Summer hot extremes and antecedent drought conditions in Australia

Patrícia Páscoa1,2,3 | Célia M. Gouveia1,3 | Ana Russo 3 | Andreia F. S. Ribeiro3,4

1Instituto Português do Mar e da Atmosfera, Lisbon, Portugal
2Environmental Physics Laboratory (EPhysLab), CIM-UVigo, Universidad de Vigo, Ourense, Spain
3Instituto Dom Luiz, Faculdade de Ciências da Universidade de Lisboa, Lisbon, Portugal
4Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland

Correspondence
Célia M. Gouveia, Instituto Português do Mar e da Atmosfera, 1749-077 Lisbon, Portugal.
Email: celia.gouveia@ipma.pt

Funding information
Fundo para a Ciência e a Tecnologia, Grant/Award Numbers: PCIF/GRF/0204/2017, FTDC/CTA-CLI/2802/2017; Swiss National Science Foundation, Grant/Award Number: 186282

Abstract
The compound occurrence of extreme weather and/or climate events can cause stronger negative impacts than the individual events, and its frequency is increasing in several regions of the world. In this work, the effect of antecedent drought conditions on hot extremes during the months of December–February in Australia was analysed for two periods (1979–2019 and 1950–2019). The standardized precipitation evapotranspiration index (SPEI) and the indices number of hot days (NHD) and number of hot nights (NHN) were used to assess drought and extreme temperature events. While the link between dry and heat events is more important in the north in February, in December and January it is strong in the east coast. When temporal lags of 1–3 months are considered, there is a strong correlation between SPEI and NHD/NHN for the concurrent month on most of the study area. For the previous 1–3 months, the area and the correlation values decreased, but consistent spatial patterns were obtained for each month, namely negative correlations on the southwest and southeast in December, and the east in February. Tropical areas showed large areas of correlation between SPEI and NHN, including for the previous 3 months, whereas temperate climates showed the smaller area of correlation with NHN, including at the concurrent month. Significant correlations obtained for lead times longer than 1 month, namely with night heat extremes, point to a predictive ability in several regions of Australia. Moreover, the correlation coefficients obtained using the more recent period (1979–2019) show similar spatial patterns, but with higher values than for the 1950–2019 period. The results highlight the prospect of an early prediction of hot summer extremes in regions affected by drought in spring.

KEYWORDS
compound events, drought, dryness, heatwaves, number of hot days, standardized precipitation and evapotranspiration index
1 | INTRODUCTION

Extreme weather and climate events are known to cause negative impacts on natural ecosystems and on human societies (Seneviratne et al., 2012a; Ummenhofer and Meehl, 2017; Herold et al., 2018; Geirinhas et al., 2020), and the study of the occurrence of these events is of high importance, since it can contribute to mitigating their impacts or developing adaptation measures. Under future climate conditions, several features of extreme events (e.g., frequency, intensity, spatial extent, duration, and timing) are expected to change and result in unprecedented extreme weather and climate events (Seneviratne et al., 2012a; Zscheischler et al., 2018; IPCC, 2021). Recently, attention has been devoted to the simultaneous or sequential occurrence of extreme events, designated compound events (Seneviratne et al., 2012a; Hao et al., 2018; Russo et al., 2019), due also to the higher impacts they cause, when compared to the individual events (Zscheischler et al., 2020). In particular, compound drought and extreme heat events are related to increased yield losses (Feng et al., 2019; Beillouin et al., 2020; Ribeiro et al., 2020a), wildfire occurrence (Gouveia et al., 2016; Turco et al., 2019; Deb et al., 2020), and decreased vegetation photosynthetic activity (Fu et al., 2020). These compound events have also been shown to be increasing in frequency (Zscheischler and Seneviratne, 2017; Hao et al., 2018; Bezak and Mikoš, 2020; Yu and Zhai, 2020) in several world regions, highlighting the need to study the events and their impacts.

The relation between drought and extreme heat events, particularly the effect of antecedent drought conditions on the occurrence of temperature extremes has been identified in several world regions (Mueller and Seneviratne, 2012; Liu et al., 2019), such as the Mediterranean basin (Russo et al., 2019; Ribeiro et al., 2020a), China (Hao et al., 2017; Zhang et al., 2019) and Australia (Perkins et al., 2015; Herold et al., 2016; Holmes et al., 2017). Previous studies have highlighted the role of spring precipitation deficits, increased solar radiation, and warming in amplifying the high-temperature anomalies in extreme summers due to soil moisture depletion (e.g., Fischer et al., 2007a; Barriopedro et al., 2011) and worked on that assumption to analyse ecosystems productivity (e.g., Bastos et al., 2021) and fires (e.g., Abram et al., 2021; van Oldenborgh et al., 2021). Moreover, although drought events do not directly cause extreme temperatures, the occurrence of previous drought conditions seems to have an enhancing effect on subsequent hot events, by increasing the number of hot days (Mueller and Seneviratne, 2012; Quesada et al., 2012) and therefore allowing to a certain extent the anticipation of a higher probability of occurrence of summer hot extreme events (Russo et al., 2019).

Several authors have devoted their attention to analysing the physical mechanisms responsible for the amplification, triggering, and interaction between hot and dry events, analysing the level to which heatwaves could enhance already established drought conditions, or the extent to which prolonged drought and subsequent surface sensible heat fluxes can amplify heatwaves. Namely, Miralles et al. (2014) demonstrated for Europe that conditions of dry soils can also intensify heat entrainment from the top of the atmospheric boundary layer and favour the near-surface multi-day storage of heat in the residual boundary layer. A recent study for southeastern Brazil also concluded that the feedback between land and atmosphere conditions was associated to a high coupling (water-limited) regime, which promotes the re-amplification of hot spells that resulted in mega heatwave episodes (Geirinhas et al., 2021). The potential of soil dryness to sustain anticyclones, and therefore to increase the intensification of heatwave periods has also been referenced by Fischer et al. (2007b). This feedback mechanism has been also analysed by Schumacher et al. (2019), which showed that soil desiccation upwind promotes temperature escalation in downwind locations via heat advection.

The association between drought and hot extremes has been previously analysed based on a variety of indicators, both for drought as well as for temperature extremes. Namely, drought indices, such as the standardized precipitation index (SPI; McKee et al., 1993), and the standardized precipitation evapotranspiration index (SPEI; Vicente-Serrano et al., 2010), have been previously used to study this compound event, due mainly to the scarcity of soil moisture data (Seneviratne et al., 2010). Whan et al. (2015) did not find a strong correlation between SPI-3 and soil moisture in central and southeastern Europe and hypothesized that this was due to the noninclusion of evapotranspiration, which has been shown to be an important factor in the areas analysed. On the other hand, the suitability of SPEI as a proxy for soil moisture was shown by Herold et al. (2016) and by Russo et al. (2019), respectively, for Australia and the Mediterranean basin. Both SPI and SPEI have also the advantage of being multiscalar, thus allowing the assessment of drought conditions at different time scales (McKee et al., 1993; Vicente-Serrano et al., 2010). On the other hand, extreme heat events can be assessed with extreme temperature indices. These indices can be threshold-based or percentile-based, and the latter allow for a comparison of different regions. The indices number of hot days (NHD) and number of hot nights (NHN) are percentile-based (Zhang et al., 2011) and have also been...
successfully used in studies of compound dry and heat events (Mueller and Seneviratne, 2012; Holmes et al., 2017; Russo et al., 2019).

Australia has long been a land of weather extremes, recurrently being affected by droughts (Verdon-Kidd and Kiem, 2009; Kim et al., 2016), flooding rains (Johnson et al., 2016) and bushfires (Sharple et al., 2016; Lindenmayer and Taylor, 2020; Tran et al., 2020). Moreover, the 2009 heatwave in Southeastern Australia was associated with drought conditions that strongly enhanced temperature extremes (Kala et al., 2015). The recent 2019–2020 bushfire season was also possibly driven by the high temperatures recorded and the severe drought conditions, as measured by SPEI-6 (Deb et al., 2020; Nolan et al., 2020). Recent extreme weather events have raised the question on whether the patterns and nature of these events are changing as a result of climate change (IPCC, 2012; 2021). An increasing trend in temperature extremes has been registered (Perkins-Kirkpatrick et al., 2016; Alexander and Arblaster, 2017), as well as a decreasing trend in precipitation in some regions and seasons (Cai et al., 2014). Moreover, population trends, urbanization and residential shifts to high-risk areas will intersect with climate change to increase Australia’s exposure to natural hazards (Australian Government, 2015).

The present work is devoted to the analysis of two types of extreme weather events affecting Australia, droughts and heat waves, and to their synergetic effect. Therefore, the effect of antecedent drought conditions on summer hot extremes in Australia is analysed, using the drought index SPEI at several time scales as a soil moisture proxy, and the extreme temperature indices NHD and NHN. The analysis is performed on a monthly time scale and considers drought conditions of up to three previous months. Moreover, we used two time periods, 1979–2019 and 1950–2019, to assess changes in the relationship that may have occurred more recently. Although several studies have analysed the relation between hot extremes in the summer months and antecedent drought conditions in Australia and found strong correlations in several regions (Mueller and Seneviratne, 2012; Perkins et al., 2015; Herold et al., 2016; Holmes et al., 2017; Liu et al., 2019), they considered either only the hottest month (Mueller and Seneviratne, 2012; Liu et al., 2019) or the aggregated months of summer (Perkins et al., 2015; Herold et al., 2016; Holmes et al., 2017; Loughean et al., 2017). Here we analyse all individual summer months, that is, December–February, which will allow us a better insight into the relationship between drought and temperature extremes, in terms of spatial and temporal scales. The high spatial resolution and monthly time scales allow us to better identify possible different regional patterns, and also different responses occurring at different time periods. Furthermore, SPEI computed at several time scales is proposed to assess the influence of cumulative soil moisture deficits on hot extremes. Finally, we would like to highlight that to the authors’ knowledge, the index NHN has not yet been used to perform a similar analysis in the study area, which can be an important aspect considering that the night-time warming is more common than greater daytime warming worldwide (Cox et al., 2020) and is expected to continue to rise (https://www.eea.europa.eu/data-and-maps/figures/increase-in-the-number-of).

This analysis will contribute to a better understanding on how droughts relate with extreme temperatures for different climatic areas over Australia, and to assess if this relation is somehow lagged. It will allow to respond to several key questions, namely (a) What is the relationship between drought conditions and hot extremes in Australia, considering different monthly lags and drought time scales? (b) What areas and climatic zones present this correlation? (c) Has this correlation changed with time?

2 | DATA AND METHODS

2.1 | Study area and climate regions

The Australian climate shows a spatial variability and can be an important factor in the phenomenon studied here. Hence, the different climate regions of Australia were assessed using the Köppen-Geiger classification computed by Beck et al. (2018). The authors used three temperature and four precipitation datasets, which have been explicitly corrected for topographic effects. This map has a 0.008° spatial resolution and contains 30 climate classes. The map was resampled to match the ERA5 spatial resolution, using a majority rule and a nearest-neighbour interpolation. Figure 1a depicts the climate regions of Australia, excluding three classes due to the insignificant area occupied. Most of Australia is classified as arid (77.07%), with the remaining ~33% being divided among the other nine classes. The two classes of Arid desert were excluded from the analysis (and masked), and the remaining were aggregated in three regions, as shown in Figure 1b. The northern region is classified as tropical, the coastal areas in the southwest and east are mainly temperate, and the remaining is arid.

2.2 | Indices of extreme temperature

Two indices of extreme temperature were computed, namely the number of hot days (NHD) and the number
of hot nights (NHN), which are defined as the number of days, per month, exceeding the 90th percentile of daily maximum and minimum temperature, respectively (Fischer et al., 2007a; Zhang et al., 2011). These indices have been used in similar studies (Fischer et al., 2007a; Mueller and Seneviratne, 2012; Holmes et al., 2017; Ribeiro et al., 2020a; Russo et al., 2019), and have been shown to be suitable to this type of analysis. Both NHD and NHN were computed for two distinct datasets, namely ERA5 and ACORN-SAT v2. ERA5 is a reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), which covers the period from 1979 to near real time (Hersbach et al., 2020), although a preliminary version already includes data for the period 1950–1978. The hourly data are available with a 0.25 spatial resolution. The ACORN-SAT v2 dataset, hereby called the ACORN, includes maximum and minimum temperature data for 112 locations in Australia (Trewin et al., 2020). This dataset covers the period from 1910 to May of 2019, although not all locations have data for the full period, and only 60 locations cover the period 1910–2018 (Trewin et al., 2020). Moreover, 93 locations have data covering the period 1950–2019. These locations cover a great part of the country, despite some voids due to the inexistence or the short period covered by the data (Trewin et al., 2020), as shown in Figure 1b. The ACORN temperature data has been homogenized until 2016 (Trewin et al., 2020). Therefore, gridded hourly 2 m temperature data was retrieved from the ERA5 dataset, for the period from 1950 to present. Daily maximum and minimum temperatures were computed from the hourly data, which were then used to compute NHD and NHN on a gridded base. Additionally, daily maximum and minimum temperatures from the ACORN dataset were also used to compute the extreme temperature indices.

NHD and NHN were computed for two periods, namely 1979–2019 and 1950–2019, using the Climpact package for R, which includes a bootstrap resampling procedure to remove inhomogeneities caused by the use of a base period (Zhang et al., 2011). The base period used for the computation of the indices was 1979–2018 and 1950–2018, respectively, since the ACORN dataset does not include the entire year of 2019.

2.3 | Drought index

The assessment of drought conditions was made using the standardized precipitation evapotranspiration index (SPEI; Vicente-Serrano et al., 2010), since this drought index has been shown to be a suitable proxy of soil
moisture over Mediterranean Europe (Russo et al., 2019), and Australia (Herold et al., 2016). The use of SPEI as a proxy for soil moisture in the study area is considered to be justified and appropriate, since there is a link between the rising temperature and the increase in drought severity in Australia (Cai et al., 2009), as well as a non-negligible effect of evapotranspiration on the soil moisture in nondry climates and seasons (Seneviratne et al., 2012b; Teuling et al., 2013; Manning et al., 2018). SPEI was computed based on monthly precipitation and temperature data obtained from the CRU TS4.04 dataset (Harris et al., 2020). The variables included in this dataset were computed by interpolation of observations from weather stations on a monthly time scale, covering the period 1901–2019, with a spatial resolution of 0.5° (Harris et al., 2020). The standard method for the estimation of the atmospheric evaporative demand (AED) is the FAO-56 Penman–Monteith (Allen et al., 1998), since it is physically based and has shown to accurately estimate AED in different climates (Allen et al., 1998). Nonetheless, it requires many meteorological variables, that may not be available or may be of low quality, which is the case of earlier years of the CRU TS4.04 dataset. For this reason, AED was obtained with the modified Hargreaves method (Doogers and Allen, 2002), since this method provides annual estimates closer to the values obtained by the FAO-56 Penman–Monteith in the study area (Doogers and Allen, 2002), when compared to the Hargreaves method (Hargreaves and Samani, 1985). SPEI was computed for the periods 1979–2019 and 1950–2019, at the time scales of 1, 3, and 6 months, and a log-logistic distribution was used to model the water deficit (Beguería et al., 2014).

2.4 Assessment of drought influence on summer extremes

This analysis was performed for the austral summer, which includes the months from December to February, and for the periods 1979–2019 and 1950–2019. The use of these time periods allowed us to assess changes in the relationship between SPEI and NHD/NHN that may have occurred, while at the same time compare our results to previously published works that have used similar time periods (Mueller and Seneviratne, 2012; Herold et al., 2016; Holmes et al., 2017; Liu et al., 2019). The correlation between SPEI and the extreme temperature indices NHD and NHN was computed for the periods 1979–2019 and 1950–2019, using a 2-tailed Spearman’s rank correlation coefficient, and a level of significance of 0.1. This method was used since it does not require the variables to be normally distributed (Schober et al., 2018). For each month, SPEI on the concurrent and previous 1–3 months was correlated with NHD/NHN, which amounts to a cross-correlation with the lags from 0 to 3. All monthly time series were detrended prior to the computation of the correlation, using a polynomial with a degree chosen by Akaike information criteria (Fang, 2011; Pascoa et al., 2017). The results of the correlation were analysed in more detail on each aggregated climatic region shown in Figure 1b.

3 RESULTS

The significant correlations between NHD/NHN and SPEI at the time scales of 1, 3, and 6 months are shown in Figures 2–9, for the concurrent and previous 1–3 months (lag of 0–3 months), and for the time periods 1979–2019 and 1950–2019. The figures show the results obtained with the extreme temperature indices computed with both datasets, although for the case of the ACORN dataset, only the sign of the correlation is presented (crosses/circles respectively for positive/negative correlation values) for a better visualization of results.

For both periods, and for the case of the ERA5 dataset, the correlations obtained are mostly negative, indicating a positive effect of dry conditions on temperature extremes. In general, the area presenting significant negative correlations is larger and the correlation is stronger when considering NHD, compared to NHN. The SPEI time scale does not significantly influence the results obtained, whereas for a larger lag, the area presenting significant correlations decreases, and the correlation is weaker. An extremely small number of pixels present a significant positive correlation, mostly near coastal areas, but it is much weaker when compared with the negative correlations obtained. Although the spatial patterns are very similar, the correlations are slightly stronger in the period 1979–2019, with the differences in the median correlation coefficient ranging from 0.05 for lag 0 to almost 0.1 for lag 3 (Figures S1 and S2, Supporting Information).

Concerning the concurrent SPEI and NHD/NHN months (lag of 0 months), significant negative correlations are found on most of the study area on both periods (Figures 2 and 6), although some coastal areas do not present a significant correlation, particularly for NHN. When considering the lag of 1 month, there are still large areas showing significant negative correlations, namely the eastern and northern regions in December, the eastern region in January, and the north and southeast in February (Figures 3 and 7). For the lags 0 and 1, the correlations are stronger in February, and the median value
FIGURE 2  Correlation between NHN/NHD and SPEI for the time scales of 1, 3, and 6 months, on the months of December to February, computed with a lag of 0 (concurrent) months. Circles and crosses represent negative and positive significant correlations obtained with the ACORN dataset, respectively. The minimum significant correlation is ±0.26, corresponding to 39 degrees of freedom [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 3  As in Figure 2 but computed with a lag of 1 month [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 4  As in Figure 2 but computed with a lag of 2 months [Colour figure can be viewed at wileyonlinelibrary.com]
FIGURE 5  As in Figure 2 but computed with a lag of 3 months [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 6  As in Figure 2, but for the period 1950–2019. The minimum significant correlation is ±0.198, corresponding to 68 degrees of freedom [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 7  As in Figure 2 but computed with a lag of 1 month for the period 1950–2019 [Colour figure can be viewed at wileyonlinelibrary.com]
of the correlation coefficient reaches 0.5 for NHN and almost 0.6 for NHD, for lag 0 in the period 1979–2019 (Figures S1 and S2). For the lags of 2 and 3 months (Figures 4, 5, 8, and 9), the areas presenting a significant negative correlation continue to diminish, as well as the correlation coefficients (Figures S1 and S2). Still, there are regions consistently showing significant correlation values, such as the southwest and southeast in December, and in February, the east for the case of NHN and the southeast for the case of NHD. It should be noted that several areas with significant correlations for both NHD and NHN are coincident, and when they are not coincident, they are complementary and show a consistent spatial pattern. In particular, in the case of the 3-month lag, results for NHD show spatial patterns of synergetic effect of drought conditions in spring on day hot extremes over southeastern and southwestern regions, while the driver effect on night hot extremes (as obtained from NHN) is located over eastern regions (Figures 5 and 9).

The results obtained using the ACORN dataset are in good agreement with the results of the ERA5 dataset. In particular, the location of the stations presenting a significant correlation value generally agree with the ones obtained with ERA5, although in some cases, significant values are obtained in areas where the correlation with ERA5 is weaker and nonsignificant. Some locations near the coast show a positive correlation between SPEI and NHN, and in most cases it coincides with areas where ERA5 pixels present a nonsignificant correlation. The percentage of ACORN locations showing significant negative correlations is shown on Tables 1 and 2, for the periods 1979–2019 and 1950–2019, respectively. The results
obtained with NHD for lag 0 exceed 80% and largely outnumber the results for NHN, on both periods. For the remaining lags the differences are smaller. Similar to the results obtained for ERA5 (Figures 2–9), the percentage ACORN locations with significant negative correlation decreases with the longer lag, whereas the SPEI time scale does not seem to affect the results much. Moreover, the values are generally higher for the longer period.

The area of significant negative correlations occurring on each aggregated climate region is presented in Figures 10 and 11, for the periods 1979–2019 and 1950–2019, respectively, as a percentage of each climate region, and computed with ERA5. As previously mentioned, the results are not influenced by the SPEI time scale, and so only the results of SPEI-3 are shown. The results for the two periods do not differ much, although the areas are slightly larger for the longer period. For tropical and arid climates, the area in February for lag 1 is almost as large as for lag 0, for both time periods, likely due to the correlations occurring in the north and east. Also in February, the area for Lag 3 computed with NHN for the long period is almost 50%, which is the largest for this lag. In the arid region, the differences between the area obtained with NHN and NHD are small. For the lag 0, the area presenting significant correlation values obtained with NHN is much smaller in the temperate climate, compared with NHD and with the tropical and arid regions, possibly due to the absence of significant correlations in the southwest.

### Discussion

The results obtained with the two datasets are in agreement, indicating a good quality of the temperature extremes computed with the ERA5 dataset, and the independence of the results on the dataset used. A similar approach was used also by Liu et al. (2019), which used both a gridded and a station-based dataset and reached a similar conclusion for low latitudes and using SPI and NHD on a global scale. The study by Liu et al. (2019) nevertheless did not account for the night-time temperature nor the influence of the water balance, which is an important feature in some areas.

The comparison of the results obtained for the period 1979–2019 with those obtained for 1950–2019 showed us that the area of significant correlations did not change much, although the median correlation coefficients became larger. Several heatwave events have already been linked to antecedent drought conditions in Europe (Miralles et al., 2012; Dirmeyer et al., 2021), Brazil (Geirinhas et al., 2021), and India (Guntu and Agarwal, 2021). The frequency of heatwave events has been shown to have increased in Australia (Perkins-Kirkpatrick et al., 2017; Jyoteeshkumar Reddy et al., 2021), and the frequency of compound dry and hot events is likely to increase in the future in this country (Wu et al., 2020). The stronger correlations obtained here for the 1979–2019 period indicate a possible increase of the effect of previous drought conditions on temperature extremes in more recent years.

**Table 1** Percentage ACORN stations showing a significant negative correlation between SPEI and NHD/NHN for the period 1979–2019

|       | NHN Dec | Jan | Feb | NHD Dec | Jan | Feb |
|-------|---------|-----|-----|---------|-----|-----|
| SPEI-1 Lag 0 | 25.9 | 25.9 | 30.4 | 80.4 | 80.4 | 84.8 |
| Lag 1 | 29.5 | 27.7 | 24.1 | 43.8 | 26.8 | 40.2 |
| Lag 2 | 6.3 | 20.5 | 15.2 | 8.0 | 22.3 | 12.5 |
| Lag 3 | 9.8 | 13.4 | 10.7 | 7.1 | 8.0 | 4.5 |
| SPEI-3 Lag 0 | 38.4 | 34.8 | 33.0 | 86.6 | 80.4 | 85.7 |
| Lag 1 | 26.8 | 30.4 | 25.0 | 46.4 | 35.7 | 39.3 |
| Lag 2 | 8.0 | 27.7 | 15.2 | 8.0 | 26.8 | 11.6 |
| Lag 3 | 8.0 | 12.5 | 12.5 | 7.1 | 8.0 | 12.5 |
| SPEI-6 Lag 0 | 32.1 | 46.4 | 36.6 | 82.1 | 75.0 | 79.5 |
| Lag 1 | 21.4 | 36.6 | 22.3 | 35.7 | 39.3 | 39.3 |
| Lag 2 | 8.0 | 19.6 | 17.0 | 8.9 | 19.6 | 15.2 |
| Lag 3 | 6.3 | 9.8 | 15.2 | 9.8 | 5.4 | 19.6 |

**Table 2** Percentage ACORN stations showing a significant negative correlation between SPEI and NHD/NHN for the period 1950–2019

|       | NHN Dec | Jan | Feb | NHD Dec | Jan | Feb |
|-------|---------|-----|-----|---------|-----|-----|
| SPEI-1 Lag 0 | 33.0 | 31.3 | 45.5 | 87.5 | 84.8 | 90.2 |
| Lag 1 | 41.1 | 35.7 | 31.3 | 58.9 | 41.1 | 51.8 |
| Lag 2 | 10.7 | 25.9 | 22.3 | 12.5 | 25.9 | 25.9 |
| Lag 3 | 10.7 | 20.5 | 21.4 | 12.5 | 17.9 | 22.3 |
| SPEI-3 Lag 0 | 42.9 | 37.5 | 49.1 | 89.3 | 87.5 | 90.2 |
| Lag 1 | 38.4 | 37.5 | 33.9 | 59.8 | 46.5 | 52.7 |
| Lag 2 | 14.3 | 31.3 | 24.1 | 14.3 | 28.6 | 28.6 |
| Lag 3 | 13.4 | 19.6 | 16.1 | 14.3 | 18.8 | 29.5 |
| SPEI-6 Lag 0 | 45.5 | 43.8 | 54.5 | 91.1 | 87.5 | 89.3 |
| Lag 1 | 36.6 | 36.6 | 35.7 | 51.8 | 43.8 | 50.9 |
| Lag 2 | 18.8 | 32.1 | 25.0 | 17.0 | 23.2 | 35.7 |
| Lag 3 | 10.7 | 15.2 | 18.8 | 14.3 | 8.0 | 40.2 |
FIGURE 10 Area of significant negative correlations between NHD/NHN and SPEI-3, on the months of December–February, on each of the aggregated climate regions, and for a lag of 0 (concurrent) to 3 months, for the period 1979–2019 [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 11 As in Figure 10 but for the period 1950–2019 [Colour figure can be viewed at wileyonlinelibrary.com]
does not provide information about the effect of the antecedent soil moisture or present a predictive ability, it amounts to the coupling of the soil moisture and temperature during hot events. This has been shown to be high in regions where a relation between extreme heat and previous drought conditions has also been established (Miralles et al., 2012; Mueller and Seneviratne, 2012; Quesada et al., 2012; Russo et al., 2019).

The results obtained here with the time lag of 1 month generally agree with the results previously obtained for Australia, namely a significant negative correlation in the north and in the southeast (Mueller and Seneviratne, 2012; Herold et al., 2016; Holmes et al., 2017). Nonetheless, using the individual months of December to February allowed us to identify that the patterns obtained are not constant throughout these months. For instance, the correlation appears to be stronger in the north in February, as indicated by the larger areas of significant correlations, whereas for the eastern coast, the months of December and January are more important, albeit with regional differences. Contrary to the present work, in some previous studies no correlation was found in the southwestern region between antecedent drought conditions and hot extremes (Mueller and Seneviratne, 2012; Herold et al., 2016; Loughran et al., 2017), or the correlation found was weak (Perkins et al., 2015). This is likely due to the fact that in these works the heat index was defined differently to how it is defined here, and the antecedent climate conditions were also represented using different variables and for aggregated months. By contrast, Holmes et al. (2017) and Liu et al. (2019) used the index NHD and were able to identify significant correlations in the southwest, using different datasets.

Lead times longer than 1 month have been shown to present a relationship with hot extremes in some regions of the Mediterranean (Russo et al., 2019; Ribeiro et al., 2020a), and the high number of stations obtained here showing a significant correlation at lag times of 2 or 3 months points to a predictive ability in several regions of Australia. Although the correlation coefficients decrease with the lag, some areas present significant correlations at all lags (e.g., the southwest and the southeast computed with NHD in December, and the east computed with NHD in February), indicating a strong and persistent relationship between antecedent drought conditions and hot extremes. This is in agreement with some works for other regions, namely Russo et al. (2019), which showed that some regions in the Mediterranean present a strong correlation at longer lead times, whereas Quesada et al. (2012) identified a strong relation between the precipitation in winter and spring and summer heatwaves in southern Europe. Moreover, Perkins et al. (2015) and Loughran et al., 2017 used a long lead time and had already found that the conditions on the preceding late winter to spring may be important in predicting summer heatwaves in some regions of Australia. These results may be related with the precipitation distribution throughout the year. In areas where the precipitation in the months of December–February is low, a negative precipitation anomaly in these months likely does not impact the soil moisture as much as in areas where the precipitation in this season is high and the correlation with hot extremes depends on this relation. On the other hand, if the dry summers are preceded by winter/spring months with relatively high precipitation values, the effect on the soil moisture can also be high and important in the following months. The southwest of Australia presents this precipitation regime (Figure S3), as opposed to the North and East, where precipitation values are much higher in the months of December–February, which are part of the wet season (November–April). In these regions, antecedent soil moisture deficits are likely compensated by concurrent precipitation, and therefore, the correlation is much weaker at longer lead times. A similar effect has been shown by Gouveia et al. (2016), when studying the influence of the winter drought in the extreme fire season of 2007 in Greece.

The southwestern and southeastern regions present significant correlations at lags of 2 and 3 months, and Herold et al. (2018) showed that these regions are expected to become drier in the spring in the near future (2020–2039), and in the winter, spring, and summer in the period 2060–2079. The coupling of soil moisture and temperature in the summer has been shown to change, namely in the United States (Hao et al., 2020), and is projected to change in some regions of the world (Seneviratne et al., 2010), and an increased dryness may alter the relation of soil moisture and hot extremes (Seneviratne et al., 2010).

The analysis made on each aggregated climate region shows small areas of correlation between SPEI and NHD on the temperate climate, whereas the opposite occurs on the tropical and arid climates, particularly at the concurrent month.

The results obtained here with a correlation analysis for the different time scales of SPEI did not show significant differences, highlighting the fact that the accumulation period used and therefore the memory of the drought phenomena is not a crucial factor here, compared to the time lags, but it is likely that consecutive dry months should have a severe effect, particularly in the tropical areas, where the coupling of soil moisture with hot extremes is very high. A different methodology, considering only dry events, and not all events as was done here, may be more appropriate to study this particular situation, such as quantile regressions (Mueller and Seneviratne, 2012) or copula
functions (Ribeiro et al., 2020a; 2020b). Besides the possibility of predicting extreme heat events, compound drought and heat events are also related to the occurrence of many environmental impacts, such as bushfires and crop losses (Gouveia et al., 2016; Ribeiro et al., 2020b), and the dependence between multiple climate stressors and the associated impacts should be further considered in future work across this region.

5 CONCLUSIONS

This study assessed the influence of the antecedent drought conditions on the occurrence of summer hot extremes in Australia. For this, the indices NHD and NHN were used to characterize the hot extremes in the three summer months, and the index SPEI was computed to assess the drought conditions in the summer months and in the preceding 1–3 months, at several time scales. Both indices of extreme temperature presented strong correlations with SPEI, although correlations with NHN are more evident in tropical climates. There is a strong coupling between soil moisture and temperature in most of the study area, but the study of the individual summer months showed different spatial patterns throughout the season. This allowed us to identify for different regions the month or months where the correlation with SPEI was higher. The area of significant correlation decreased with the longer lags, but large regions of Australia still present a strong correlation with SPEI. This feature presents the possibility of an early prediction of hot summer extremes in regions affected by drought in previous spring. Finally, we would like to highlight the fact that the results for the more recent period (1979–2019) showed an intensification of the median correlation coefficients which reflects the increase of the frequency of dry and hot events in Australia and the possible influence of climate change (and the impacts in temperature and precipitation).

ACKNOWLEDGEMENTS

This work was partially supported by projects FireCast (PCIF/GRF/0204/2017), and IMPECAF (PTDC/CTA-CLI/28902/2017). Andreia F. S. Ribeiro acknowledges funding from the Swiss National Science Foundation (project number 186282).

AUTHOR CONTRIBUTIONS

Patricia Páscoa: Data curation; formal analysis; investigation; methodology; visualization; writing – original draft; writing – review and editing. Célia M. Gouveia: Conceptualization; investigation; methodology; supervision; writing – review and editing. Ana Russo: Conceptualization; formal analysis; investigation; methodology; project administration; supervision; writing – review and editing. Andreia Ribeiro: Investigation; methodology; writing – review and editing.

DATA AVAILABILITY STATEMENT

The Köppen–Geiger classification data was downloaded from http://www.gloh2o.org/koppen/, the ERA5 temperature data was downloaded from https://cds.climate.copernicus.eu/, the ACORN-SAT v2 temperature data was downloaded from http://www.bom.gov.au/climate/data/acorn-sat/, and the CRU TS 4.04 temperature and precipitation data was downloaded from https://crudata.uea.ac.uk/cru/data/hrg/.

ORCID

Patricia Páscoa https://orcid.org/0000-0001-6874-0599
Ana Russo https://orcid.org/0000-0003-0481-0337
Andreia F. S. Ribeiro https://orcid.org/0000-0003-0481-0337

REFERENCES

Abram, N.J., Henley, B.J., Sen Gupta, A., Lippmann, T.J., Clarke, H., Dowdy, A.J., Nolan, R.H., Zhang, T., Wooster, M.J., Wurtzel, J.B., Meissner, K.J., Pitman, A.J., Ukkola, A.M., Murphy, B.P., Tapper, N.J., and Boer, M.M. (2021) Connections of climate change and variability to large and extreme forest fires in southeast Australia. Communications Earth & Environment, 2, 8. https://doi.org/10.1038/s43247-020-00065-8.
Alexander, L.V. and Arblaster, J.M. (2017) Historical and projected trends in temperature and precipitation extremes in Australia in observations and CMIP5. Weather Climate Extremes, 15, 34–56. https://doi.org/10.1016/j.wace.2017.02.001.
Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. (1998) Crop evapotranspiration. In: Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper 56. Rome: FAO.
Australian Government. (2015) National Climate Resilience and Adaptation Strategy. Canberra: Australian Government. Available at: https://www.environment.gov.au/system/files/resources/3b44e21e-2a78-4809-87c7-a1386e350c29/files/national-climate-resilience-and-adaptation-strategy.pdf [Accessed on 22nd January 2021].
Barriendropedro, D., Fischer, E.-M., Luterbacher, J., Trigo, R.M. and García-Herrera, R. (2011) The hot summer of 2010: re-drawing the temperature record map of Europe. Science, 332, 220–224. https://doi.org/10.1126/science.1201224.
Bastos, A., Orth, R., Reichstein, M., Ciais, P., Viovy, N., Zaehle, S., Anthoni, P., Arneth, A., Gentine, P., Joetzjer, E., Lienert, S., Loughran, T., McGuire, P.C., Sungmin, O., Pongratz, J., and Sitch, S. (2021) Vulnerability of European ecosystems to two compound dry and hot summers in 2018 and 2019. Earth System Dynamics, 12(4), 1015–1035. https://doi.org/10.5194/esd-12-1015-2021.
Beck, H.E., Zimmermann, N.E., McVicar, T.R., Vergopolan, N., Berg, A. and Wood, E.F. (2018) Present and future Köppen–
Geiger climate classification maps at 1-km resolution. *Scientific Data*, 5, 180214. https://doi.org/10.1038/sdata.2018.214.

Beguería, S., Vicente-Serrano, S.M., Reig, F. and Latorre, B. (2014) Standardized precipitation evapotranspiration index (SPEI) revisited: parameter fitting, evapotranspiration models, tools, datasets and drought monitoring. *International Journal of Climatology*, 34, 3001–3023. https://doi.org/10.1002/joc.3887.

Beillouin, D., Schuafferger, B., Bastos, A., Ciais, P. and Makowski, D. (2020) Impact of extreme weather conditions on European crop production in 2018. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 375, 20190510. https://doi.org/10.1098/rstb.2019.0510.

Bezak, N. and Mikos, M. (2020) Changes in the compound drought and extreme heat occurrence in the 1961–2018 period at the European scale. *Water*, 12, 3543. https://doi.org/10.3390/w12123543.

Cai, W., Purich, A., Cowan, T., van Rensch, P. and Weller, E. (2014) Rising temperature depletes soil moisture and exacerbates severe drought conditions across Southeast Australia. *Geophysical Research Letters*, 36, L21709. https://doi.org/10.1029/2009GL040334.

Cai, W., Purich, A., Cowan, T., van Rensch, P. and Weller, E. (2014) Did climate change-induced rainfall trends contribute to the Australian millennium drought? *Journal of Climate*, 27, 3145–3168. https://doi.org/10.1175/JCLI-D-13-00322.1.

Cox, D.T.C., Maclean, I.M.D., Gardner, A.S. and Gaston, K.J. (2020) Global variation in diurnal asymmetry in temperature, cloud cover, specific humidity and precipitation and its association with leaf area index. *Global Change Biology*, 26, 7099–7111. https://doi.org/10.1111/gcb.15336.

Deb, P., Morakhami, H., Abbasazadeh, P., Kiem, A.S., Engröst, J., Keellings, D. and Sharma, A. (2020) Causes of the widespread 2019–2020 Australian bushfire season. *Earth’s Futures*, 8, e2020EF001671. https://doi.org/10.1029/2020EF001671.

Dirmeyer, P.A., Balsamo, G., Blyth, E.M., Morrison, R. and Cooper, H.M. (2021) Land–atmosphere interactions exacerbated the drought and heatwave over northern Europe during summer 2018. *AGU Advances*, 2(2), 1–16. https://doi.org/10.1029/2020av000283.

Doogers, P. and Allen, R.G. (2002) Estimating reference evapotranspiration under inaccurate data conditions. *Irrigation and Drainage Systems*, 16, 33–45. https://doi.org/10.1023/A:101558322413.

Doogers, P. and Allen, R.G. (2002) Estimating reference evapotranspiration under inaccurate data conditions. *Irrigation and Drainage Systems*, 16, 33–45. https://doi.org/10.1023/A:101558322413.

Fang, Y. (2011) Asymptotic equivalence between cross-validations and Akaike information criteria in mixed-effects models. *Journal of Data Science*, 9, 15–21. https://doi.org/10.6339/JDS.201101_09(1).0002.

Feng, S., Hao, Z., Zhag, X. and Hao, F. (2019) Probabilistic evaluation of the impact of compound dry-hot events on global maize yields. *Science of the Total Environment*, 689, 1228–1234. https://doi.org/10.1016/j.scitotenv.2019.06.373.

Fischer, E.M., Seneviratne, S.I., Luthi, D. and Schar, C. (2007a) Contribution of land–atmosphere coupling to recent European summer heat waves. *Geophysical Research Letters*, 34, L06707. https://doi.org/10.1029/2006GL029068.

Fischer, E.M., Seneviratne, S.I., Vidale, P.L., Lüthi, D. and Schär, C. (2007b) Soil moisture–atmosphere interactions during the 2003 European summer heat wave. *Journal of Climate*, 20, 5081–5099. https://doi.org/10.1175/JCLI4288.1.

Fu, Z., Ciais, P., Bastos, A., Stoy, P.C., Yang, H., Bastos, A., Stoy, P.C., Yang, H., Green, J.K., Wang, B., Yu, K., Huang, Y., Knohl, A., Sigut, L., Gharun, M., Cuntz, M., Arriga, N., Roland, M., Peichl, M., Migliavacca, M., Cremonese, E., Varlugin, A., Brümmer, C., Gourléz de la Motte, L., Fares, S., Buchmann, N., el-Madany, T.S., Pitacco, A., Vendrame, N., Li, Z., Vincke, C., Magliulo, E. and Koebisch, F. (2020) Sensitivity of gross primary productivity to climatic drivers during the summer drought of 2018 in Europe. *Philosophical Transactions of the Royal Society B*, 375, 20190747. https://doi.org/10.1098/rstb.2019.0747.

Geirinhias, J.L., Russo, A., Libonati, R., Sousa, P.M., Miralles, D. and Trigo, R.M. (2021) Recent increasing frequency of compound summer drought and heatwaves in Southeast Brazil. *Environmental Research Letters*, 16(3), 034036. https://doi.org/10.1088/1748-9326/abeb69.

Geirinhias, J.L., Russo, A., Libonati, R., Trigo, R.M., Castro, L.C.O., Peres, L.F., de Magalhães, A.F.M. and Nunes, B. (2020) Heat-related mortality at the beginning of the twenty-first century in Rio de Janeiro, Brazil. *International Society of Biometeorology*, 64, 1319–1332. https://doi.org/10.1007/s00484-020-01908-x.

Gouveia, C.M., Bistinas, I., Libero, M.L.R., Bastos, A., Koutsias, N. and Trigo, R. (2016) The outstanding synergy between drought, heatwaves and fuel on the 2007 southern Greece exceptional fire season. *Agricultural and Forest Meteorology*, 218–219, 135–145. https://doi.org/10.1016/j.agrformet.2015.11.023.

Guntu, R.K. and Agarwal, A. (2021) Disentangling increasing compound extremes at regional scale during Indian summer monsoon. *Scientific Reports*, 11, 16447. https://doi.org/10.1038/s41598-021-95775-0.

Hao, Z., Hao, F., Singh, V.P. and Ouyang, W. (2017) Quantitative risk assessment of the effects of drought on extreme temperature in eastern China. *Journal of Geophysical Research-Atmospheres*, 122, 9050–9059. https://doi.org/10.1002/2017JD027030.

Hao, Z., Hao, F., Singh, V.P. and Zhang, X. (2018) Changes in the severity of compound drought and hot extremes over global land areas. *Environmental Research Letters*, 13, 124022. https://doi.org/10.1088/1748-9326/aaee96.

Hao, Z., Li, W., Singh, V.P., Xia, Y., Zhang, X. and Hao, F. (2020) Impact of dependence changes on the likelihood of hot extremes under drought conditions in the United States. *Journal of Hydrology*, 581, 124410. https://doi.org/10.1016/j.jhydrol.2019.124410.

Hargreaves, G.L. and Samani, Z.A. (1985) Reference crop evapotranspiration from temperature. *Applied Engineering in Agriculture*, 1, 96–99.

Harris, I., Osborn, T.J., Jones, P. and Lister, D. (2020) Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. *Scientific Data*, 7, 109. https://doi.org/10.1038/s41597-020-0453-3.

Herold, N., Ekström, M., Kala, J., Goldie, J. and Evans, J.P. (2018) Australian climate extremes in the 21st century according to a regional climate model ensemble: implications for health and agriculture. *Weather Clim Extremes*, 20, 54–68. https://doi.org/10.1016/j.wace.2018.01.001.

Herold, N., Kala, J. and Alexander, L.V. (2016) The influence of soil moisture deficits on Australian heatwaves. *Environmental Research Letters*, 11, 064003. https://doi.org/10.1088/1748-9326/11/6/064003.
Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragni, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R., Holm, E., Janisková, M., Kellay, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., Rosnay, P., Rozum, I., Vamborg, F., Villaume, S. and Thépaut, J.N. (2020) The ERA5 global reanalysis. Quarterly Journal of the Royal Meteorological Society, 146, 1999–2049. https://doi.org/10.1002/qj.3803.

Holmes, A., Rüdiger, C., Mueller, B., Hirschi, M. and Tapper, N. (2017) Variability of soil moisture proxies and hot days across the climate regimes of Australia. Geophysical Research Letters, 44, 7265–7275. https://doi.org/10.1002/2017GL073793.

IPCC. (2012) Managing the risks of extreme events and disasters to advance climate change adaptation. In: Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S.K., Tignor, M. and Midgley, P.M. (Eds.) A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change, Vol. 582. Cambridge and New York, NY: Cambridge University Press.

IPCC. (2021) Summary for policymakers. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou Cambridge and New York, NY: Cambridge University Press (in press).

Johnson, F., White, C.J., van Dijk, A., Ekstrom, M., Evans, J.P., Jakob, D., Kiem, A.S., Leonard, M., Rouillard, A. and Westra, S. (2016) Natural hazards in Australia: floods. Climatic Change, 139, 21–35. https://doi.org/10.1007/s10584-016-1689-y.

Jyoteshkumar Reddy, P., Perkins-Kirkpatrick, S.E. and Sharplees, J. J. (2021) Intensifying Australian heatwave trends and their sensitivity to observational data. Earth’s Futures, 9, e2020EF001924. https://doi.org/10.1029/2020EF001924.

Kala, J., Evans, J.P. and Pittman, A.J. (2015) Influence of antecedent soil moisture conditions on the synoptic meteorology of the Black Saturday bushfire event in Southeast Australia. Quarterly Journal of the Royal Meteorological Society, 141, 3118–3129. https://doi.org/10.1002/qj.2596.

Kiem, A.S., Johnson, F., Westra, S., van Dijk, A., Evans, J.P., O’Donnell, A., Rouillard, A., Barr, C., Tyler, J., Thyer, M., Jakob, D., Woldemeskel, F., Sivakumar, B. and Mehrotra, R. (2016) Natural hazards in Australia: droughts. Climatic Change, 139, 37–54. https://doi.org/10.1007/s10584-016-1798-7.

Lindemayer, D.B. and Taylor, C. (2020) New spatial analyses of Australian wildfires highlight the need for new fire, resource, and conservation policies. Proceedings of the National Academy of Sciences of the United States of America, 117(22), 12481–12485. https://doi.org/10.1073/pnas.2002269117.

Liu, X., Tang, Q., Liu, W., Yang, H., Groissman, P., Leng, G., Ciais, P., Zhang, X. and Sun, S. (2019) The asymmetric impact of abundant preceding rainfall on heat stress in low latitudes. Environmental Research Letters, 14, 044010. https://doi.org/10.1088/1748-9326/ab018a.

Loughran, T.M., Perkins-Kirkpatrick, S.E. and Alexander, L.V. (2017) Understanding the spatio-temporal influence of climate variability on Australian heatwaves. International Journal of Climatology, 37, 3963–3975. https://doi.org/10.1002/joc.4971.

Manning, C., Widmann, M., Bevacqua, E., van Loon, A.F., Maraun, D. and Vrac, M. (2018) Soil moisture drought in Europe: a compound event of precipitation and potential evapotranspiration on multiple time scales. Journal of Hydro-meteorology, 19(8), 1255–1271. https://doi.org/10.1175/JHM-D-18-0017.1.

Mckee, T.B., Doesken, N.J., and Kleist, J. (1993) The relationship of drought frequency and duration to time-scales. Paper presented at Proceedings of the 8th Conference on Applied Climatology, Anaheim, CA, USA, January 17–22, 1993.

Miralles, D.G., Teuling, A.J., van Heerwaarden, C.C. and de Arellano, J.V.-G. (2014) Mega-heatwave temperatures due to combined soil desiccation and atmospheric heat accumulation. Nature Geoscience, 7, 345–349. https://doi.org/10.1038/ngeo2141.

Miralles, D.G., van den Berg, M.J., Teuling, A.J. and de Jeu, R.A.M. (2012) Soil moisture–temperature coupling: a multiscale observational analysis. Geophysical Research Letters, 39, L21707. https://doi.org/10.1029/2012GL053703.

Mueller, B. and Seneviratne, S.I. (2012) Hot days induced by precipitation deficits at the global scale. Proceedings of the National Academy of Sciences of the United States of America, 109(31), 12398–12403. https://doi.org/10.1073/pnas.1204330109.

Nolan, R.H., Boer, M.M., Collins, L., de Dios, V.R., Clarke, H., Jenkins, M., Kenny, B. and Bradstock, R.A. (2020) Causes and consequences of eastern Australia’s 2019–20 season of mega-fires. Global Change Biology, 226, 1039–1041. https://doi.org/10.1111/gcb.14987.

Páscoa, F., Gouveia, C.M., Russo, A. and Trigo, R.M. (2017) The role of drought on wheat yield interannual variability in the Iberian Peninsula from 1929 to 2012. International Journal of Biometeorology, 61, 439–451. https://doi.org/10.1007/s00484-016-1224-x.

Perkins, S.E., Argüeso, D. and White, C.J. (2015) Relationships between climate variability, soil moisture, and Australian heatwaves. Journal of Geophysical Research-Atmospheres, 120, 8144–8164. https://doi.org/10.1002/2015JD023592.

Perkins-Kirkpatrick, S.E., Fischer, E.M., Angélil, O. and Gibson, P. B. (2017) The influence of internal climate variability on heatwave frequency trends. Environmental Research Letters, 12, 044005. https://doi.org/10.1088/1748-9326/aa63fe.

Perkins-Kirkpatrick, S.E., White, C.J., Alexander, L.V., Argüeso, D., Boschat, G., Cowan, T., Evans, J.P., Ekström, M., Oliver, E.C., Phatak, A. and Purich, A. (2016) Natural hazards in Australia: heatwaves. Climatic Change, 139, 101–114. https://doi.org/10.1007/s10584-016-1650-0.

Quesada, B., Vautard, R., You, P., Hirschi, M. and Seneviratne, S.I. (2012) Asymmetric European summer heat predictability from wet and dry southern winters and springs. Nature Climate Change, 2, 736–741. https://doi.org/10.1038/NCLIMATE1536.

Ribeiro, A.F.S., Russo, A., Gouveia, C.M., Páscoa, P. and Zscheischler, J. (2020b) Risk of crop failure due to compound dry and hot extremes estimated with nested copulas. Biogeosciences, 17, 4815–4830. https://doi.org/10.5194/bg-17-4815-2020.
Ribeiro, A.F.S., Russo, A., Gouveia, C.M. and Pires, C.A.L. (2020a) Drought-related hot summers: a joint probability analysis in the Iberian Peninsula. *Weather and Climate Extremes*, 30, 100279. https://doi.org/10.1016/j.wace.2020.100279.

Russo, A., Gouveia, C.M., Dutra, E., Soares, P.M.M. and Trigo, R.M. (2019) The synergy between drought and extremely hot summers in the Mediterranean. *Environmental Research Letters*, 14, 014011. https://doi.org/10.1088/1748-9326/aaf09e.

Schober, P., Boer, C. and Schwarte, L.A. (2018) Correlation coefficients: appropriate use and interpretation. *Anesthesia & Analgesia*, 126(5), 1763–1768. https://doi.org/10.1213/ANE.0000000000002864.

Schumacher, D.L., Keune, J., van Heerwaarden, C.C., Vilà-guerau de Arellano, J., Teuling, A.J. and Miralles, D.G. (2019) Amplification of mega-heathwaves through heat torrents fueled by upwind drought. *Nature Geoscience*, 12, 712–717. https://doi.org/10.1038/s41561-019-0431-6.

Seneviratne, S.I., Corti, T., Davin, E.L., Hirschi, M., Jaeger, E.B., Lehner, I., Orlowsky, B. and Teuling, A.J. (2010) Investigating soil moisture–climate interactions in a changing climate: a review. *Earth Science Reviews*, 99, 125–161. https://doi.org/10.1016/j.earscirev.2010.02.004.

Seneviratne, S.I., Lehner, I., Gurtz, J., Teuling, A.J., Lang, H., Moser, U., Grebner, D., Menzel, L., Schroff, K., Vitvar, T. and Zappa, M. (2012b) Swiss prealpine Rietholzbach research catchment and lysimeter: 32 year time series and 2003 drought event. *Water Resources Research*, 48(6), W06526. https://doi.org/10.1029/2011WR011749.

Seneviratne, S.I., Nicholls, N., Easterling, D., Goodess, C., Kanae, S., Kossin, J., Luo, Y., Marengo, J., McCraven, K., Rahimi, M., Reichstein, M., Sorteberg, A., Vera, C., Zhang, X., Alexander, L., Allen, S., Benito, G., Cavazos, T., Clague, J., Conway, D., Della-Marta, P.M., Gerber, M., Gong, S., Goswami, B.N., Hemes, M., Hugel, C., van den Hurk, B., Kharin, V.V., Kitoh, A., Klein, T., Albert MG., Li, G., Mason, S.J., McGuire, W., van Oldenborgh, G.J., Orlowski, B., Smith, S., Thiaw, W., Velegrakis, A., Yiou, P., Zhang, T., Zhou, T. and Francis, W.T. (2012a) Changes in climate extremes and their impacts on the natural physical environment. In: Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., et al. (Eds.) Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge, UK and New York, NY: Cambridge University Press, pp. 109–230.

Sharpley, J.J., Cary, G.J., Fox-Hughes, P., Mooney, S., Evans, J.P., Fletcher, M.S., Fromm, M., Grierson, P.F., McRae, R. and Baker, P. (2016) Natural hazards in Australia: extreme bushfire. *Climatic Change*, 139, 85–99. https://doi.org/10.1007/s10584-016-1811-9.

Teuling, A.J., van Loon, A.F., Seneviratne, S.I., Lehner, I., Aubinet, M., Heinesch, B., Berghofner, C., Grünwald, T., Prasse, H. and Spank, U. (2013) Evapotranspiration amplifies European summer drought. *Geophysical Research Letters*, 40(10), 2071–2075. https://doi.org/10.1002/grl.50495.

Tran, B.N., Tanase, M.A., Bennet, L.T. and Aponte, C. (2020) High-severity wildfires in temperate Australian forests have increased in extent and aggregation in recent decades. *PLoS One*, 15(11), e0242484. https://doi.org/10.1371/journal.pone.0242484.

Trewin, B., Braganza, K., Fawcett, R., Grainger, S., Jovanovic, B., Jones, D., Martin, D., Smalley, R. and Webb, V. (2020) An updated long-term homogenized daily temperature data set for Australia. *Geoscience Data Journal*, 7, 149–169. https://doi.org/10.1002/gdj3.95.

Turco, M., Jerez, S., Augusto, S., Tarin-Carrasco, P., Ratola, N., Jiménez-Guerrero, P. and Trigo, R.M. (2019) Climate drivers of the 2017 devastating fires in Portugal. *Scientific Reports*, 9, 13886. https://doi.org/10.1038/s41598-019-50281-2.

Ummenhofer, C.C. and Meehl, G.A. (2017) Extreme weather and climate events with ecological relevance: a review. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 372, 1723. https://doi.org/10.1098/rstb.2016.0135.

van Oldenborgh, G., Krikken, F., Lewis, S., Leach, N.J., Lehner, F., Saunders, K.R., Weele, M., Haustein, K., Li, S., Wallom, D., Sparrow, S., Arrigi, J., Singh, R.K., Aalst, M.K., Phillip, S.Y., Vautard, R. and Otto, F.E. (2021) Attribution of the Australian bushfire risk to anthropogenic climate change. *Natural Hazards and Earth System Sciences*, 21(3), 941–960. https://doi.org/10.5194/nhess-21-941-2021.

Verdon-Kidd, D.C. and Kiem, A.S. (2009) Nature and causes of protracted droughts in southeast Australia: comparison between the federation, WW1, and Big Dry droughts. *Geophysical Research Letters*, 36, L22707. https://doi.org/10.1029/2009GL041067.

Vicente-Serrano, S.M., Begueria, S. and López-Moreno, J.I. (2010) A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index (SPEI). *Journal of Climate*, 23, 1696–1718. https://doi.org/10.1175/2009JCLI2909.1.

Whan, K., Zscheischler, J., Orth, R., Shongwe, M., Rahimi, M., Asare, E.O. and Seneviratne, S.I. (2015) Impact of soil moisture on extreme maximum temperatures in Europe. *Weather Climate Extremes*, 9, 57–67. https://doi.org/10.1016/j.wace.2015.05.001.

Wu, X., Hao, Z., Tang, Q., Singh, V.P., Zhang, X. and Hao, F. (2020) Projected increase of compound dry and hot events over global land areas. *International Journal of Climatology*, 41, 393–403. https://doi.org/10.1002/joc.6626.

Yu, R. and Zhai, P. (2020) More frequent and widespread persistent compound drought and heat event observed in China. *Scientific Reports*, 10, 14576. https://doi.org/10.1038/s41598-020-71312-3.

Zhang, J., Yang, Z., Wu, L. and Yang, K. (2019) Summer high temperature extremes over northeastern China predicted by spring soil moisture. *Scientific Reports*, 9, 12577. https://doi.org/10.1038/s41598-019-49053-9.

Zhang, X., Alexander, L., Hegerl, G.C., Jones, P., Tank, A.K., Peterson, T.C., Trewin, B. and Zwiers, F.W. (2011) Indices for monitoring changes in extremes based on daily temperature and precipitation data. *WIREs Climate Change*, 2, 851–870. https://doi.org/10.1002/wcc.147.

Zscheischler, J., Martius, O., Westra, S., Bevacqua, E., Raymond, C., Horton, R.M., Hurk, B., AghaKouchak, A., Jézéquel, A., Mahecha, M.-D., Maraun, D., Ramos, A.R., Thiery, W. and Vignotto, E. (2020) A typology of compound weather and
climate events. *Nature Reviews Earth & Environment*, 1, 333–347. https://doi.org/10.1038/s43017-020-0060-z.

Zscheischler, J. and Seneviratne, S.I. (2017) Dependence of drivers affects risks associated with compound events. *Science Advances*, 3(6), e1700263. https://doi.org/10.1126/sciadv.1700263.

Zscheischler, J., Westra, S., Van Den Hurk, B.J.J.M., Seneviratne, S. I., Ward, P.J., Pitman, A., AghaKouchak, A., Bresch, D.N., Leonard, L., Wahl, T. and Zhang, X. (2018) Future climate risk from compound events. *Nature Climate Change*, 8, 469–477. https://doi.org/10.1038/s41558-018-0156-3.

**SUPPORTING INFORMATION**

Additional supporting information may be found in the online version of the article at the publisher’s website.

**How to cite this article:** Páscoa, P., Gouveia, C. M., Russo, A., & Ribeiro, A. F. S. (2022). Summer hot extremes and antecedent drought conditions in Australia. *International Journal of Climatology*, 42(11), 5487–5502. https://doi.org/10.1002/joc.7544