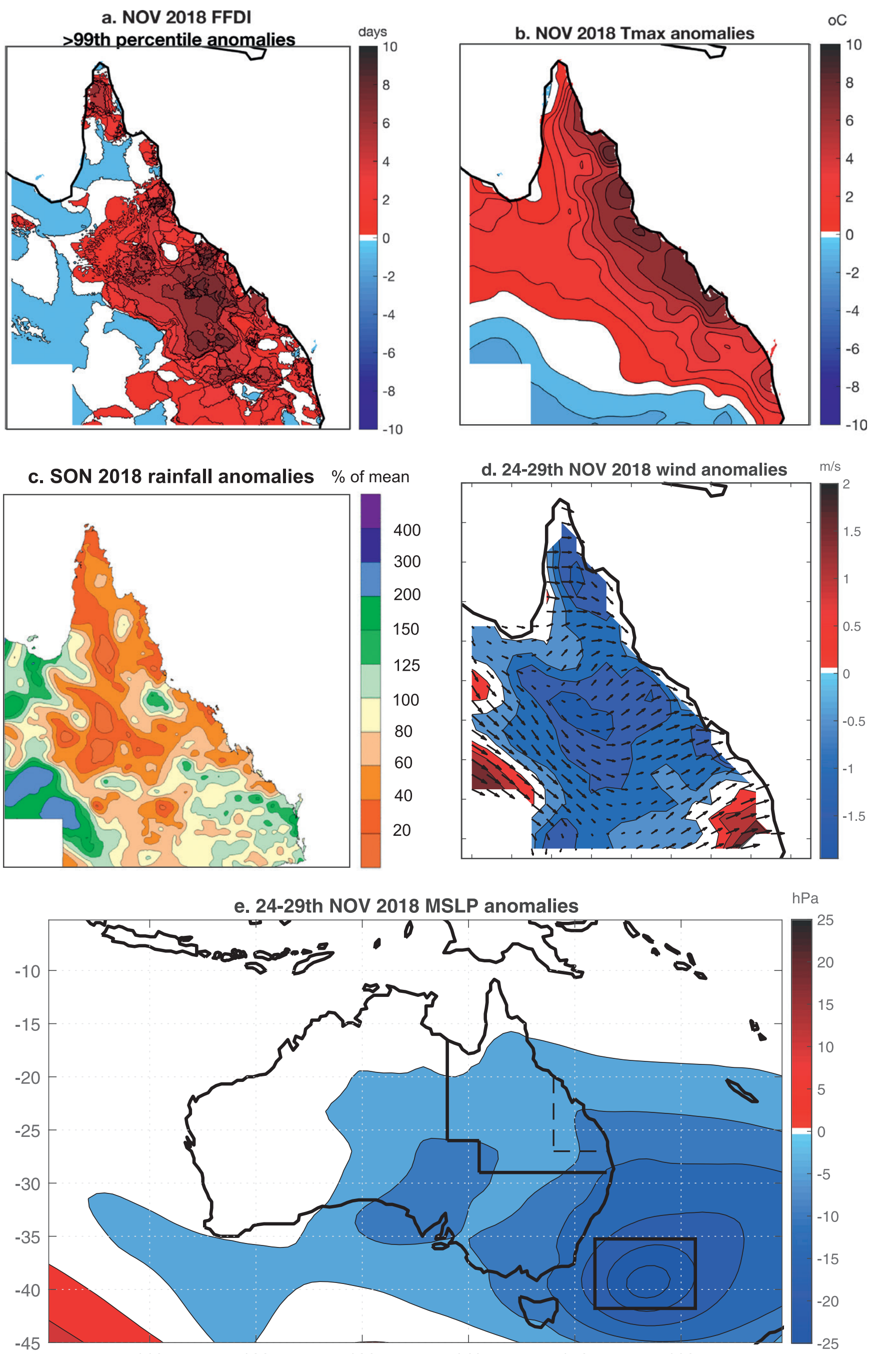

Fig. 1. Summary of key observed meteorological and climatological conditions in Queensland state, northeastern Australia, during the November 2018 fire event. (a) FFDI anomaly (number of days for November 2018 > 99th percentile from 1950–2017 compared to long-term November average from 1950). (b) November 2018 average of daily Tmax anomalies (°C) (relative to long-term average from 1911). (c) Precipitation anomalies for SON (%) relative to mean). (d) Wind speed (m s-1) and (e) direction, and (f) MSLP anomalies (hPa) for the event (24–29 Nov, relative to long-term November mean from 1979). Queensland state is shown, with area of interest for fire shown by dashed box, and the area of anomalously low MSLP in the Tasman Sea.

conditions were made more likely due to anthropogenic forcings.

OBSERVED LARGE-SCALE FACTORS.

We focus on the state of Queensland and the region of highest observed fire danger (hereafter "fire region"), which encompasses the major areas burnt.

Temperature. Observed daily maximum temperatures (T_{max}) were anomalously high during November (Fig. 1b). High Tmax and daily minimum temperature (T_{min}) were persistent throughout the event particularly for T_{min} (see Fig. ES1 in the online supplement). Over this period, Queensland area-averaged minimum temperatures are above the observed 95th percentile, and records were broken in many locations (Australian Bureau Of Meteorology 2018). Above-average temperatures also occurred in both regions over spring and November.

Precipitation. Seasonal rainfall was below average over the antecedent spring period (Fig. 1c), which likely favored drier soil moisture conditions and increased Tmax values (Kirono et al. 2017). While rainfall occurred across the state in the days prior to the event (Fig. ES1c), the heatwave event itself lacked significant rainfall. In the major fire-affected regions, August to October is the driest period of the year, and November marks the transition between the dry and wet seasons; for example, Mackay (northern

Table 1. Summary of observed 2018 meteorological and climatological conditions for Queensland and large-scale indices. For the FFDI, the count of FFDI days above the 99th percentile is given for the fire region for November, as are temperature and precipitation values for the fire region for 5-day periods and the annual average large-scale index values. Maximum (or minimum) observed anomalies and ranking of 2018 anomalies (relative to 1961–90) are indicated.

Variable (QLD)	2018 anomaly	Maximum/minimum anomaly	Ranking
FFDI days > 99th percentile (NOV)	4	4 (2018)	1st since 1950
Temperature (EVENT)	3.9°C	3.9°C (2018)	1st since 1950
Temperature (NOV)	1.65°C	2.8°C (2014)	4th since 1950
Precipitation (EVENT)	−1.9 mm day^{-1}	−2.1 mm day^{-1} (2006)	7th since 1950
Precipitation (SON)	−0.2 mm day^{-1}	−0.7 mm day^{-1} (2002)	31st since 1950
Index	2018	Maximum Anomaly	Ranking
ENSO (ANN)	0.66	2.3 (2015)	13th since 1950
SAM (ANN)	2.4	2.4 (2018)	1st since 1950
IOD (ANN)	0.9	1.3 (1997)	2nd since 1950

point of fire region) averages 83 mm for the August–October period and 88 mm for November.

Large-scale context. The state of large-scale ocean–atmosphere modes of variability during 2018 are summarized in Table 1. Most notably, strong positive southern annular mode (SAM) and Indian Ocean dipole (IOD) conditions were observed; however, both these modes are typically associated with rainfall variations over southern Australia, with minimal impact in the north (Risbey et al. 2009; Ummenhofer et al. 2009; Hendon et al. 2016). El Niño–Southern Oscillation (ENSO) conditions were largely neutral. We note that subseasonal drivers, particularly the Madden–Julian Oscillation (MJO), were also influential during the fire event, with MJO-associated tropical cloud and rainfall bands likely contributing to the observed anomalous westward wind flow (Australian Bureau of Meteorology 2018).

OBSERVED SYNOPTIC-SCALE FACTORS. *Wind speed and direction.* During the event, anomalous westerly winds (at 10 m) were observed (Fig. 1d). While wind speed was below the long-term November average for most of Queensland (except in coastal southern Queensland), the westerly direction was anomalous for this time of year, which usually experiences landward flow, with westerly winds reported at some tropical coastal sites where they are historically extremely rare in November (Australian Bureau of Meteorology 2018). Anomalous wind features are hence both a risk factor and a key driver of temperature and humidity extremes.

MSLP. Composited daily mean sea level pressure (MSLP) during the 5-day event shows a key low pressure system over southeastern Australia and the Tasman Sea (Fig. 1e), which was noted as a driver of the anomalous southwest to westerly wind flow over Queensland (Australian Bureau Of Meteorology 2018). We use the region of observed anomalously low MSLP in the Tasman Sea (36°–42°S, 152°–162°E) to examine synoptic factors in model simulations.

Humidity. Relative humidity (at 2 m) observed during the event was significantly below average, particularly for the coastal regions of Queensland (not shown).

MODELED LARGE-SCALE CONTRIBUTING FACTORS. Background climatic conditions observed in 2018 are first examined using CMIP5 monthly and seasonal model data, with risk ratios (RRs) associated with anthropogenic forcings calculated for exceeding 2018 observed anomalies for each variable (see section 2 in the online supplemental material). RRs are a quantification of the change in the probability of an extreme that can be attributed to anthropogenic forcings (e.g., an RR value of 2 indicates a doubling of attributable risk).

Temperature. Notable differences in the distribution of temperatures in the fire region occur in CMIP5 experiments with different forcings (Fig. 2a), with a substantial warm shift in temperatures in RCP8.5 simulations compared to historicalNat scenarios. The shift in probabilities is particularly the case for warm tail temperatures anomalies, consistent with previous studies quantitatively attributing observed Australian temperature extremes to anthropogenic forcings (e.g., Black et al. 2015; Lewis and Karoly 2013; Perkins and Gibson 2015). The RR for exceeding observed 2018 November temperature anomalies is 4.5.

Precipitation. The distributions of area-average Queensland September–November (SON) rainfall differ between the CMIP5 historicalNat and RCP8.5 simulations at the dry end of the distribution (Fig. 2b; see also Fig. ES2b). This indicates that conditions drier than average are simulated to occur somewhat less often under anthropogenically forced runs (years 2005–36) compared to natural runs. The RR for rainfall deficits lower than observed conditions in spring 2018 is 1.5. We note that observed regional rainfall trends are weak and rainfall projections are model dependent (Kirtman et al. 2013), and attribution of events may be spatiotemporal scale or definition dependent (Angélil et al. 2017).

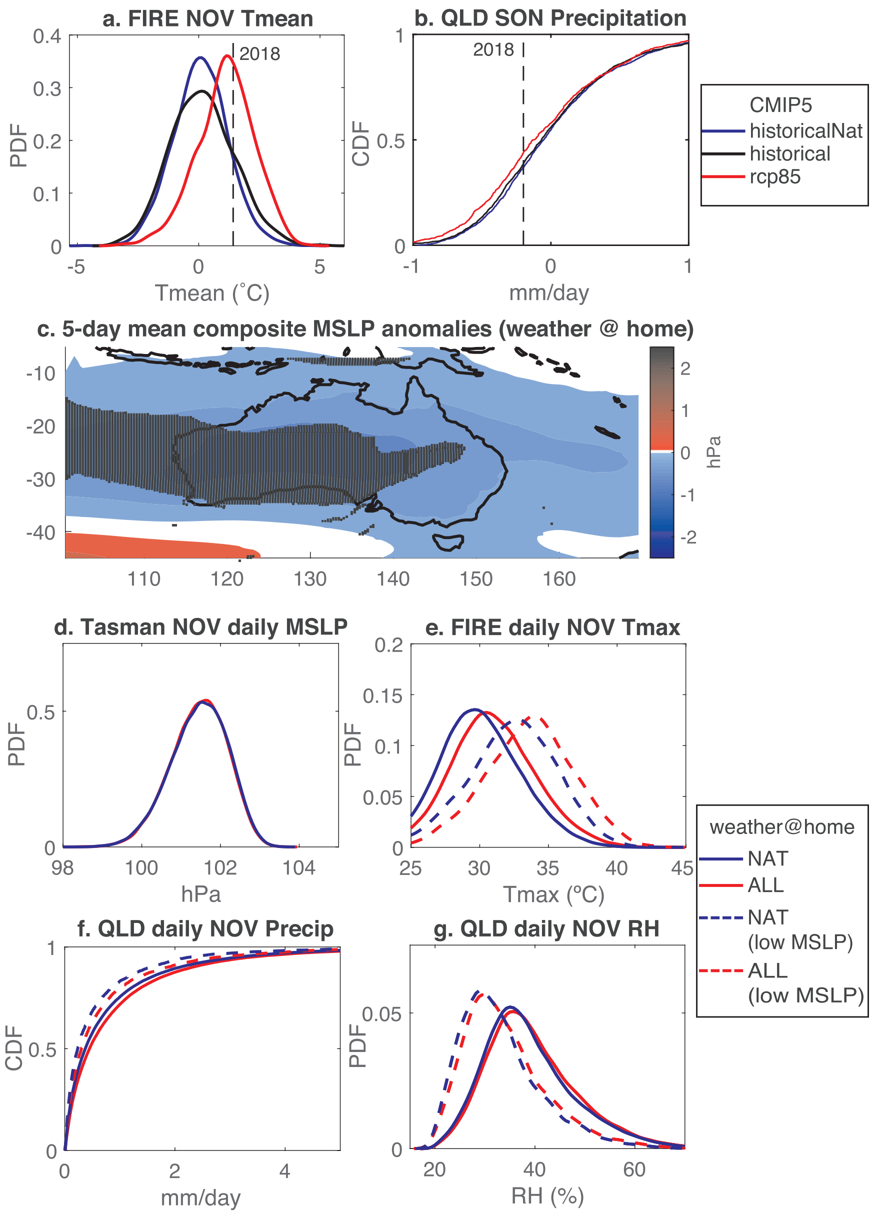

Fig. 2. Summary of modeled conditions in Queensland. Plot shows comparison of CMIP5 historicalNat (blue), historical (black), and RCP8.5 (red) experiments for (a) daily fire region area-averaged November temperature (°C) probability distributions and (b) Queensland (QLD) area-average SON precipitation (mm day−1) cumulative distributions for anomalies relative to each model's 1961–90 climatology, with 2018 observed anomalies noted by a vertical dashed line. For the weather@home ensemble, plots shows (c) anomalies (ALL − NAT) of 5-day running mean MSLP(hPa) with stipples showing anomalies larger than the standard deviation of daily November values. PDFs are given for weather@home (d) daily November MSLP conditions in Tasman region for ALL (red) and NAT (blue), (e) daily fire region area-averaged November temperature (°C), and QLD area-average (f) precipitation (mm day−1) and (g) relative humidity (%). For weather@home plots, dashed lines show distributions of variables during times only when 5-day running mean MSLP in the Tasman Sea box is below the 10th percentile of all days.

MODELED SYNOPTIC-SCALE CONTRIBUTING FACTORS. We next explore synoptic-scale factors in a large single-model ensemble of atmosphere-only simulations [weather@home; see Black et al. (2016) and section 3 of our online supplemental material). The fires were characterized by a distinct synoptic evolution over the 5-day period beginning 24 November and notably low MSLP in the Tasman Sea.

MSLP. We compare the occurrence of low area-average MSLP anomalies in the Tasman region (Fig. 1e) between the experiments conducted with present-day atmospheric composition (ALL) and preindustrial atmospheric composition and composite surface field modified by removing different anthropogenic response pattern estimates (NAT). There are no significant changes in 5-day mean November daily MSLP patterns in these scenarios (Fig. 2c) and the daily area-average Tasman Sea MSLP distributions are indistinguishable between experiments (Fig. 2d).

Temperature. There is a clear warm shift in November daily temperatures in both the fire region (Fig. 2e) and QLD (Fig. ES2a) in the ALL forcing simulations. There is an additional contribution to warm simulated temperatures from prevailing low MSLP patterns. When daily temperature anomalies in the fire region are compared for all simulated with those where area-average Tasman region MSLP anomalies are below the 10th percentile value of all values (MSLPLOW), a further warm shift in temperatures occurs.

Precipitation. For daily area-average Queensland, low precipitation values in November are most likely in the NAT simulations and particularly days sorted by MSLPLOW. While CMIP5 analysis indicated antecedent rainfall deficits were more likely under greenhouse gas forcings, low daily rainfall in Queensland does not have a discernible anthropogenic influence (Fig. 2f), although we note that persistent low daily rainfall or consecutive dry day indices were not examined.

Humidity. There was little notable difference simulated between daily November conditions in the ALL and NAT scenarios for humidity (Fig. 2g), although low daily humidity values in Queensland are more likely for MSLPLOW.

SUMMARY. We have provided a qualitative examination of the extreme fire and heatwave event of November 2018 in Queensland by deconstructing various contributing factors. As the FFDI measure combines multiple, interdependent variables, we explored components separately in observations and climate models (summarized in Table 2). The fires (and conditioning heatwave) were a complex compound extreme event with multiple contributing factors occurring on a range of spatiotemporal scales. The high 2018 November temperatures and low antecedent spring rainfall in Queensland were

Table 2. Summary of (i) observed 2018 meteorological and climatological conditions, (ii) assessment of their influence (higher/lower) on the extreme observed FFDI during November and the event, (iii) assessment of whether these were conditions were lower, higher, or the same in weather@home simulations during low Tasman Sea MSLP occurrences, and (iv) assessment of whether observed conditions are altered by simulated anthropogenic forcings influences (higher/lower or same probability with and without anthropogenic forcings, or N/A for not assessed) in CMIP5 [where the risk ratio (RR) is provided] and weather@home (where qualitative assessment is made).

Variable	(i) 2018 anomaly (relative to climatology)	(ii) Contribution to FFDI (lower or higher FFDI)	(iii) Lower/higher/ same with low Tasman MSLP	(iv) Lower/ higher/same with anthropogenic GHG
FIRE temperature (NOV)	H	H	H	H (RR = 4.5)
FIRE temperature (EVENT)	H	H	H	H
QLD precipitation (SON)	L	H	N/A	L (RR = 1.5)
QLD precipitation (NOV)	L	H	L	L
QLD humidity (EVENT)	L	H	L	S
Tasman MSLP (EVENT)	L	H		S
QLD/FIRE WINDS (EVENT)	L (and westerly direction)	H	N/A	N/A

key contributors to the elevated fire risk, in addition to the evolution of synoptic conditions that resulted in low humidity and anomalous westerly winds.

Sustained low rainfall and extreme high temperatures were notable antecedent conditions prior to the event, and these large-scale factors, in particular, are thought to result in increased availability of larger fuel elements, which can lead to increases in fire intensity and energy release from a fire (Sharples et al. 2016). Both CMIP5 and weather@home model datasets indicate that anthropogenic forcings in model simulations increase the likelihood of higher Queensland and fire region temperatures. CMIP5 models also provide some evidence of increased likelihood of dry spring conditions with enhanced anthropogenic greenhouse gases. The large-scale ocean–atmosphere modes of climate variability that were anomalously positive in 2018 (IOD and SAM) do not typically influence northern Australian climates, although negative SAM is strongly correlated with high FFDI in southern Australia.

As with all short-duration extremes, the evolution of synoptic conditions was critical to the fire event. These conditions included a significantly late start to the wet season, a sustained low pressure system to the south of the state, and unusual westerly wind flow. These conditions occurred in conjunction with a severe and persistent heatwave (high minimum and maximum temperatures) and very low humidity, leading to FFDI measures of "extreme" or "catastrophic" over much of Queensland. This synoptic pattern was not shown to be more likely in ALL forcings simulations of weather@home as diagnosed by low MSLP conditions in the Tasman Sea. MSLPLOW days in weather@home were associated with warmer temperatures and low humidity in Queensland.

FUTURE CLIMATE RISKS. Although complex events are challenging to understand, attempts to evaluate possible changes in future fire danger in eastern Australia are critical for adaption. While we have not provided a quantitative extreme event attribution assessment of this event, ours is one of many results that points to increasing fire danger risks in eastern Australia. In Australia, an overall increase in the FFDI has been observed in many regions, particularly for southern and eastern Australia in recent decades (Dowdy 2018), with future projections clearly showing an increase in the FFDI throughout Australia based on a comprehensive set of modeling approaches (Dowdy et al. 2019).

Previous notable heatwave events in the region in 1995, 1994, and 1969 were also associated with strong low pressure systems to the south and westerly wind flow, but were not accompanied by compound bushfires in northern or central Queensland (Australian Bureau of Meteorology 2018). The 2018 conditioning heatwave event was more severe and persistent than previous analogs, with no event of this scale previously occurring at such northerly coastal locations. Events that are unprecedented in a given region, such as the 2018 event, reveal that firefighting preparation and training cannot rely on previous events as guidance for the most dangerous conditions they can expect in the current and future climate in which large-scale fires occur more regularly. This demonstrates that providing information to regions with developing future risk of extreme or catastrophic FFDI measures, or with enhanced risk outside the historical fire season, is of critical importance.

Future exhaustive examinations of fire events should additionally consider the evolution of synoptic conditions during the event, the accumulated antecedent rainfall and soil moisture deficits, the weighting of these variables in indices such as the FFDI, and the ability of models to simulate each variable for the region and season in question. Under this comprehensive framework, quantitative attribution statements may provide insight.

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REFERENCES

Angélil, O., D. Stone, M. Wehner, C. J. Paciorek, H. Krishnan, and W. Collins, 2017: An independent assessment of anthropogenic attribution statements for recent extreme temperature and rainfall events. *J. Climate*, **30**, 5–16, https://doi.org/10.1175/JCLI-D-16-0077.1.

Australian Bureau of Meteorology, 2018: Special Climate Statement 67—An extreme heatwave on the tropical Queensland coast. Bureau of Meteorology, 30 pp., http://www.bom.gov.au/climate/current/statements/scs67.pdf.

Black, M. T., 2017: An attribution study of southeast Australian wildfire risk. Ph.D. thesis, University of Melbourne, 179 pp., http://hdl.handle.net/11343/123669.

——, D. J. Karoly, and A. D. King, 2015: The contribution of anthropogenic forcing to the Adelaide and

Melbourne, Australia, heat waves of January 2014 [in "Explaining Extreme Events of 2014 from a Climate Perspective"]. *Bull. Amer. Meteor. Soc.*, 96 (12), S145–S148 , https://doi.org/10.1175/BAMS-D-15-00097.1.

——, and Coauthors, 2016: The weather@home regional climate modelling project for Australia and New Zealand. *Geosci. Model Dev.*, **9**, 3161–3176, https://doi.org/10.5194/gmd-9-3161-2016.

Cannon, A. J., 2018: Multivariate quantile mapping bias correction: An N-dimensional probability density function transform for climate model simulations of multiple variables. *Climate Dyn.*, 50, 31–49, https://doi.org/10.1007/S00382-017-3580-6.

Dowdy, A. J., 2018: Climatological variability of fire weather in Australia. *J. Appl. Meteor. Climatol.*, **57**, 221–234, https://doi.org/10.1175/JAMC-D-17-0167.1.

——, H. Ye, A. Pepler, M. Thatcher, S. L. Osbrough, J. P. Evans, G. Di Virgilio, and N. McCarthy, 2019: Future changes in extreme weather and pyroconvection risk factors for Australian wildfires. *Sci. Rep.*, **9**, 10073, https://doi.org/10.1038/s41598-019-46362-x.

Hendon, H. H., D. W. J. Thompson, and M. C. Wheeler, 2016: Australian rainfall and surface temperature variations associated with the Southern Hemisphere annular mode. *J. Climate*, 20, 2452–2467, https://doi.org/10.1175/JCLI4134.1.

Kirono, D. G. C., K. J. Hennessy, and M. R. Grose, 2017: Increasing risk of months with low rainfall and high temperature in southeast Australia for the past 150 years. *Climate Risk Manage.*, **16**, 10–21, https://doi.org/10.1016/j.crm.2017.04.001.

Kirtman, B., and Coauthors, 2013: Near-term climate change: Projections and predictability. Climate Change 2013: The Physical Science Basis. T. F. Stocker et al., Eds., Cambridge University Press, 953–1028.

Lewis, S. C., and D. J. Karoly, 2013: Anthropogenic contributions to Australia's record summer temperatures of 2013. *Geophys. Res. Lett.*, **40**, 3705–3709, https://doi.org/10.1002/grl.50673.

Noble, I. R., A. M. Gill, and G. A. V. Barry, 1980: McArthur's fire-danger meters expressed as equations. *Aust. J. Ecol.*, **5**, 201–203, https://doi.org/10.1111/j.1442-9993.1980.tb01243.x.

Perkins, S. E., and P. B. Gibson, 2015: Increased risk of the 2014 Australian May heatwave due to anthropogenic activity [in "Explaining Extreme Events of 2014 from a Climate Perspective"]. *Bull. Amer. Meteor. Soc.*, **96** (12), S154–S157, https://doi.org/10.1175/BAMS-D-15-00074.1.

Risbey, J. S., M. J. Pook, P. C. McIntosh, M. C. Wheeler, and H. H. Hendon, 2009: On the remote drivers of rainfall variability in Australia. *Mon. Wea. Rev.*, **137**, 3233–3253, https://doi.org/10.1175/2009MWR2861.1.

Sharples, J. J., and Coauthors, 2016: Natural hazards in Australia: Extreme bushfire. *Climatic Change*, **139**, 85–99, https://doi.org/10.1007/s10584-016-1811-1.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl, 2012: An overview of CMIP5 and the experiment design. *Bull. Amer. Meteor. Soc.*, **93**, 485–498, https://doi.org/10.1175/BAMS-D-11-00094.1.

Ummenhofer, C. C., M. H. England, P. C. Mclntosh, G. A. Meyers, M. J. Pook, J. S. Risbey, A. Sen Gupta, and A. S. Taschetto, 2009: What causes southeast Australia's worst droughts? *Geophys. Res. Lett.*, **36**, L04706, https://doi.org/10.1029/2008GL036801.

Zscheischler, J., and Coauthors, 2018: Future climate risk from compound events. *Nat. Climate Change*, **8**, 469–477, https://doi.org/10.1038/s41558-018-0156-3.