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Flash drought in Australia and its relationship to evaporative demand

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Abstract

Flash droughts can be distinguished by rapid intensification from near-normal soil moisture to drought conditions in a matter of weeks. Here, we provide the first characterisation of a climatology of flash drought across Australia using a suite of indices. The experiment is designed to capture a range of conditions related to drought: evaporative demand describes the atmospheric demand for moisture from the surface; precipitation, the supply of moisture from the atmosphere to the surface; and evaporative stress, the supply of moisture from the surface relative to the demand from the atmosphere. We show that regardless of the definition, flash droughts occur in all seasons. They can terminate as rapidly as they start, but in some cases can last many months, resulting in a seasonal-scale drought. We show that flash-drought variability and its prevalence can be related to phases of the El Niño–Southern Oscillation, highlighting scope for seasonal-scale prediction. Using a case study in southeast Australia, we show that monitoring precipitation is less useful for capturing the onset of flash drought as it occurs. Instead, indices like the Evaporative Demand Drought Index and Evaporative Stress Index are more useful for monitoring flash-drought development.

1. Introduction

Flash drought distinguishes a subset of droughts that are differentiated by a sudden onset with rapid intensification (Svoboda *et al* 2002). A deficit in precipitation is a prerequisite for drought development, but the severity and speed of development of flash drought are typically influenced by other environmental factors: for example, high temperatures, low humidity, strong winds, and clear skies. These lead to increased evaporative demand (E_0), compounding the lack of precipitation, and depleting soil moisture reserves through increased evapotranspiration (ET) where moisture is available to evaporate (Anderson *et al* 2013, Otkin *et al* 2013, 2018a). The persistence of these weather anomalies for weeks to months can deplete near-surface moisture, resulting in a transition from energy-limited to water-limited ET, increasing vegetation stress, and leading to the

rapid emergence of drought (Ford *et al* 2015, Ford and Labosier 2017, Otkin *et al* 2018a).

To date, flash droughts have typically been identified by examining large and rapid changes in one or more metrics that reflect changes in sub-surface soil moisture. Usually, definitions have some condition that the metric should indicate a state of drought following the period of rapid change, for example falling to below the 20th percentile after two, four, or eight weeks (Svoboda *et al* 2002). These definitions exclude short periods of rapid deterioration that do not lead to drought impacts, while including periods when the initial conditions are near normal (Otkin *et al* 2018a).

Ford and Labosier (2017) used 0–40 cm soil moisture observations to assess flash drought in the United States. They provided a definition whereby the soil-moisture percentile (where higher percentiles indicate wetter soils) for a given location changed from

above the 40th percentile to below the 20th percentile over a 20-day period. However, soil-moisture observations at the appropriate level for vegetation growth (i.e. the root zone) are often sparsely available in time and space, particularly for Australia. Consequently, Otkin *et al* (2013) and Otkin *et al* (2018a) have advocated for the use of the evaporative stress index (ESI, Anderson *et al* 2013) as a viable alternative to direct soil moisture observations. The ESI expresses the ratio of ET to E_0, estimated as reference evapotranspiration, as standardised anomalies and reflects changes from energy-limited conditions to water-limited conditions, showing the transition from moisture-rich to moisture-depleted environments (Otkin *et al* 2013, 2018a, 2019, Christian *et al* 2019). Pendergrass *et al* (2020) proposed using the evaporative demand drought index (EDDI, Hobbins *et al* 2016), based on standardised anomalies of E_0 from reference evapotranspiration. When increasing, the EDDI highlights changes toward moisture-stressed environments. The Pendergrass *et al* (2020) definition requires an increase toward drying in EDDI of 50 percentiles over two weeks, which must be sustained for at least a further two weeks. In this study, the experiment is designed to use a number of different indices to distinguish between the moisture supply at the surface (Standardised Precipitation Index; SPI), moisture demand of the atmosphere from the surface (EDDI), and moisture supply from the surface to the atmosphere (ESI). A similar approach was taken by Hoffmann *et al* (2021) in the evaluation of flash-drought detection globally in CMIP5 models.

Australia is drought-prone and susceptible to periods of high evaporative demand. Agricultural productivity makes up approximately 2.2% of Australia's GDP and 11% of its goods and services export (2018–2019, Jackson *et al* 2020). Flash droughts present a significant risk to agricultural productivity (Otkin *et al* 2018b, Jin *et al* 2019). However, only Nguyen *et al* (2019) and Nguyen *et al* (2021) have examined flash drought in Australia. In both studies, they used the ESI to identify flash droughts in northeast Australia in January 2018 and east Australia in June 2019, respectively. Thus, there remains a need to characterise flash drought across Australia. Here, we present the first examination of Australia—wide flash drought, using a suite of indices that encode its connections to evaporative demand, evapotranspiration, and precipitation. Flash droughts are initially identified using the Standardised Soil-moisture Index (SSI), and their detection is then tested using the EDDI, ESI, and SPI. We also present a case study of a flash drought in an important cropping region in southeast Australia in the spring of 2015, and use this to highlight the importance of monitoring evaporative demand as an early warning tool for flash drought.

2. Data and methods

In order to compare land-surface and atmospheric variables from a consistent source, we use reanalysis data from the European Centre for Medium-range Weather Forecasts (ECMWF) ERA5 global reanalysis (Hersbach *et al* 2020), from 1979 to 2019 at a spatial resolution of approximately 31 km. ERA5-Land, from which soil moisture data are obtained, is derived from the land component of ERA5, rerun at an enhanced spatial resolution of approximately 9 km, and is available from 1981 (Copernicus Climate Change Service 2019). All reanalysis products show biases in their representation of the water balance (Lorenz and Kunstmann 2012). However, there are smaller errors in ERA5 than other reanalysis products when compared to *in situ* observations (e.g. Mahto and Mishra 2019, Li *et al* 2020). Also, biases in the data are eliminated when looking at anomalies, as we do in the estimation of the drought indices used. The atmospheric variables, described below, are used to compute flash-drought indices based on evapotranspiration, evaporative demand, and precipitation.

Flash drought is identified from the ERA5-Land layer 2 (7–28 cm) soil moisture from 1981 to 2019 and compared to rapid changes in: the ESI, representing changes from energy-limited to water-limited conditions (Otkin *et al* 2018a); the EDDI, indicating changes in evaporative demand, which increases in drier conditions (Hobbins *et al* 2016); and the SPI (McKee *et al* 1993), which represents anomalous rainfall. The SPI is computed because Koster *et al* (2019) have highlighted precipitation deficits as the primary drivers of flash drought in the Northern Hemisphere. The SPI is used rather than the Standardised Precipitation-Evapotranspiration Index (SPEI) specifically to examine precipitation independently of any other variable. The experiment is thus designed to evaluate moisture supply at the surface (SPI), moisture demand of the atmosphere from the surface (EDDI), and moisture supply from the surface to the atmosphere (ESI). In the following section, these indices are described, including their use in definitions of flash drought.

2.1. EDDI formulation

The EDDI is a non-parametric percentile-based formulation of evaporative demand. Best practice requires the use of a fully physical function of radiative and meteorological forcings to calculate evaporative demand:

$$E_0 = f(T, q, R_n, U_z, P_a), \quad (1)$$

where T is temperature; q is specific humidity; R_n is downwelling shortwave radiation at the surface; U_z is wind speed; and P_a is atmospheric surface pressure. Here, we estimate evaporative demand (E_0) using the

American Society of Civil Engineers (Allen *et al* 2005) standardised reference ET equation, a widely accepted parameterisation of the Penman–Monteith equation (Monteith 1965). The EDDI is standardised using an inverse-normal approximation to obtain empirically derived probabilities (Abramowitz and Stegun 1965). This probability-based approach means that the EDDI can be usefully compared to other standardised indices (Farahmand and AghaKouchak 2015). A full description of the Penman–Monteith estimate of reference evapotranspiraton and the standardisation approach for EDDI is available in Hobbins *et al* (2016).

An EDDI value of zero indicates that the aggregated E_0 is equal to the climatological median value for that day of year. Negative EDDI values indicate wet anomalies, and positive values dry anomalies: drought intensity increases with increasingly positive EDDI. The EDDI can be estimated at a point, or calculated using spatial-mean E_0 over a particular region, and aggregated over daily to inter-annual time scales, as appropriate to the experimental criteria. Here, the EDDI is calculated at the grid-point scale, and a 14 day aggregation period is used, representing a dynamic, synoptic time scale. EDDI is then translated into wetness and drought categories based on the percentile ranks (see colour bar for figure 5(b)).

2.2. SSI, ESI, and SPI formulation

The non-parametric standardisation approach outlined in section 2.1 can be applied to other drought indices. In this way, the SSI for layer 2 (7–28 cm) which represents the upper level of root-zone soil moisture, SPI, and ESI are calculated for the same 14-day aggregation period used for the EDDI so that all are directly comparable.

The precipitation data is expressed as an accumulated daily total in units of mm day^{-1}, and the SPI calculated using the standardised approach outlined above for the EDDI.

The ESI (Anderson *et al* 2007) represents the land surface response to drought, and is calculated from the ratio of actual ET to E_0:

$$r_{\text{ET}} = \frac{\text{ET}}{E_0}. \tag{2}$$

Reference evapotranspiration or evaporative demand (denoted E_0 here) is calculated as for the EDDI. Actual or observed ET is calculated directly from ERA5's surface latent heat flux and expressed in units of mm day^{-1}. The ESI is then standardised following the same approach as the EDDI.

The soil-moisture data is expressed in units of kg m^{-2}, and the SSI is calculated using the same standardised approach as before.

2.3. Identification of flash drought

Flash droughts are identified in the SSI based on the definition of Ford and Labosier (2017). Here we require the 14-day aggregated SSI to decline from at or above the 40th percentile (near-normal conditions) to at or below the 20th percentile (moderate drought by US Drought Monitor definitions, Svoboda *et al* (2002)) in 14 days, and remain at or below the lower threshold for a further 14 days, in line with the EDDI definition of flash drought previously described. To identify flash droughts using the EDDI, ESI, and SPI, we apply a definition proposed by Pendergrass *et al* (2020) to all three indices. This requires a 50 percentile increase toward drying in the index over 14 days, sustained for at least another 14 days. In addition, we require that the test index at the end of the intensification period, i.e. on day 14, must fall above the 80th percentile (for EDDI) or below the 20th percentile (for ESI and SPI).
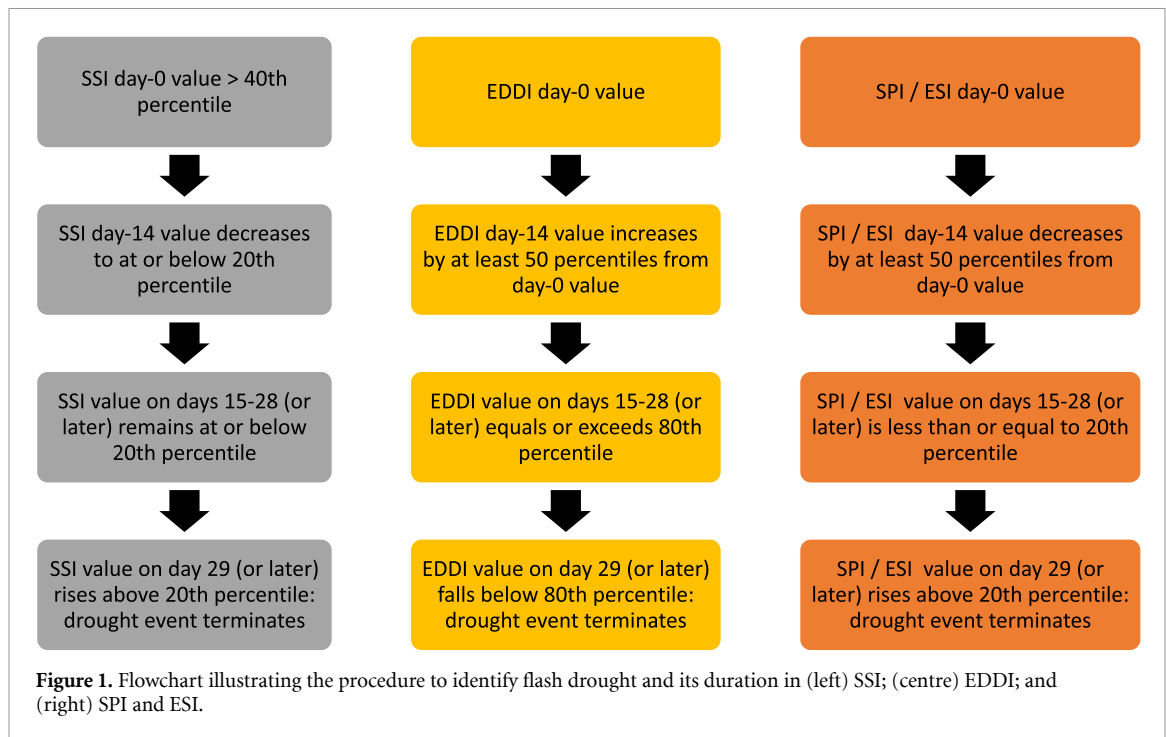
Hobbins *et al* (2016), Otkin *et al* (2018a), and Pendergrass *et al* (2020) focus the definition of flash drought on the sudden onset and rapid intensification as well as the actual condition of drought. Other studies include criteria for flash drought termination in their definitions. For example, Yuan *et al* (2019) and Mahto and Mishra (2020) impose termination criteria to exclude seasonal or persistent long-term droughts. See Lisonbee *et al* (2021) for a review of flash-drought definitions. Here we have followed the arguments of Hobbins *et al* (2016), Otkin *et al* (2018a) and Pendergrass *et al* (2020) and avoided explicit termination criteria that would limit duration; instead, the drought is considered to end as soon as the test index falls below the 80th percentile again (for EDDI) or rises above the 20th percentile (for SSI, ESI, and SPI); see figure 1.

3. Results

The flash droughts computed using the SSI are defined as 'truth' for the purposes of comparison. We first describe the nature of flash drought in Australia, and compare the efficacy of the SPI, ESI, and EDDI, described in section 2, in the detection of the SSI flash droughts. Second, we examine the development of a 2015 flash drought in an important southeast Australian cropping region and provide insight into the role these indices could play in assessing the development of a real-world flash drought. Statistical significance is provided at the one-tailed 5% level in all cases.

3.1. Flash drought in Australia

Figure 2(a) shows a climatology of flash droughts detected using soil moisture. The plot shows the percentage of days in the period 1981–2019 on which an SSI flash drought is detected. The percentage of days includes every day in the at-least 28-day period covered by the definition above. The highest frequency of SSI flash droughts is in the wetter coastal regions of the southwest, southeast, and east of Australia, as well as Tasmania and the subtropical regions

Figure 1. Flowchart illustrating the procedure to identify flash drought and its duration in (left) SSI; (centre) EDDI; and (right) SPI and ESI.

of the north and northeast, where the largest variations in soil moisture typically occur (Pendergrass *et al* 2020). A region of high frequency in the arid inland region of central Australia is likely spurious, as observational data with which to constrain the reanalyses are sparse.
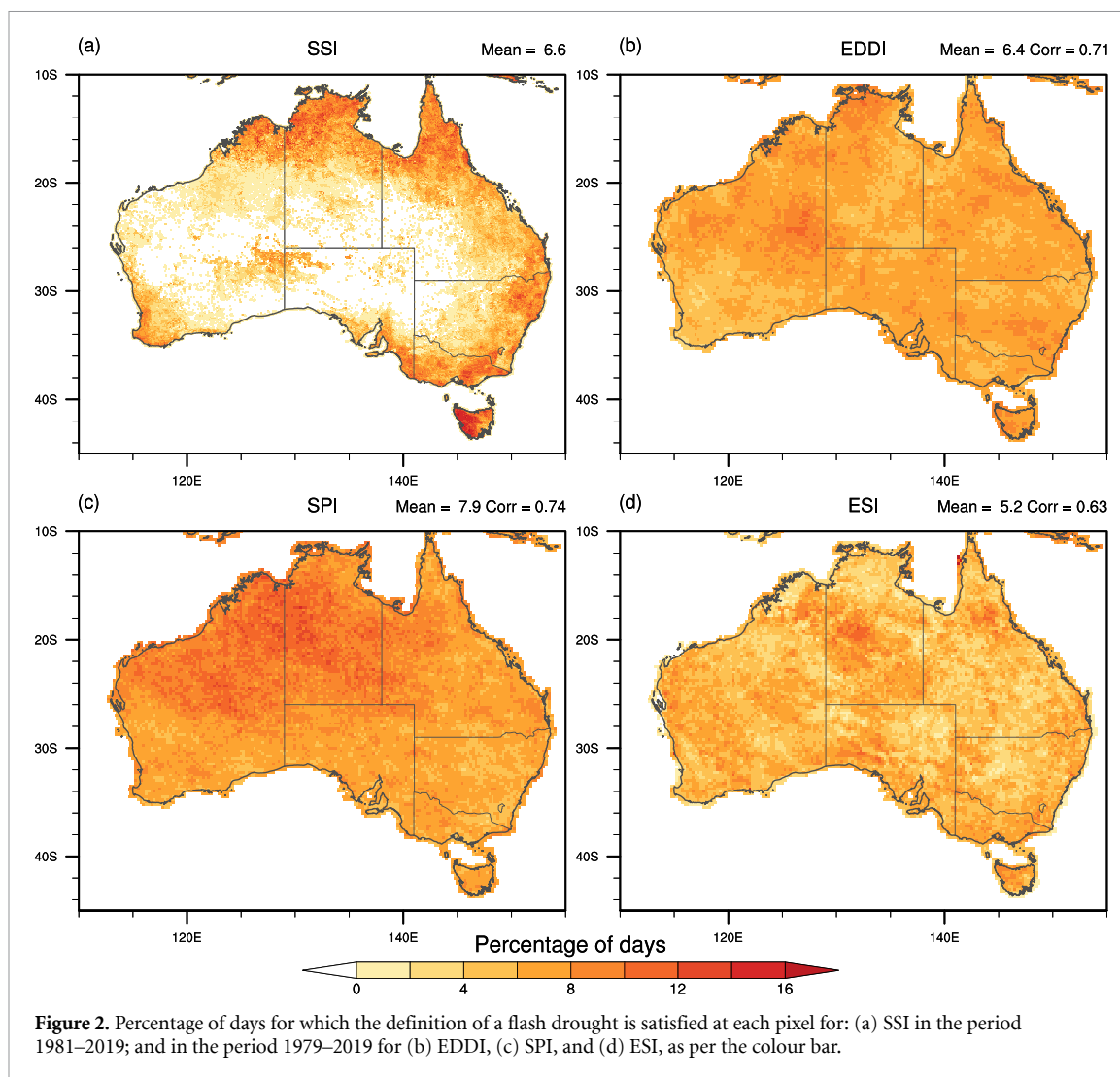
Figures 2(b)–(d) show the climatologies of flash droughts computed from the EDDI, SPI, and ESI respectively. The indices record similar mean numbers of flash droughts over Australia as the SSI, as shown at the top right of each panel, with values ranging from 5.2% to 7.9% of days in the climatology. However, the spatial patterns of flash droughts across the continent differ considerably, with the non-SSI metrics showing little spatial variability across the continent compared to the SSI. This is reflected in the pattern correlations between the SSI and each index which range from 0.63 for the ESI to 0.74 for the SPI. Note that the SSI was translated onto the coarser ERA5 grid prior to calculation of this pattern correlation. The differences in spatial patterns reflect the importance of land-surface properties to soil moisture, for example, the heterogeneous nature of the drainage properties of soil types. The above results show that the indices are more representative of SSI flash droughts in non-desert regions (figure 2).

Figure 3 shows the seasonal proportion of land pixels for which at least one flash-drought event is detected. SSI flash droughts are recorded in all seasons for both Australian and regional Australian analyses, including temperate and tropical parts of the country (not shown). SSI flash droughts are most common during the austral summer (December–February, DJF) and to a lesser extent, autumn (March–May, MAM) (figure 3(a)), when evaporative demand is

highest. The dominance of summer flash droughts is reflected in all drought indices. However, the relative frequencies of other seasons differ to those in the SSI (figures 3(b)–(d)). Larger areas are affected by flash droughts computed from the EDDI and SPI as compared to SSI droughts. Similarly, Hoffmann *et al* (2021) found that the SPI and the EDDI overestimate flash-drought frequency relative to the SSI in CMIP5 models. Significant increasing trends in the proportion of the continent affected by flash droughts computed using the EDDI range from 19% to 37% per decade (figure 3(b)), and likely reflect increasing temperatures. However, the lack of a trend in the SSI shows that any trend in evaporative demand is not having a significant effect on soil-moisture flash droughts (figure 3(a)).

While Otkin *et al* (2018a) and Pendergrass *et al* (2020) assert that flash droughts should have no characteristic duration in their definition, no study has explicitly examined the typical durations of flash drought. It is unclear whether flash droughts terminate as quickly as they onset, or how often they herald the onset of a longer drought. If the latter cases predominate, this could provide a significant avenue for improving seasonal-scale drought forecasting based on its onset by flash drought at sub-seasonal time scales (Pendergrass *et al* 2020).

Figures 4(a) and (b) show histograms of drought durations for all SSI flash droughts in Australia, and for the Wimmera region in southeast Australia (see figures 5–7), for which we present a case study in section 3.2. For both regions, the majority of flash droughts are of short duration, lasting for about one month. However, all histograms are multi-modal. For example, summer (DJF) and autumn (MAM)

Figure 2. Percentage of days for which the definition of a flash drought is satisfied at each pixel for: (a) SSI in the period 1981–2019; and in the period 1979–2019 for (b) EDDI, (c) SPI, and (d) ESI, as per the colour bar.

flash droughts are the most frequent in the Wimmera. While the majority of these only last around one month, there are a significant number that last around six months or longer in summer, and over seven months in autumn. This represents several instances when flash drought in the Wimmera has onset in summer or autumn and remained in drought through the following winter and sometimes into spring. Thus, we show here that flash drought can be a catalyst for seasonal-scale drought. These findings are consistent with Nguyen *et al* (2019) and Nguyen *et al* (2021), who have shown two examples of flash drought in Australia that persisted into multi-month dry conditions.

The relationships between the SSI and the various drought indices highlight the skill those indices have in representing soil-moisture flash droughts. Correlations between the SSI and each index are computed at the grid-point scale (not shown), and between the seasonal proportional areas shown in figure 4(c). In all cases, the SPI shows the strongest and most significant correlations with the SSI, highlighting the ultimate dependence of flash drought on precipitation, as was also described by Koster *et al* (2019). The

ESI has the strongest relationships during the austral spring (September–November, SON) and summer (DJF) for the covariation in proportional area affected by flash drought (figure 3(d)), which are statistically significant year-round at the grid-point scale. The EDDI shows the weakest relationship with the SSI, although these are mostly statistically significant at the grid-point scale (not shown), but not between the time series of proportional areas (figure 4(c)). We note that this does not indicate that evaporative demand is unimportant for flash drought, it simply shows that rapid changes in evaporative demand are mostly unrelated to flash drought. Hobbins *et al* (2016), Otkin *et al* (2018a) and Hoffmann *et al* (2021) have previously highlighted the high rate of false positives in the detection of flash drought using the EDDI and this is likely reflected in the correlations here.

Seasonal-scale Australian droughts have some predictability because of their strong relationship to the El Niño–Southern Oscillation (ENSO). As described earlier, flash drought leads to seasonal-scale drought in some instances. Thus, we now examine the relationship between ENSO and flash drought.
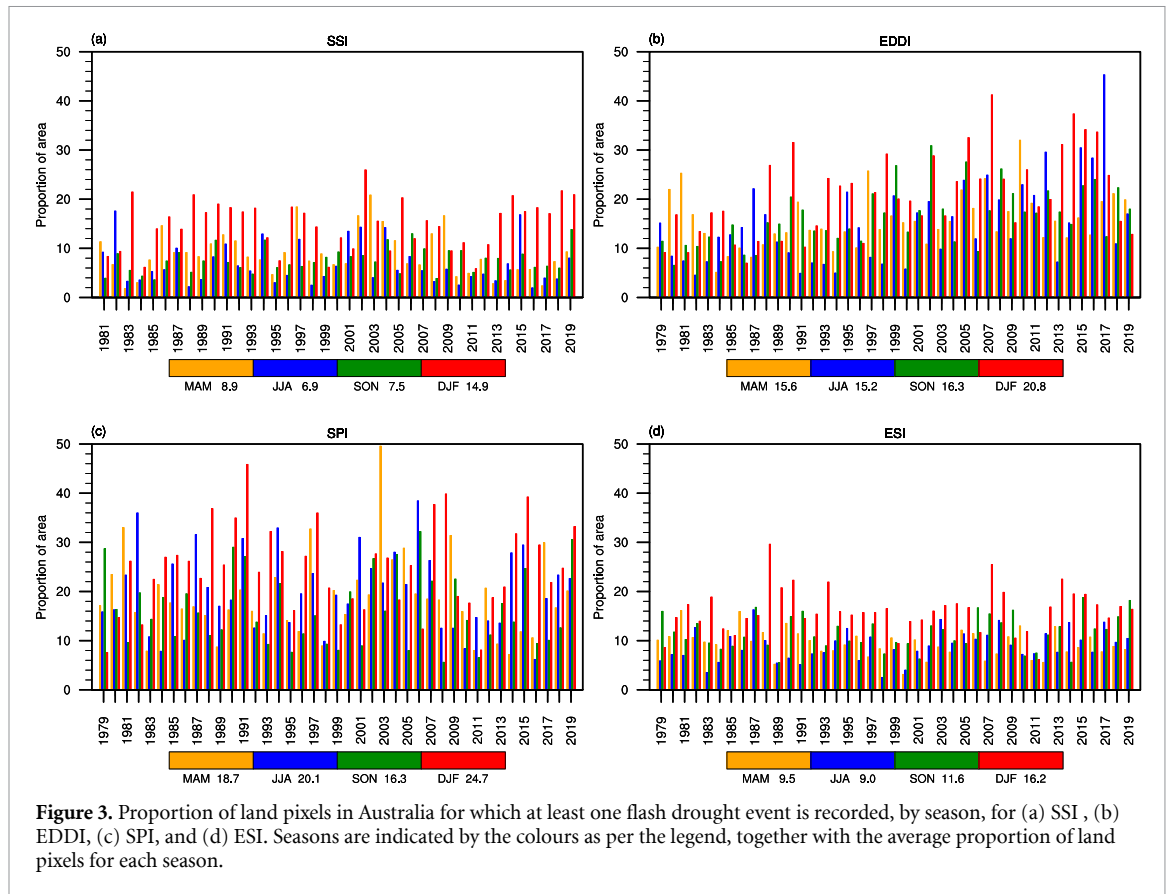
Figure 3. Proportion of land pixels in Australia for which at least one flash drought event is recorded, by season, for (a) SSI , (b) EDDI, (c) SPI, and (d) ESI. Seasons are indicated by the colours as per the legend, together with the average proportion of land pixels for each season.

Correlations between the proportional area time series of each drought index and the Niño 3.4 index (Trenberth 1997) are shown in figure 4(d) for Australia, the Murray–Darling Basin, which is responsible for a large proportion of Australia's primary productivity, and the Wimmera, described later in section 3.2. In most cases, the proportional-area time series of the SSI, SPI, and ESI show statistically significant relationships to winter (June–August, JJA) and spring (SON) Niño 3.4. The positive correlations indicate that El Niño events are associated with a larger area affected by flash drought computed from each of these indices. This relationship is of a similar sign and strength to that of El Niño and seasonal precipitation, suggesting that flash-drought variability is simply a response to precipitation variability, with the ESI reflecting the associated water-limited conditions. The connection to precipitation is confirmed by the lack of any significant relationship with the time series computed from the EDDI during winter and spring.
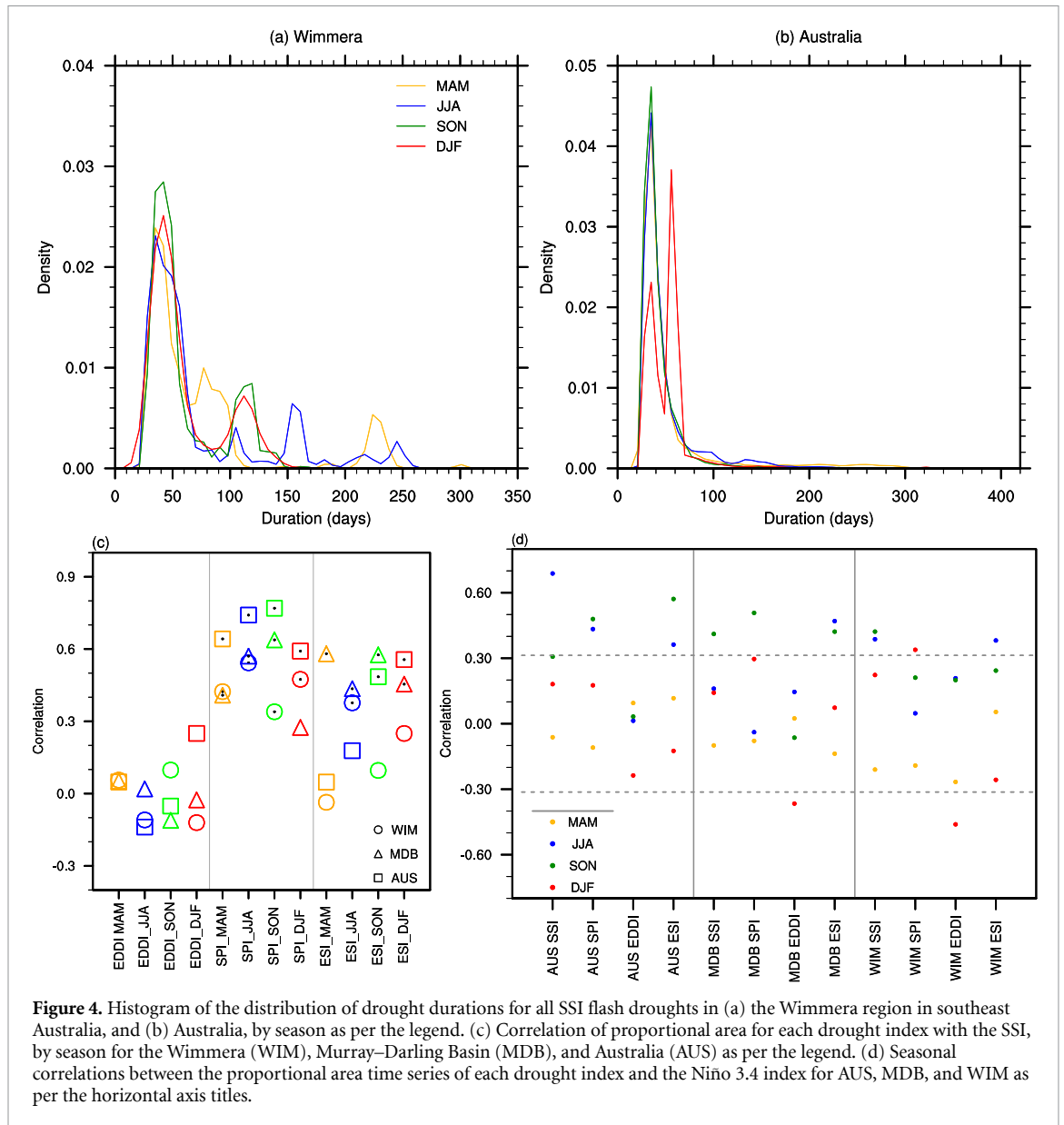
Interestingly, the Niño 3.4 index explains up to around 20% of the variance in the area affected by rapid changes in the EDDI during DJF in the Murray–Darling Basin, and the Wimmera. The relationship implies that La Niñas are significantly associated with periods of rapid change in evaporative demand during DJF. Although this seems counterintuitive, given that the relationship between seasonal-scale drought and ENSO is with the El Niño phase (Chiew *et al* 1998), there is evidence that La Niñas are associated

with heat waves in southeast Australia, particularly over the Wimmera region. This is because of a physical connection to tropical cyclones, which are more likely to occur during a La Niña (Parker *et al* 2014).

3.2. The role of evaporative demand in a southeast Australian flash drought

The Wimmera region is located in southeast Australia (see boundaries in figures 5–7). It is primarily a cropping region, producing cereals, pulses, and oilseeds (figure S1 (available online at stacks.iop.org/ERL/16/064033/mmedia)) and has no significant topography (figure S2). In 2015, winter was drier than normal, associated with a strong El Niño (Bureau of Meteorology 2015). There was some rain with reasonable accumulations (15–25 mm) during the first week of September. A warm spell began in mid-September, which intensified into a severe heat wave by early October, with temperatures above 35°C persisting for several days in some areas. By the end of October, the Wimmera had descended into severe or extreme drought conditions, defined as sub-surface soil moisture below the 10th and 5th percentiles, respectively. A media report described the event as devastating for pulse crops. Wheat production was cut by an estimated 23%, with a forecast $500 million loss in potential yields (Grindlay 2015).

The progression of this event, which changed from drier-than-normal conditions to severe or extreme drought within 3–4 weeks, is typical for a

Figure 4. Histogram of the distribution of drought durations for all SSI flash droughts in (a) the Wimmera region in southeast Australia, and (b) Australia, by season as per the legend. (c) Correlation of proportional area for each drought index with the SSI, by season for the Wimmera (WIM), Murray–Darling Basin (MDB), and Australia (AUS) as per the legend. (d) Seasonal correlations between the proportional area time series of each drought index and the Niño 3.4 index for AUS, MDB, and WIM as per the horizontal axis titles.
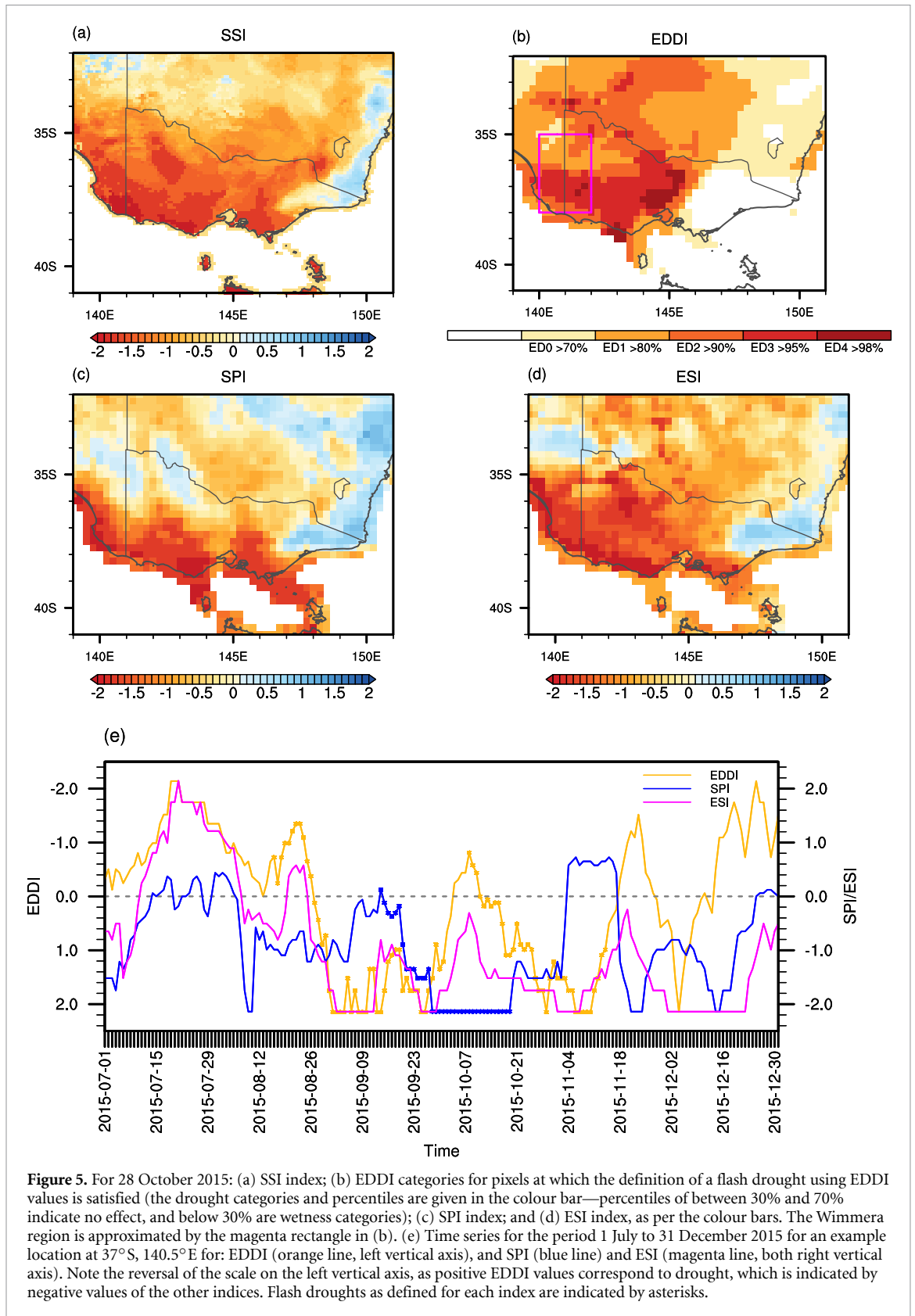
flash drought. Figures 5(a–d) show the state of the four indices examined in section 3.1 at the end of October 2015, after the drought has onset. The ESI, EDDI, and SPI all indicate a flash drought, which is further highlighted in the time series in figure 5(e). Note that the SSI shows flash drought for the most northerly part of the region only (figure 6). This is because elsewhere in the region, soil moisture was slightly below the threshold of the 40th percentile at the onset of the event. However, it was above the 35th percentile everywhere but the far south of the region (not shown). For comparison, figure S4 replicates parts of figure 5 using 30day aggregated EDDI and ESI calculated from the Australian Bureau of Meteorology's Australian Water Resource Assessment Landscape (AWRA-L) model, which assimilates station- and satellite-based observational data to generate ET fluxes with high spatial and temporal resolutions. The consistency between AWRA-L and ERA5 in this case

study shows that the analysis is robust to the choice of dataset.

The role of evaporative demand in the Wimmera flash drought is presented in figures 6 and 7, which show the progression of the meteorological conditions of the 2015 event. Figure 6(a) shows the cool conditions during the first week of September, with specific humidity and mean sea level pressure (MSLP) near average, and surface net shortwave solar radiation (SSR) below average (figure 7(a)), suggesting normal evaporative demand. Soil moisture across the Wimmera is between the 35th and 40th percentile, indicating possible replenishment of this soil layer from the rain event in the first week of September (figure 6(b)).

Meteorological conditions change in the week starting 22 September and become conducive to high evaporative demand (figure 6(d)). The surface air mass becomes very dry with specific humidities below

Figure 5. For 28 October 2015: (a) SSI index; (b) EDDI categories for pixels at which the definition of a flash drought using EDDI values is satisfied (the drought categories and percentiles are given in the colour bar—percentiles of between 30% and 70% indicate no effect, and below 30% are wetness categories); (c) SPI index; and (d) ESI index, as per the colour bars. The Wimmera region is approximated by the magenta rectangle in (b). (e) Time series for the period 1 July to 31 December 2015 for an example location at 37°S, 140.5°E for: EDDI (orange line, left vertical axis), and SPI (blue line) and ESI (magenta line, both right vertical axis). Note the reversal of the scale on the left vertical axis, as positive EDDI values correspond to drought, which is indicated by negative values of the other indices. Flash droughts as defined for each index are indicated by asterisks.
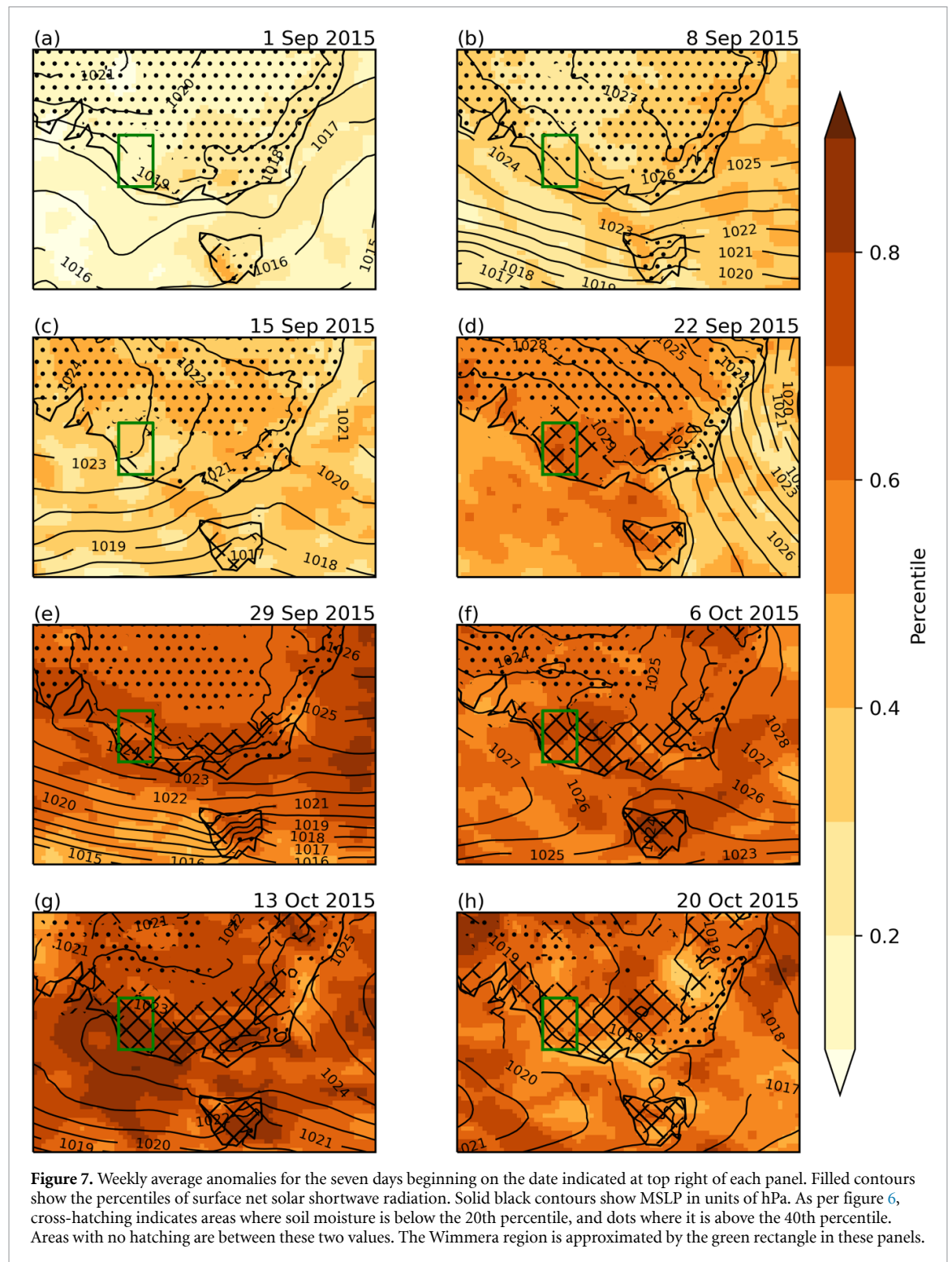
the 20th (40th) percentile in the north (south) of the Wimmera. Soil moisture rapidly declines to below the 20th percentile across the region. The MSLP is uniformly much higher than average, with a large surface anticyclone centred slightly to the west of the region, leading to increased incoming SSR (figure 7(d)).

During the week beginning 29 September surface temperatures remain elevated with anomalies of 7°C–8°C across the region, and 5°C–6°C for the Wimmera. The dry air mass remains (figure 6(e)), and SSR is higher than normal, at the 60th–70th percentile (figure 7(e)). For the next three weeks, soil moisture

Figure 6. Weekly average anomalies for the seven days beginning on the date indicated at top right of each panel. Filled contours are 2 m temperature anomaly per the colour bar. Grey dashed contours show percentiles of specific humidity anomaly. Solid black contours show percentiles of MSLP anomaly. Cross-hatching indicates areas where soil moisture is below the 20th percentile, and dots where it is above the 40th percentile. Areas with no hatching are between these two values. The Wimmera region is approximated by the green rectangle in these panels.

evaporates further to below the 10th percentile across most of the Wimmera by the week beginning 13 October (figure 6(g)) and to below the 5th percentile by the week beginning 20 October (figure 6(h)). A ridge of high pressure dominates the region from 22 September to 20 October (figures 6(d)–(h)). Figure S3 shows the changes in the Normalised Difference Vegetation Index (NDVI) during this flash drought.

Figure 5(e) shows the value of the various indices for the identification and monitoring of flash droughts. The EDDI and the ESI reflect the initial period of rapid intensification, however only the EDDI flags the event as a flash drought. This suggests that, at least in some cases, the EDDI can be an effective pre-warning tool for flash drought. Although the SPI was shown to be a useful indicator for flash

Figure 7. Weekly average anomalies for the seven days beginning on the date indicated at top right of each panel. Filled contours show the percentiles of surface net solar shortwave radiation. Solid black contours show MSLP in units of hPa. As per figure 6, cross-hatching indicates areas where soil moisture is below the 20th percentile, and dots where it is above the 40th percentile. Areas with no hatching are between these two values. The Wimmera region is approximated by the green rectangle in these panels.

drought variability in section 3.1, it does not provide any useful pre-warning for flash drought in this case because of its sensitivity to the rainfall event at the beginning of September.

4. Conclusion

This study is the first to provide a climatology that characterises flash drought across Australia, and to compare various indices for their utility in

flash-drought prediction and monitoring. The use of indices that distinguish between the effects of supply and demand in the characterisation of flash drought is unique to this study. Our analysis reveals that flash droughts can occur year-round. This can either be as a brief drought, or they can be the catalyst for a longer-term drought lasting many months. As with other studies, we show that precipitation variability is a primary indicator of flash-drought variability (Koster *et al* 2019). However, using a case

study, we also show that precipitation-based drought indices are not necessarily informative for short-term (weeks) monitoring of flash-drought development. The ESI provides a reasonable representation of flash-drought variability and highlights the onset of the flash drought in the Wimmera (Otkin *et al* 2018a, Nguyen *et al* 2019). Despite its high false alarm rate (Hobbins *et al* 2016, Hoffmann *et al* 2021), we demonstrate that the rapid increases in evaporative demand highlighted by the EDDI can provide an early warning tool when used for monitoring in conjunction with other indices, like the ESI or direct soil-moisture observations. However, we provided an example of one case study only. Assessing the vulnerability to flash drought, and the utility of drought indices for prediction and monitoring, for different regions and seasons is essential to guide future efforts to target prediction and early warning, and are worthy of further research.

Data availability statement

The ERA5 and ERA5-Land data utilised in this study are available from ECMWF (see Copernicus Climate Change Service (2019)).

The data that support the findings of this study are available upon reasonable request from the authors.

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