Climate Dynamics (2020) 54:3041–3052
https://doi.org/10.1007/s00382-020-05167-9

Climatology of thunderstorms, convective rainfall and dry lightning environments in Australia

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Received: 25 July 2019 / Accepted: 3 February 2020 / Published online: 17 February 2020

Abstract

The thunderstorm climatology of Australia is examined, including convective rainfall events. Lightning observations are used to train a systematic method for indicating thunderstorm activity, with the method applied to environmental variables obtained from reanalysis data from 1979 to 2016. A range of maps showing seasonal averages in thunderstorm conditions as well as associated rainfall are presented. Long-term climate change trends are also examined, as well as the influence of large-scale drivers such as the El Niño-Southern Oscillation, Indian Ocean Dipole and Southern Annular Mode. Rainfall observations are examined for days on which thunderstorm activity is indicated based on this method, enabling new insight on convection-related rainfall. Low rainfall days are also used to examine the climatology of dry lightning as this is important for understanding the risk of wildfire ignitions. A long-term decrease in thunderstorm activity is indicated for many regions of Australia, as well as some regions of increase. The results also indicate a long-term increase in thunderstorm-related rainfall, noting implications for water availability, design standards and flood risk factors. The findings for northern Australia help provide insight on some aspects of the Australian monsoon, including based on a reduced frequency of days with convective environments as well as indicating an increased intensity of convective rainfall events. An increase in convective rainfall is indicated for both northern and southern Australia, while for non-convective rainfall the results indicate an increase in northern Australia and a decrease in southern Australia. Long-term changes in dry lightning events are also identified, depending on the region and season, noting implications for wildfire management.

Keywords Thunderstorms · Convection · Precipitation · Climate · Bushfires

1 Introduction

Thunderstorms are relatively small-scale weather systems characterised by strong convective processes that can cause hazards such as lightning, hail, tornadoes, as well as extreme wind gusts, rainfall and flooding. Additionally, lightning accompanied by low amounts of rainfall, known as 'dry lightning' (Rorig and Ferguson 1999; Dowdy and Mills 2012), is the primary natural cause of wildfire ignition throughout the world. Although thunderstorms can result in severe impacts, such as loss of life and damage to property, they can also have positive impacts including heavy rainfall events that can contribute to water availability. Consequently, they are of importance to many sectors including emergency services, insurance, health, energy, water and wildfire management.

The regional characteristics of rainfall depend on the combined influence of a range of different physical processes, including various weather systems such as thunderstorms, cyclones and fronts (Dowdy and Catto 2017) as well as the large-scale driving factors that can modify the weather systems. These large-scale driving factors include natural modes of atmospheric and ocean variability (e.g., the El Niño-Southern Oscillation: ENSO) as well as long-term climatological changes associated with anthropogenic increases in atmospheric greenhouse gas concentrations (Reisinger et al. 2014). Previous studies have focused on weather systems such as cyclones and fronts as well as the rainfall that they produce in regions of Australia (Catto et al. 2012; Lavender and Abbs 2013). Complementary to previous research, this study examines thunderstorm conditions and associated rainfall from 1979 to 2016 throughout Australia, including large-scale driving factors that can

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potentially influence thunderstorm activity as well as long-term changes in their climatology.

Consideration of the Clausius–Clapeyron relation, including in relation to temperature increases of about a 1 °C in recent decades (Reisinger et al. 2014; CSIRO and Bureau of Meteorology 2015), provides a plausible physical mechanism for increased convective rainfall intensity in some cases. Warmer air has the potential to contain higher amounts of water vapour which can provide more moisture available for producing rainfall, as well as for enhanced latent heat release leading to increased thunderstorm intensity in some cases. This combination of factors can result in scaling rates for rainfall intensity increases larger than the 6–7% increase per degree of warming indicated based on the Clausius–Clapeyron relation alone (known as super Clausius–Clapeyron scaling rates). For example, a recent study based on observations for Australia reported that short duration (e.g., hourly) rainfall extremes have increased in magnitude by about 2–3 times Clausius–Clapeyron scaling rates in recent decades (Guerreiro et al. 2018). However, previous studies such as this have not directly examined changes in thunderstorm activity together with changes in rainfall, as is one of the aims of this study. Additionally, the average occurrence frequency of 'dry thunderstorm' events (i.e., with little rainfall on the ground) has not been examined in the literature previously, with an aim of this study being to examine spatial features and temporal variability of the risk of dry lightning (including average values for individual seasons and long-term changes in occurrence frequency).

As noted in the recent review paper of Allen and Allen (2016), there is a research need in Australia for improved observational or proxy climatologies of thunderstorms and associated hazards, including in relation to the potential influence of climate change on thunderstorm characteristics as well as the influence of various natural drivers of variability (such as ENSO). Long-term observations data for thunderstorms and associated hazards (e.g., tornadoes and hail events) are generally not spatially or temporally homogenous for different regions of Australia, with datasets based on reports and damage records being more likely to include events in the densely populated near-coastal regions of Australia than sparsely populated regions further inland. Observations obtained from ground-based lightning detections systems (such as that of Global Position and Tracking System Pty. Ltd. Australia: GPATS) are also not spatially or temporally homogenous, including due to a trend towards increased detection efficiency relating to an increasing number of sensors being installed around Australia and changes in software used for the raw data processing (Kuleshov et al. 2011). Consequently, previous studies have used a range of different approaches for identifying thunderstorm activity in Australia. This includes satellite observations of lightning to provide climatology information for different times of the year throughout Australia (Dowdy and Kuleshov 2014) and seasonal forecasting throughout the world (Dowdy 2016), as well as satellite observations of overshooting convective cloud-tops over Australia to provide insight into the development and evolution of hazardous storms (Bedka et al. 2018). Relatively few studies have examined trends in thunderstorm activity in Australia, noting one recent study based on station observations of lightning flash counts which indicated a potential long-term decrease in lightning activity in southern Australia during the cooler months of the year (Bates et al. 2015). A potential long-term change in the strength of coupling between lightning and fire activity has also been reported, associated with an increased strength of climate-fire teleconnections during the onset of the 21st century (Mariani et al. 2018).

Approaches for identifying thunderstorm environments based on reanalysis data have been developed by previous studies. For example, Brooks et al. (2003) used indicators of convective available potential energy (CAPE) and wind shear from 0–6 km (S06) to identify severe thunderstorm environments based on the ERA-Interim reanalysis (Dee et al. 2011), with a similar approach applied for Australia by Allen and Karoly (2014). The method used here builds on these previous bivariate approaches but uses locally defined thresholds for environmental conditions as well as ground-based lightning observations for systematically training the method. Lightning is caused by strong potential differences from electrically charged regions of a cloud, with these charged regions generated by strong updrafts resulting from deep convective processes (Lang and Rutledge 2002), such that lightning data are used here as a proxy for indicating the occurrence of deep convective processes that characterise thunderstorm activity.

The data used and methods applied in this study are detailed in Sect. 2 of this paper. Results are presented in Sect. 3, including on training the method for indicating thunderstorm events (based on lightning observations from 2005 to 2016), developing the climatology of thunderstorm environments and associated rainfall (from 1979 to 2016), as well as comparisons with large-scale modes of variability and examination of long-term climate change. Conclusions are then presented in Sect. 4.

2 Data and methods

Lightning observations are used here to indicate thunderstorm activity. Lightning data were obtained from two datasets, both covering the time period from 2005 to 2016. The two lightning datasets are GPATS which has coverage throughout Australia as well as the World Wide Lightning Location Network (WWLLN) which has global coverage (Hutchins et al. 2013; Virts et al. 2013). These datasets comprise lightning observations based on the time of arrival of the electromagnetic disturbance propagating away from the lightning discharge as recorded at a network of ground-based radio receivers (Cummins and Murphy 2009) and contain information about the time and location of individual lightning strokes, noting that a single lightning flash as seen by a human eye can sometimes contain multiple lightning strokes (i.e., flash multiplicity).

Rainfall data are obtained from a gridded analysis of observations based on a grid of 0.05° in latitude and longitude throughout Australia (i.e., the gridded rainfall product of the Australia Water Availability Project: AWAP (Jones et al. 2009)). This grid is used for the analysis presented throughout this study, including for collating the lightning observations into the AWAP grid cells (noting that the spatial resolution for the lightning data is finer than this grid). Although a dataset of long-term homogenous rainfall data is not currently available for Australia, King et al. (2013) concluded that the AWAP product is suitable for use in studies on trends and variability in rainfall (including extremes) across much of Australia while noting caution in areas of low station density (as is done in this study with regions of low station density masked following common practice for these AWAP rainfall data). In particular, the AWAP rainfall data are used for the purposes of this study to provide an indication of broad-scale regional climate features throughout Australia averaged over relatively long time periods, rather than provide information for individual storm systems (e.g., for case study approaches for which station data may be preferable for some applications such as examining the magnitude of extreme precipitation events at a given location).

The method used here for indicating thunderstorm environments is based on a combination of convective available potential energy (CAPE) and bulk wind shear from 0–6 km (S06), obtained from the ERA-Interim reanalysis (Dee et al. 2011) produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), using a diagnostic quantity defined as $CAPE*S06^{1.67}$. This method is similar to earlier approaches such as that of Brooks et al. (2003) and Allen and Karoly (2014) but is applied here using locally defined threshold values of this diagnostic. A value of this diagnostic quantity that exceeds the threshold at a given location is used here to indicate the occurrence of a thunderstorm environment for that location and time step of the reanalysis data. The threshold values are defined by the value of the diagnostic that is exceeded as frequently as the occurrence of lightning events (i.e., a quantile matching methodology). Grid cells with at least 2 or more lightning strokes observed within ± 1 degree of latitude or longitude during an individual 6-h time step are used to represent the occurrence of a lightning event. This 1° range is a somewhat arbitrary choice, with the results presented here found to be broadly similar for some changes to this range. The 6-h time step is selected to match that of the ERA-Interim reanalysis. This type of approach is similar to previous studies that have used ground-based lightning observations in this way, including in relation to examining thunderstorm environments and associated rainfall (Dowdy 2015; Dowdy and Catto 2017).

The ERA-Interim reanalysis (Dee et al. 2011) is used here from 1979 to 2016, with a time step of 6-hours and a grid spacing of 0.75° in both latitude and longitude. The ERA-Interim reanalysis is used for the diagnostics that represent the thunderstorm environments, based on CAPE (using the most unstable level based on maximum equivalent potential temperature) and S06 (bulk wind shear from 0–6 km). The CAPE and S06 data are bilinearly interpolated to 0.05° latitude and longitude consistent with the grid of the AWAP rainfall data (Jones et al. 2009), with this 0.05° grid used for all analysis and results presented for this study.

The detection efficiencies of the GPATS and WWLLN systems vary temporally and spatially including due to ongoing changes in the hardware and software used by the providers of these lightning data. Consequently, the number of strokes recorded represents a lower bound measure of the number that occurred. However, most thunderstorms produce many lightning strokes such that there is a high chance of detecting at least two or more strokes using these networks in combination with each other.

The relationship between the thunderstorm environments and large-scale modes of variability is examined, including for the El Niño-Southern Oscillation (ENSO), Indian Ocean Dipole (IOD) and Southern Annular Mode (SAM). Indices representing these modes of variability were obtained from National Oceanic and Atmospheric Administration (NOAA), including for NINO3.4 as an oceanic measure used to represent ENSO and the Dipole Mode Index (DMI) used to represent IOD. An index representing the Southern Annular Mode (SAM) is used based on data provided by the British Antarctic Survey (BAS), as described by Marshall (2003).

Results are presented in some cases for individual seasons, with seasons considered here as December to February (DJF), March to May (MAM), June to August (JJA) and September to November (SON). For calculating the correlations with indices representing the large-scale modes of variability (ENSO, IOD and SAM), data from December 1979 to November 2016 are used to create seasonal values from one year to the next (i.e., 37 years of seasonal values), including for the number of thunderstorm environments identified at each location as well as for the indices representing the large-scale modes of variability (i.e., NINO3.4, DMI and SAM).

The Pearson's correlation coefficient, r, is used to examine relationships between the occurrence of thunderstorm environments and large-scale modes of variability. It is calculated individually for each season at each individual grid-cell location. Results are shown for $|r| > 0.275$ representing a confidence level of 90% (i.e., two-tailed probability $p < 0.1$ of no relationship) with degrees of freedom $df = 35$ based on 37 years of seasonal values. This 90% threshold is a somewhat arbitrary choice, with the results only intended to indicate notable features at a regional scale, rather than interpreted as definitively showing whether or not a relationship exists at an individual location. Additionally, it is acknowledged that 10% of cases on average will be indicated as being significant due to random chance alone at the 90% confidence level.

An aim of this study is to examine changes in the climatology of thunderstorm environments and their associated rainfall amounts. This is done based on comparing the mean value for the first half of the study period (used to represent the climatology during the earlier time period from 1979 to 1997) with the mean value for the second half of the study period (used to represent the climatology during the later time period from 1998 to 2016). Statistical significance is indicated using a bootstrap method that ranks the magnitude of a change (i.e., the difference in mean values from the first half to the second half of the study period) with a 5000-member randomised sample of the data used to calculate the mean values. Results are presented for a confidence level above 90% based on this two-tailed nonparametric approach, noting that this 90% threshold is a somewhat arbitrary choice, with the bootstrapping results only intended to help indicate notable features at a regional scale (rather than be interpreted as definitively showing whether or not a change has occurred at an individual location). It is also acknowledged that there are a range of statistical tests that can be applied to examine stationarity, with the method used here selected to align with the specific aims of this study including as described above.

3 Results

3.1 Identifying thunderstorm environments

Figure 1a shows the average annual occurrence frequency of lightning events, based on 6-h time steps throughout the period 2005–2016, calculated for each individual 0.05° grid cell location. This indicates more thunderstorm activity towards the north and east as compared to the south and west of Australia in general, similar to previous results based on satellite observations of lightning (Dowdy and Kuleshov 2014). Threshold values are shown in Fig. 1b of the diagnostic measure (i.e., $CAPE*S06^{1.67}$) calculated from reanalysis data, with values higher than this used to indicate thunderstorm environments at a given location. The threshold is calculated as the value of the diagnostic that produces the same occurrence frequency of thunderstorm environments as the lightning events. A feature of this study is that the threshold values are calculated individually for each location to help optimise the method for application over the wide range of different climatic conditions that exist throughout Australia.

This diagnostic approach correctly indicates the occurrence of lightning events at a given location about 50% of the time throughout the land regions of Australia, based on systematically testing this for each 6-hourly time step from 2005 to 2016. This is shown by the Probability of Detection (POD) in Fig. 1c (i.e., POD = number of correctly identified events divided by the total number of events). Lower POD values generally occur in the maritime regions further away from the Australian continent. The threshold used for the diagnostic is that which gives the same number of events as observed at a given location, such that the number of missed events equals the number of false alarms. Consequently, the False Alarm Ratio, FAR, is equal to 1-POD (with FAR calculated as the number of false alarms divided by the sum of the number of hits and false alarms). Figure 1c therefore indicates FAR values around 50% for many of the land regions of Australia where POD values are around 50%.

The threshold of the diagnostic varies between about 10,000 to 50,000 for most of the near-coastal regions of Australia, with lower values in the more inland regions. As discussed in the Introduction section, severe thunderstorm events are more commonly reported in more populated regions, such as near-coastal locations for Australia in general, whereas the lightning data used here to train the study method are intended to help provide more spatial homogeneity including for sparsely populated regions of Australia. These threshold values are somewhat lower than those applied in Australia by Allen and Karoly (2014) (e.g., threshold values including 25,000 and 68,000) while noting that they were considering a somewhat different approach and application, including the use of reports of severe thunderstorm events (rather than based on all thunderstorm events as is the intention for this study).

3.2 Mean climatology and long-term changes in thunderstorm environments

Figure 2 shows the mean number of thunderstorm environments identified from 1979 to 2016, as well as the difference in those values from the first to the second half of the time period, with results calculated individually for each season (DJF, MAM, JJA and SON). The seasonal mean values for the period 1979 to 2016 (left column panels in Fig. 2) indicate more thunderstorm activity for the warmer months of the year (i.e., around the austral summer period for DJF: Fig. 2a) than the cooler months (i.e., around the austral winter period for JJA: Fig. 2c), broadly similar to previous studies (Dowdy and Kuleshov 2014; Allen and Allen 2016). More thunderstorm activity is indicated during spring (SON:

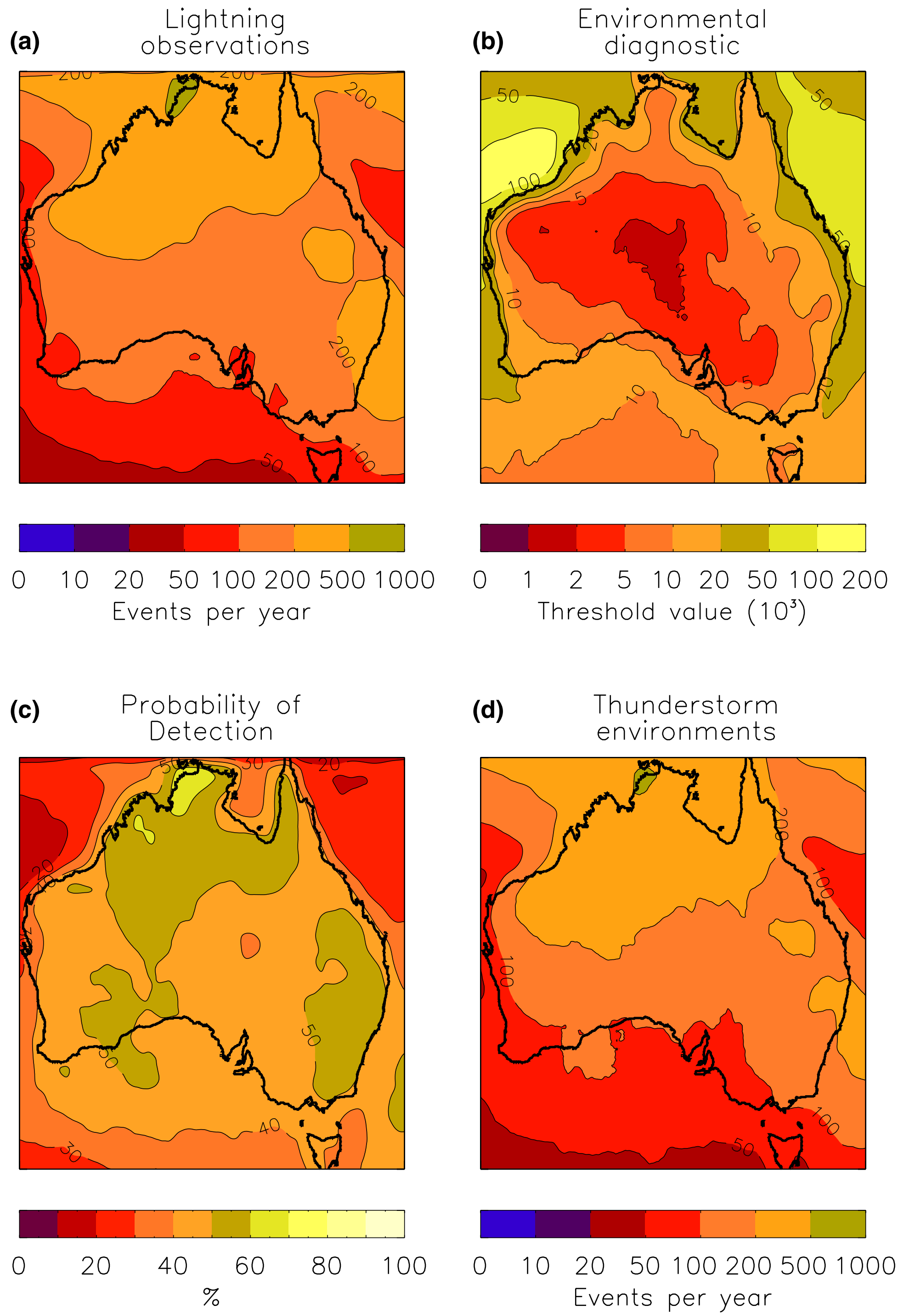


Fig. 1 Diagnostic method for indicating thunderstorm events matched to the occurrence frequency of observed lightning events. Frequency of occurrence of lightning events at 6-h intervals during the period 2005–2016 (**a**) Environmental diagnostic based on reanalysis data used to indicate thunderstorm events, with results shown for the threshold value of the diagnostic used at each location (**b**), Probability of Detection for indicating the observed lightning events (**c**) and mean number of 6-h thunderstorm environments per year from 1979 to 2016 (**d**)

Fig. 2d) than autumn (MAM: Fig. 2b) in general throughout Australia, apart from near-coastal western regions of Australia.

The difference from the first to the second half of the study period indicates a general decrease in the number of thunderstorm environments that have occurred over this 38-year period for Australia. Reductions are indicated for some individual regions, including during the warmer months of the year in parts of northern and central Australia where reductions are indicated over relatively widespread regions (e.g., from Fig. 2e for DJF). There are also some regions where an increase in thunderstorm activity is indicated, including for some parts of southern and eastern Australia (Fig. 2e–h).

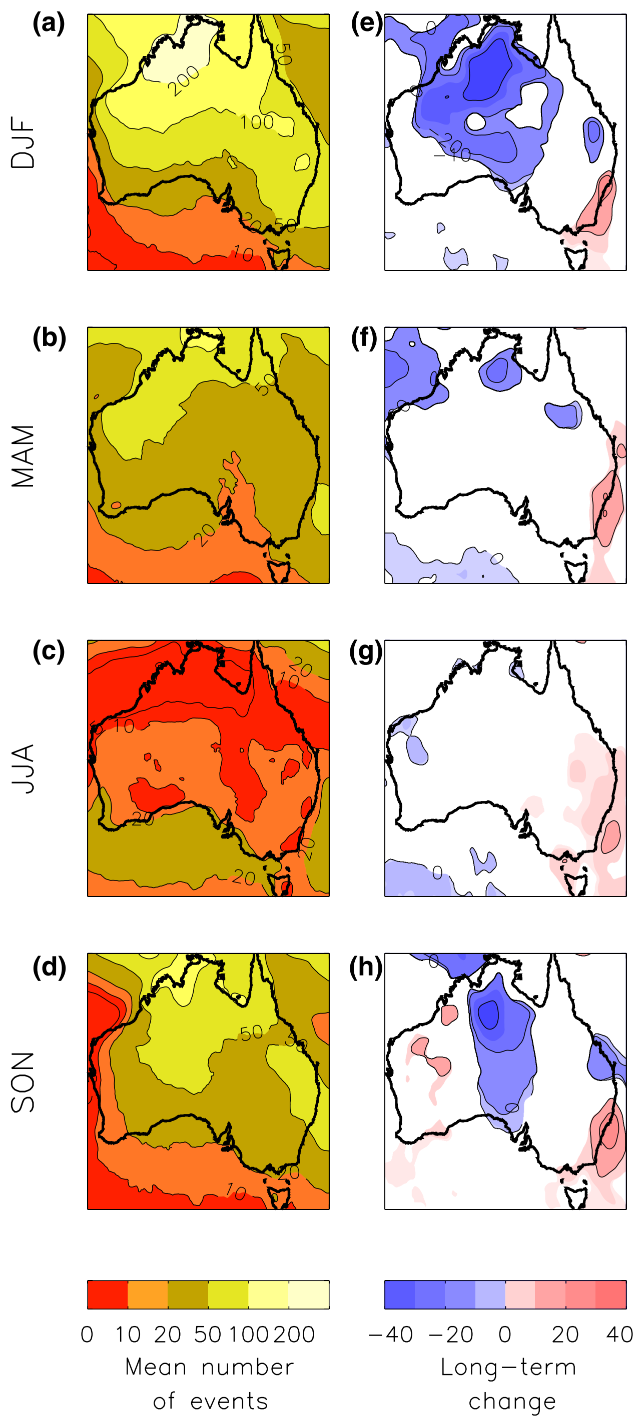


Fig. 2 Long-term maps of thunderstorm environments, presented for individual seasons (DJF, MAM, JJA and SON). Results are shown for the average number of thunderstorm environment events per season (left column panels) as well as the difference in those values from the first to the second half of the study period (middle column panels). Changes are shown only if their magnitude is statistically significant at the 90% confidence level

3.3 Relationship to large-scale modes of variability

The number of thunderstorm environments was calculated at each individual grid cell location for individual seasons. Data from December 1979 to November 2016 were used to create a time series of seasonal values from one year to the next. This time series of seasonal values at a given location was compared with similar time series for each of the three indices representing the large-scale modes of variability (i.e., DMI, SAM and NINO3.4), including using the sample Pearson's correlation coefficient, *r*. Results are presented in Fig. 3.

The relationships between the occurrence of these thunderstorm environments and the three large-scale modes of variability are relatively weak in general. There are some relatively small regions with a significant relationship indicated, such as in northern Australia during MAM for DMI (Fig. 3b), as well as near southern and eastern Australia during JJA for SAM (Fig. 3g). There is also a relatively large region near northeast Australia with larger magnitude values of *r* apparent during spring for the correlation with NINO3.4 (e.g., $r < -0.5$ in Fig. 3l). This negative correlation indicates weaker thunderstorm activity on average during El Niño conditions (characterised by higher values of NINO3.4) than La Niña conditions (characterised by lower values of NINO3.4), noting that this could relate to change in the position and characteristics of the South Pacific Convergence Zone (SPCZ) associated with ENSO (Vincent 1994).

These results are all broadly similar to previous studies, including findings based on satellite observations of lightning that reported relatively little influence from these three drivers (and others) on thunderstorm activity in Australia apart from the region near northeast Australia (also noted here in this study) for ENSO (Dowdy 2016). Similarly, Allen and Karoly (2014) found relatively weak relationships between the occurrence of severe thunderstorm environments and ENSO conditions in Australia. For studies such as these, the strengths of the relationships indicated by the correlations are, in general for most regions, broadly similar to what could be expected from a statistical perspective based on random chance alone.

3.4 Rainfall associated with thunderstorm environments

Figure 4 shows the average seasonal rainfall, presented for days on which thunderstorm environments were identified as well as for days on which thunderstorm environments were not identified, calculated for the period from 1979 to 2016. Most of the rainfall in northern Australia is associated with thunderstorm environments, particularly during the warmer months of the year (i.e., around the Australian monsoon period (Suppiah 1992)). A considerable

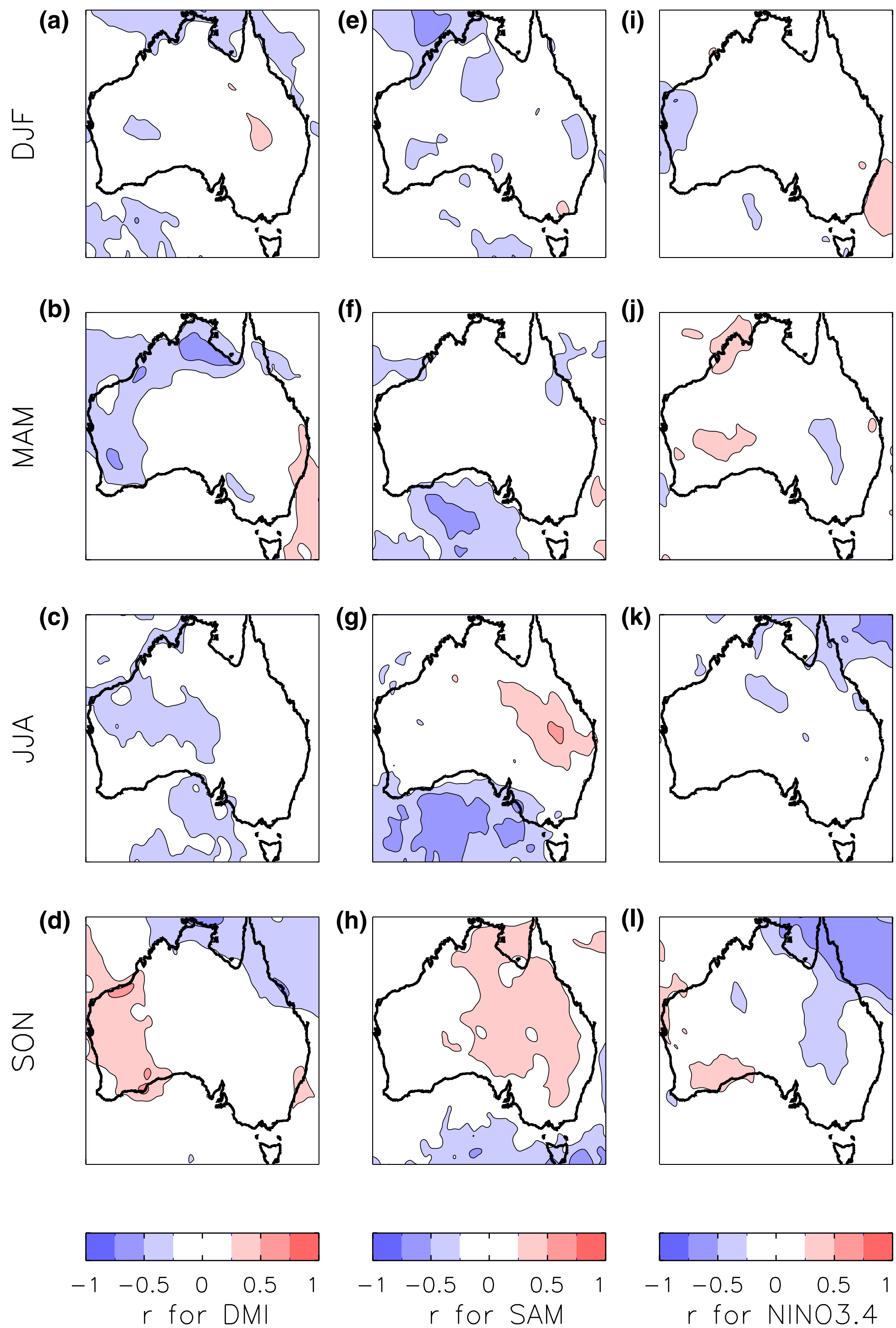
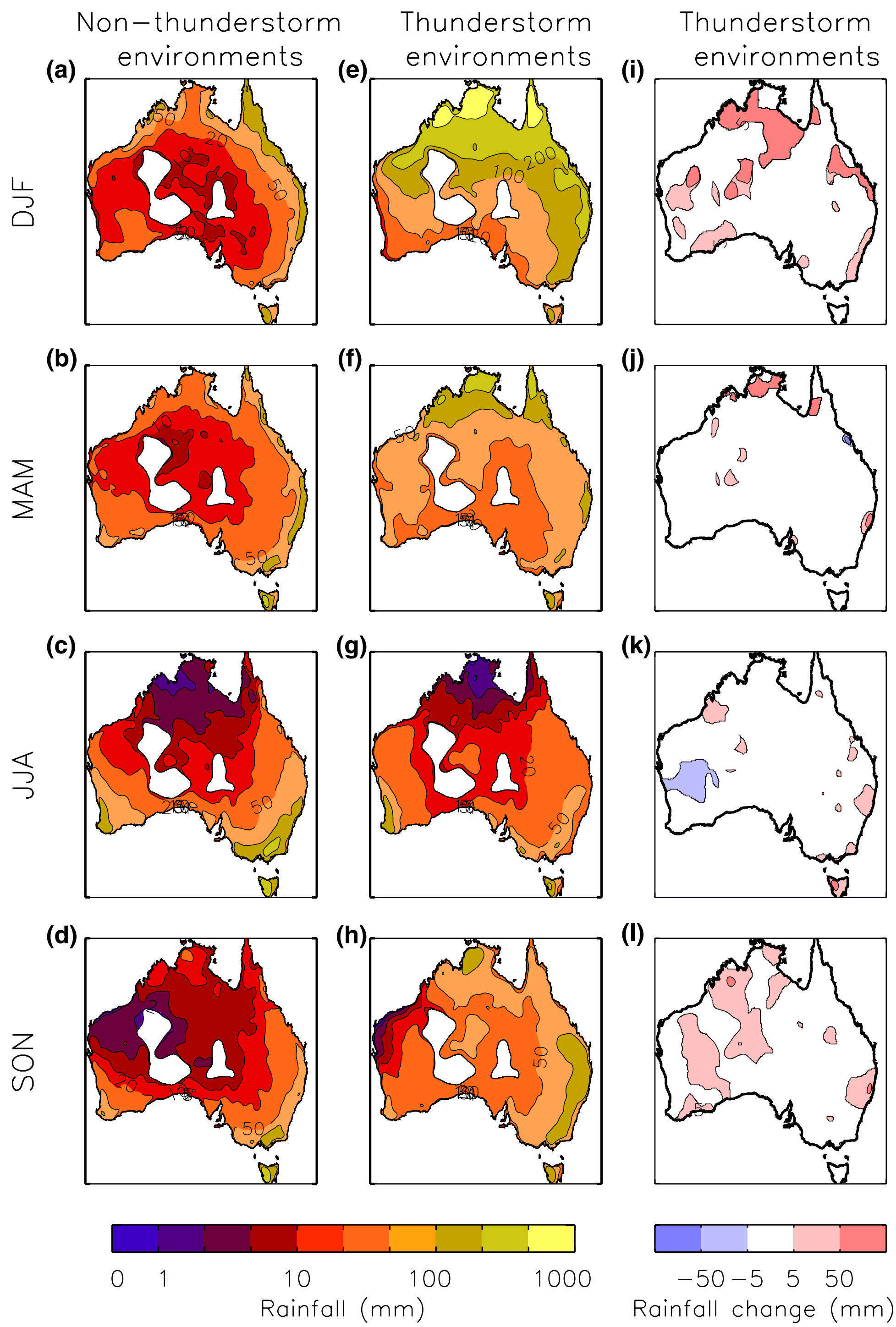


Fig. 3 Correlations between thunderstorm environments and large-scale modes of variability using the sample Pearson's correlation coefficient, *r*. Results are presented for individual seasons in four different rows (for DJF, MAM, JJA and SON) as well as different modes of variability in three different columns (for DMI representing the Indian Ocean Dipole, SAM representing the Southern Annular Mode and NINO3.4 representing the El Niño-Southern Oscillation). Results are shown only if they are statistically significant at the 90% confidence level

proportion of rainfall in other parts of Australia is also associated with thunderstorm environments particularly during the warmer months of the year along eastern Australia. Although most winter rainfall in southern Australia is not associated with thunderstorms, there are some near-coastal regions of southern Australia where thunderstorm-associated rainfall is relatively high during the cooler months of the year (e.g., as indicated for JJA from Fig. 4g). It is also noted that higher overshooting top anomalies were noted over this region by Bedka et al. (2018), which would also imply deep convection during these cooler months of the year. Results such as these could potentially indicate an influence from the moist maritime environment and relatively warm ocean (as compared to the land during

Fig. 4 Average seasonal rainfall totals based on the period 1979–2016. This is presented for days on which thunderstorm environments were identified (centre column panels) as well as for days on which no thunderstorm environments were identified (left column panels), with the white inland regions representing locations where results are not shown due to very sparse coverage of rainfall observations. The long-term change in average seasonal rainfall is also shown, calculated only for days on which thunderstorm environments were identified (right column panels). This represents the change from the first to the second half of the study period, to provide an indication of how thunderstorm-related rainfall has changed over time. Results are presented individually for four seasons (DJF, MAM, JJA and SON). Changes are shown only if their magnitude is statistically significant at the 90 percent confidence level



winter in this region) for helping provide favourable conditions for thunderstorms to occur, as well as noting that thunderstorms can sometimes occur in combination with other rain-bearing weather systems common to that region during the cooler months of the year (e.g., associated with fronts and cyclones, as an example of a compound event (Dowdy and Catto 2017)).

Long-term changes are apparent for some individual locations (Fig. 4i–l). The changes are generally positive in sign (i.e., increases), including some examples where relatively large magnitude changes are indicated (particularly around northern Australia during DJF: Fig. 4i). When averaged over Australia, the results indicate a long-term trend towards an increase in rainfall totals associated with thunderstorms, with an average increase of 21% from the first to the second half of the study period. A somewhat larger increase of 24% has occurred in the northern half of Australia (i.e., north of 27.5 °S) with a smaller magnitude increase of 13% in the southern half of Australia. These rainfall increases have occurred despite a general decrease in thunderstorm activity indicated from the first half to the second half of the study period (i.e., about 5% fewer days with thunderstorm activity based on the average change for each grid cell location throughout Australia), suggesting an average increase of about 27% in the intensity of thunderstorm-related daily rainfall.

To examine thunderstorms that do not produce much rainfall, results are shown in Fig. 5 for days on which the rainfall was lower than 2.5 mm, noting that lightning accompanied by low values of rainfall such as this is known as 'dry lightning' and is associated with a high risk of wildfire

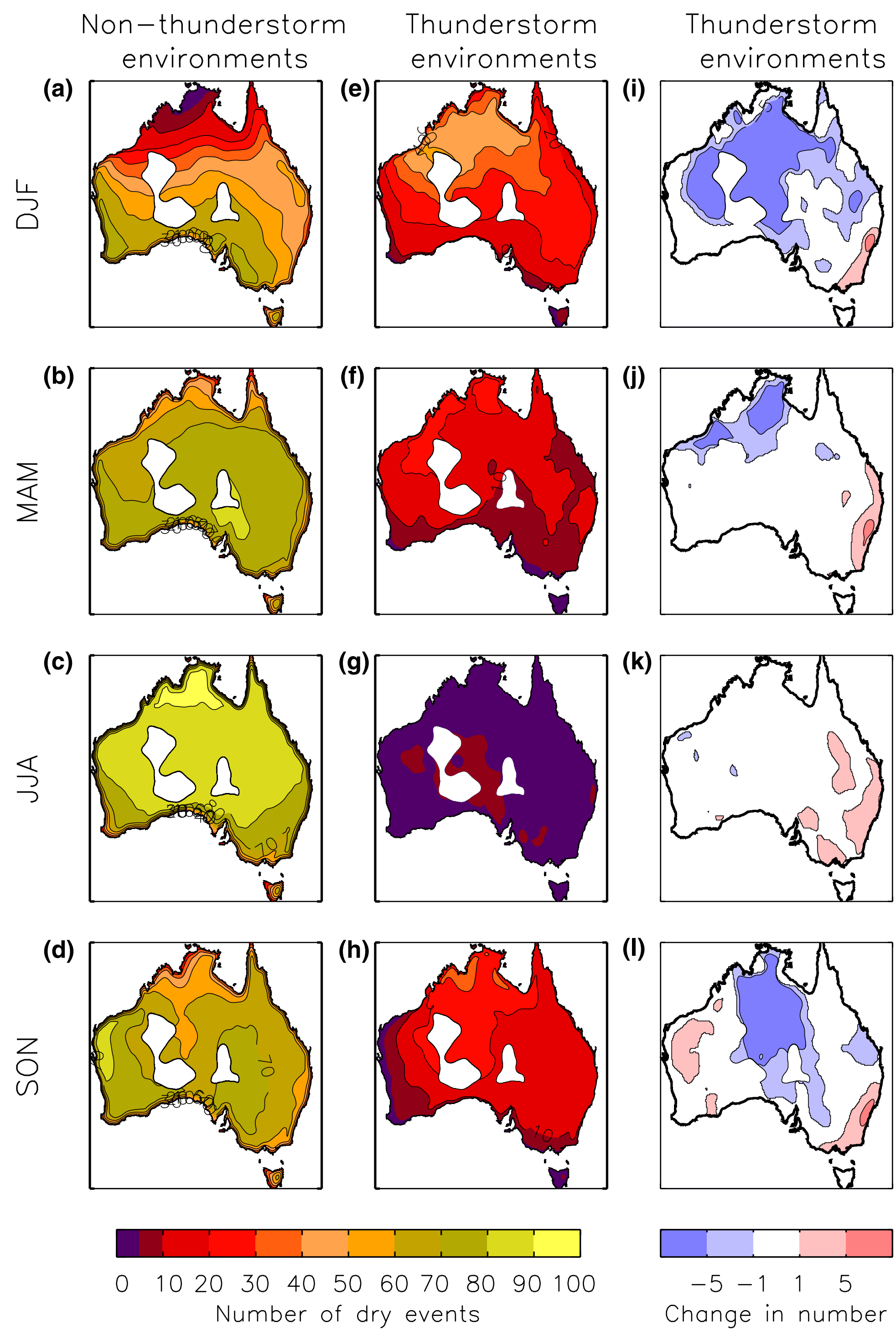


Fig. 5 Average number of days per season with rainfall less than 2.5 mm based on the period 1979–2016. This is presented for days on which thunderstorm environments were identified (centre column panels) as well as for days on which no thunderstorm environments were identified (left column panels), with the white inland regions representing locations where results are not shown due to very sparse coverage of rainfall observations. The long-term change in the average seasonal number of days with rainfall less than 2.5 mm is also shown, calculated only for days on which thunderstorm environments were identified (right column panels). This represents the change from the first to the second half of the study period, to provide an indication of how the number of dry lightning events has changed over time. Results are presented individually for four seasons (DJF, MAM, JJA and SON). Changes are shown only if their magnitude is statistically significant at the 90% confidence level

ignition (Rorig and Ferguson 1999; Dowdy and Mills 2012). The results indicate more dry lightning activity during the warmer months of the year (DJF: Fig. 5e) than the cooler months of the year (JJA: Fig. 5g) in general. More events also occur during the austral spring (SON: Fig. 5h) than autumn (MAM: Fig. 5f) in many parts of eastern and southern Australia, noting that the spring–summer period in these regions is when the near-surface weather and fuel moisture conditions are often conducive to the occurrence of dangerous wildfires (Luke and McArthur 1978; Russel-Smith et al. Russell-Smith et al. 2007; Dowdy 2018). Consequently, this climatology of dry lightning presented here is relevant for helping understand risk factors associated with wildfire ignitions, noting that this is important for bushfire management authorities in Australia.

The long-term changes in dry-lightning conditions (Fig. 5i–l) include regions of decrease as well as increase, depending on the region and season. An increase in the number of dry lightning events is indicated in parts of southeast Australia, with this being the case for each individual season based on this method. Decreases in the number of dry lightning events are indicated for parts of northern and central Australia particularly during the warmer months of the year, while noting that the cooler months of the year and into spring (SON) are typically when conditions are conducive to wildfire occurrence in northern and central Australia (Luke and McArthur 1978; Russel-Smith et al. Russell-Smith et al. 2007; Dowdy 2018).

Previous studies have reported that the statistical significance of trends in monsoonal rainfall is difficult to determine due to high intrinsic variability in the summer monsoon (CSIRO and Bureau of Meteorology 2015). The study results for northern Australia help provide insight on some aspects of the Australian monsoon, including a general reduction in the frequency of days with convective environments (i.e., days identified by the diagnostic method as having a thunderstorm environment), as well as an increased intensity of convective rainfall (based on the average rainfall on those days). As summarised in Table 1, a general increase in convective rainfall is indicated for northern and southern Australia, noting that the results are intended to be interpreted in an indicative sense to provide broad-scale climatological guidance (e.g., given potential variations based on different data and methods such as the use of other reanalyses or formulations of CAPE). In contrast to convective rainfall, the results indicate that non-convective rainfall (i.e., rainfall on days not identified as having a thunderstorm environment) has increased in northern Australia and decreased in southern Australia.

Table 1 Changes in the number of thunderstorm environment days, convective rainfall totals, non-convective rainfall totals and convective rainfall intensity

	National	North	South
Thunderstorm environment days	−5%	−8%	1%
Convective rainfall totals	21%	24%	13%
Non-convective rainfall totals	0%	18%	−11%
Convective rainfall intensity	27%	34%	11%

This is listed for the whole of Australia (National) as well as north of 27.5°S (North) and south of 27.5°S (South), based on the mean difference from the first to the second half of the study period

4 Conclusions

This study examined the climatology of thunderstorms and associated rainfall conditions throughout Australia, based on a novel diagnostic method applied to reanalysis data. This systematic method was trained using quantile-matching to lightning observations from two independent land-based sensor networks, calculated for individual grid-cell locations throughout Australia. The results were used to examine the mean climatology of thunderstorm conditions for different locations throughout Australia, allowing spatial and seasonal variations to be detailed. Large-scale modes of variability including ENSO, IOD and SAM were found to not have a strong influence on thunderstorm environments in Australia in general, apart from some examples such as an influence from ENSO indicated in far northeast regions during spring (broadly similar to some previous studies (Dowdy 2016)).

Long-term changes over the study period indicate a general reduction in thunderstorm activity for some regions of Australia, particularly in some northern and central regions during the warmer months of the year (from Fig. 2). The results also suggest an increase in thunderstorm-related rainfall of about 13–24% from the first to the second half of the study period, with the larger increases for northern Australia than southern Australia in general. Guerreiro et al. (2018) also reported larger changes for northern Australia than southern Australia in the magnitude of short duration rainfall events based on station observations, with their results indicating changes of about 2–3 times Clausius–Clapeyron scaling rates for various regions of Australia.

Dry lightning was also examined throughout Australia for each season of the year, with maps presented of the average risk of occurrence of dry lightning conditions over the study period from 1979 to 2016 (Fig. 5). Analysis of long-term changes in the occurrence frequency of dry lightning conditions indicates an increase for some regions of southeast Australia, as well as a decrease for some regions of northern and central Australia during winter and spring.

The findings presented here are intended to help provide an enhanced ability to understand and plan for the impacts of thunderstorms, including for their associated risks and benefits for different regions of Australia. This includes a range of hazards such as those associated with lightning as well as damaging winds and rainfall. The increased intensity of thunderstorm-related rainfall as indicated by the results presented here is relevant to water management and planning (e.g., as guidance for design standards or other hydrological applications). For example, in addition to contributing to water availability, convective rainfall events are also a key driver of damaging floods in Australia, particularly for localised events such as flash flooding as well as in urban areas where pre-existing soil moisture may not be a key driver of flood risk (noting a range of factors that can influence flood risk in Australia (Johnson et al. 2016)). In relation to the other extreme of the convective rainfall intensity distribution, an improved understanding of dry lightning climatology is of importance for fire management authorities in relation to wildfire ignition risk (Rorig and Ferguson 1999; Dowdy and Mills 2012; Bates et al. 2017).

Acknowledgements This research was funded by the Victorian Government through the VicWaCI Initiative and by the Bureau of Meteorology as well as the Earth Systems and Climate Change (ESCC) Hub of the Australian Government's National Environmental Science Program (NESP). Calculation of CAPE by Marcus Thatcher (CSIRO) is gratefully acknowledged. Comments provided on early versions of this manuscript by Andrew Brown, Joshua Soderholm and Justin Peter from the Bureau of Meteorology are gratefully acknowledged.

Compliance with ethical standards

Conflict of interest The author declares no conflict of interest.

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