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Using the evaporative stress index to monitor flash drought in Australia

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Abstract

Flash drought is a term and concept that has gained increasing attention in the research literature and media since it was first coined in the United States in the early 2000s to describe a drought that has undergone rapid intensification. In Australia the term has recently been used in reference to the 2017/18 drought in eastern Australia. Due to its rapid intensification, the impacts of flash droughts will likely occur too quickly for many of the usual drought-coping mechanisms to be deployed. This study proposes the use of the evaporative stress index (ESI), the standardized anomaly of the actual evapotranspiration to potential evapotranspiration ratio, to identify flash droughts in Australia computed using daily outputs from the Bureau of Meteorology's land surface water balance model AWRA-L. The case study of the January 2018 flash drought in eastern Australia is used to assess and demonstrate the suitability of the ESI. Results show that the ESI accurately highlighted the event and offered potential for flash drought pre-warning by a few weeks. In addition, the availability of long term high-resolution outputs from AWRA-L offers the ability to investigate multiple flash drought events in detail for greater understanding and to inform stakeholders.

1. Introduction

Flash drought is a relatively new term that has emerged out of the United States (US), first introduced by Svoboda *et al* (2002), but only coming into more common usage in the US in recent years in response to devastating droughts that developed rapidly during 2011 and 2012 (Otkin *et al* 2018). Although somewhat contrasting definitions for flash drought have been used in both the research literature and media, the review of Otkin *et al* (2018) strongly advocates that this type of drought should be a subset of all droughts that is differentiated by its rapid intensification. That is, as has been succinctly stated recently in the Australian media, 'the speed at which impacts are felt is the flash drought's defining feature' (Doyle 2018). This usage is consistent with what was originally intended when the term was coined by Svoboda *et al* (2002), who aimed to draw attention to the unusually rapid intensification of some droughts. Further, Otkin *et al* (2018) argue that the term flash drought can be seamlessly applied to all types of drought: meteorological, agricultural, hydrological, socioeconomic, and ecological. For example, if the impacts of a hydrological drought are felt much more rapidly than usual at a given location, then this period of rapid intensification should be classified as a 'flash' hydrological drought. Similarly, agricultural flash drought occurs when a farmer suddenly finds their farm in drought due to rapid drought intensification. Importantly, the farmer would likely not have enough time to prepare for such a rapidly developing drought, perhaps by selling stock, obtaining hay, supplying water, or deciding not to grow a crop. As defined above, flash droughts have no restriction on their duration, and Otkin *et al* (2018) propose that the term 'flash drought' should be reserved for the time period during which the rapid intensification occurred. Taking these examples, the 'flash' part of the definition is relative to the type of drought and needs to be scaled accordingly.

In this paper, our interest in flash drought centres on its impacts on vegetation and the animals that depend on this vegetation, such as livestock. This includes both vegetation that has been planted or modified for agriculture, and the vegetation of near-natural ecosystems such as native grasses and shrubs that are used for livestock grazing across vast areas of Australia. As described by Otkin *et al* (2018), the typical progression during such a flash drought is for a period of greatly enhanced evaporative demand to initially cause an increase in actual evapotranspiration (ET; the sum of evaporation from soil and transpiration from vegetation), subsequently followed by a period of rapidly decreasing soil moisture (SM) through its loss to the atmosphere and drainage with no replenishment by precipitation. This causes a transition into water-limited conditions with reduced actual ET, and the subsequent emergence of visible signs of vegetation moisture stress. For agricultural or ecological flash drought to occur, Otkin *et al* (2018) point out that more than just a precipitation deficit, which is a common feature of all droughts, will likely be required. A combination of high temperatures, low humidity, strong winds, sunny skies, and antecedent dry soils along with low precipitation can produce a flash drought that impacts the vegetation that humans and other animals depend on. For the rest of this paper our discussion focuses on agricultural flash drought.

How should we best monitor the above-described flash drought? Otkin *et al* (2018) argue that a requirement for identifying flash drought is to first choose a drought index that is sensitive to relatively rapid changes in SM, ET, evaporative demand, and/or vegetation health, and then assess changes in that index during periods of a few weeks. When the index shows a relatively large (relative to that location for that time of year) change leading to conditions that are impactful enough to be considered drought, then a flash drought is said to occur.

Several drought indices that potentially satisfy the above criteria already exist. They include the SM-based indices of Hunt *et al* (2009, 2014), Ford *et al* (2015), and Ford and Labosier (2017). For example, Ford and Labosier (2017) define flash drought based on SM percentiles for a given location dropping from above the 40th percentile to below the 20th percentile over a 20 d period. However, by focussing only on SM, this index misses the earlier signs in the typical flash drought progression that come from the increase in the evaporative demand, as described above. The evaporative demand drought index (EDDI) of Hobbins *et al* (2016) addresses this issue and therefore potentially provides early warning of flash drought. However, as Otkin *et al* (2018) point out, false alarms for flash drought are possible when solely using EDDI since there are some situations in which higher evaporative demand is at least partially offset by near to above-normal precipitation. Another approach has been to use a combination of precipitation, temperature, and SM in an index, as shown by Mo and Lettenmaier (2015, 2016). However, the specific combination and thresholds used by Mo and Lettenmaier (2015, 2016) are argued by Otkin *et al* (2018) to not represent flash drought as defined above.

Noting the issues with the above-described indices, in this study we have chosen to focus on the evaporative stress index (ESI; Anderson *et al* 2011, 2013a, 2013b), defined as the standardized anomaly of the ratio of the actual ET to the potential ET (PET), where the PET is the theoretical evapotranspiration that would occur if the surface was well supplied with water. PET is therefore a measure of the evaporative demand of the atmosphere. By including both the ET and PET, the ESI has the advantage of being sensitive to all aspects of the surface moisture supply and demand, and is therefore dependent on precipitation, SM, plant and land characteristics, humidity, wind speed (WS), air temperature, and net radiation. During a flash drought event, the ESI rapidly decreases, initially because of the increased PET, but then also due to the subsequent decrease in actual ET as the surface water supply becomes limited. The ESI has become a popular variable for consideration in drought monitoring in the US (e.g. https://drought.gov/drought/data-maps-tools/agriculture) with studies by Otkin *et al* (2013, 2016, 2018) and Anderson *et al* (2016) showing the usefulness of the ESI for pre-warning of flash drought as measured by the US Drought Monitor and crop conditions in the Americas.

Here we investigate the usefulness of the ESI for monitoring and responding to flash drought over Australia, a current key knowledge gap for agriculture in Australia. Unlike the ESI of the US-authored studies mentioned above, which estimate the ESI using land surface temperature measurements from geostationary satellites, here we compute the ESI using the ET and PET outputs of a land surface water-balance model analysis of Australia. Section 2 of this paper provides a brief description of the land surface model, its inputs, assumptions, and the details of the ESI computation. Section 3 presents results applied to the recent 2017–2019 drought in eastern Australia and considers which periods of this evolving event could be classified as flash drought, with on-the-farm evidence of the identified flash drought impacts. Concluding remarks are provided in section 4.

2. Data and method

The computation of ESI necessitates ET to capture the available SM and PET to reflect the evaporative demand. These two variables are derived from inputs of precipitation, solar radiation, temperature and WS from the Bureau's one-dimensional, 0.05° grid-based landscape water balance model over Australia (AWRA-L) version 6 that has a semi-distributed representation of the soil, groundwater and surface water stores. AWRA-L has been operational since late 2015 and outputs daily gridded SM, runoff (RO), ET, and deep drainage in real-time and back to 1911. A detailed description of the model is given by Frost *et al* (2018). PET is calculated according to the Penman (1948) equation which combines the effects of net radiation and the vapour pressure deficit, whereas ET is the sum of evaporation and transpiration in the model. The ESI and its standardized change anomalies are computed as follows:

(i) Compute daily running means of ET and PET over 2-, 4-, and 8-week windows

(ii) Compute the ET fraction: $r_{\mathrm{ET}} = \frac{\mathrm{ET}}{\mathrm{PET}}$ for each of these running windows

(iii) Compute the standardized ESI:

$$\mathrm{ESI} = \frac{r_{\mathrm{ET}} - \langle r_{\mathrm{ET}} \rangle}{\sigma(r_{\mathrm{ET}})},$$

where $\langle r_{\mathrm{ET}} \rangle$ is the ET fraction climatology and $\sigma(r_{\mathrm{ET}})$ is the ET fraction standard deviation over a baseline period. Here we use the period 1975–2018, instead of the entire period available (i.e. back to 1911) because prior to 1975 the WS input used in AWRA-L was a constant climatology. In contrast, from 1975, the use of daily varying interpolated daily wind data (McVicar *et al* 2008) allows for more realistic estimates of PET and ET.

(iv) Compute standardized ESI change anomalies over 1-, 2-, 3-, and 4-week intervals:

$$\delta\mathrm{ESI} = \frac{d\mathrm{ESI}(w_i\_dw_j) - \langle d\mathrm{ESI}(w_i\_dw_j) \rangle}{\sigma(d\mathrm{ESI}(w_i\_dw_j))},$$

where $d\mathrm{ESI}(w_i\_dw_j)$ is the change of ESI averaged over $w_i = 2$-, 4-, or 8-wk windows at $dw_j = 1$-, 2-, 3-, or 4-wk intervals, $\langle d\mathrm{ESI}(w_i\_dw_j) \rangle$ is the ESI change climatology and $\sigma(d\mathrm{ESI}(w_i\_dw_j))$ is the ESI change standard deviation over the same baseline period as above. Together, this results in 12 different ESI change anomaly variables.

The average of the data over 2-, 4-, and 8-week windows helps to eliminate short-term fluctuations in these variables due to synoptic-scale weather features. The ESI and δESI defined this way are standardized in order to put their time variation into a climatological framework compared to an absolute (non-standardized) index that is likely to have strong seasonal and regional dependence. Indeed, assuming the ESI can have larger weekly changes during the summer when evaporative demand is higher, the standardization process puts these changes into their proper climatological perspective. Further, the multiple ESIs and δESIs variables are used to capture the full range of flash drought intensities, including their period of rapid intensification.

In addition to ESI and δESI, we also use various other variables that are indicative of drought. These include:

1. Daily rootzone (0–1 m) SM and RO from AWRA-L
2. High resolution daily rainfall (PR) and surface air temperature (TS) gridded datasets from the Australian Water Availability Project (AWAP, Jones *et al* 2009)
3. Site based daily WS observations collated by the Bureau of Meteorology and interpolated to a 5 km resolution (McVicar *et al* 2008)
4. Vapour pressure (VP) which is estimated from the AWAP daily minimum temperature following the approximation given by Shuttleworth (1992) that assumes that the air is saturated at night when the temperature is at its minimum and that that VP remains constant throughout the day

Note that the AWAP and site-based datasets were also used as input to AWRA-L. Standardized anomalies of these additional variables are calculated over 4- and 8-week windows. The use of standardized anomalies specific to each grid point and time of year reduces potential impacts of systematic biases for those variables that are model outputs. AWRA-L was also assessed by Frost and Wright (2018) against various measurements or estimates of hydrological variables and compared to two other land-surface models to ensure its suitability for its purpose.

All indices and anomalies presented in this study were computed at daily resolution, with the indicated day corresponding to the last day of the given 2-, 4-, or 8-week window. We use the indices Ei, $i = 2, 4, 8$ to refer to the ESI averaged over the 2-, 4-, and 8-wk windows and Ei_jWK, $j = 1, 2, 3, 4$ to refer to the ESI change over 1-, 2-, 3-, and 4-wk intervals. Similarly, standardized anomalies of variables used in this study averaged over $i = 4$-, 8-week windows are indicated as above (SMi, ROi, PRi, TSi, WSi and VPi).

3. Results

3.1. General ESI behaviour

Figure 2 shows the daily evolution of ESI variability for the whole period of study over a single grid point representing the Gregory Downs cattle station indicated by the blue dot on figure 1. The ESI at this location seems to be insensitive to the length of averaging window, with all three timeseries (E2, E4 and E8) having comparable magnitude and variability. Positive ESI values are indicative of below normal evaporative vegetation stress, while negative ESI values indicate above normal evaporative stress. The ESI timeseries shows 8 peak values exceeding -2σ, all of which except one occurring prior to 1995. No apparent spurious jumps or long-term trend is evident in the timeseries but there is a marked interannual variability. This suggests that the ESI data is indicative

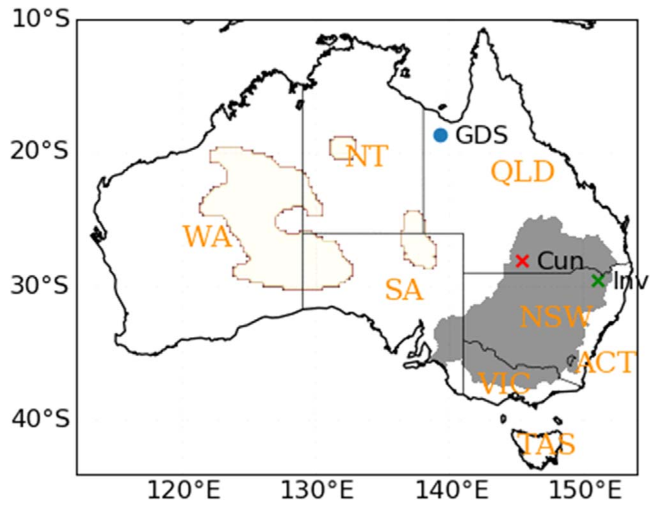

Figure 1. Australia including its six states and two territories: Western Australia (WA), Northern Territory (NT), Queensland (QLD), South Australia (SA), Victoria (VIC), New South Wales (NSW), Australian Capital Territory (ACT) and Tasmania (TAS). The blue dot indicates the Gregory Downs cattle station (GDS) located at 139.25°E–18.65°S. The red and green crosses indicate the towns of Cunnamulla (Cun) and Inverell (Inv) respectively. The grey shaded region represents the Murray Darling Basin (MDB). The areas contoured in brown are where there is an insufficient number of observing sites and will be masked out.

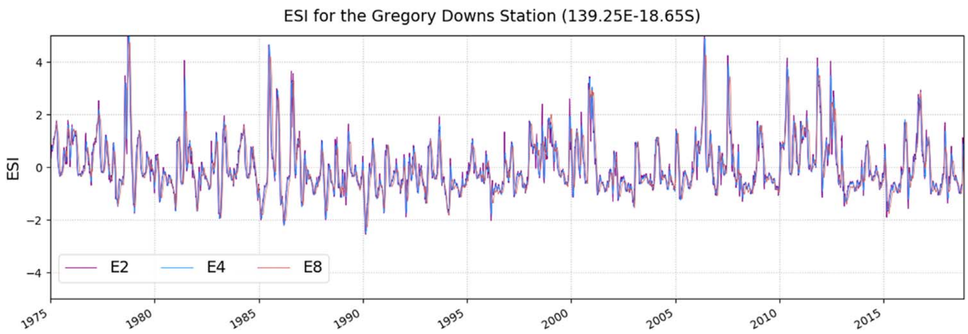

Figure 2. Timeseries of daily running mean of ESI averaged over 2-, 4-, and 8-week windows as labelled by E2, E4 and E8, respectively, for the Gregory Downs cattle station as indicated on figure 1.

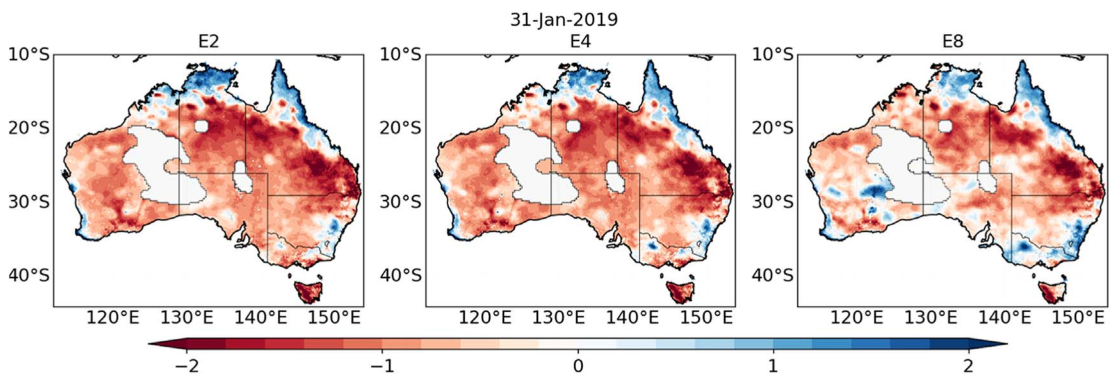

Figure 3. ESI averaged over 2-, 4-, and 8-week windows as labelled by E2, E4 and E8, respectively, for the 31 January 2019.

of physical processes, suggesting that the method may be suitable for flash drought monitoring for Australia.

Figure 3 shows a snapshot of E2, E4 and E8 for 31 January 2019. All three window-averaged ESIs are dominated by strong negative values exceeding -1σ across most of the country, indicating dry conditions for the previous 2–8 weeks, including in Tasmania. This is consistent with the recently-reported hottest January across Australia since official records began in 1910 and hottest mean temperature of 30.81 °C for any month (Bureau of Meteorology 2019a, 2019b). The heat was exacerbated by a lack of rainfall, except for coastal tropical Queensland. These extreme conditions have been the subject of media reports detailing the devastating fire

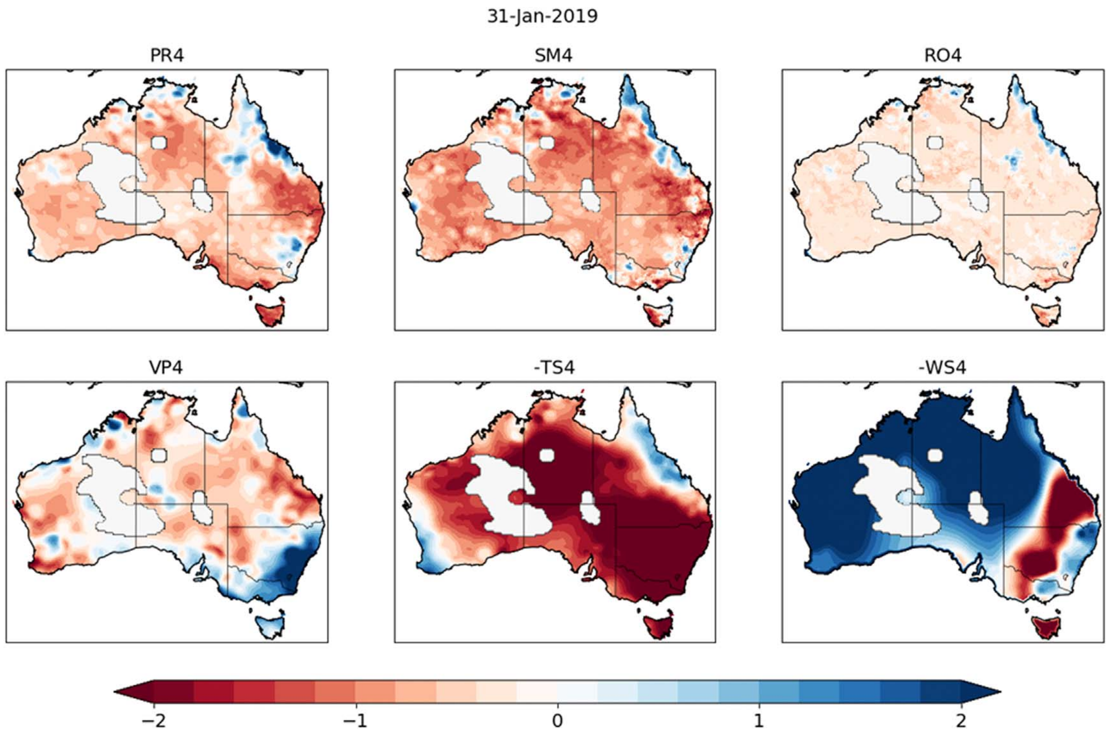

Figure 4. Standardized anomalies of (from top-left to bottom-right) precipitation (PR), root-zone soil moisture (SM), runoff (RO), actual vapour pressure (VP), surface air temperature (TS) and wind speed (WS) averaged over the 4-week window ending on the 31 January 2019. The sign of TS and WS is reversed to match the colour coding where red colours correspond to warm, dry, and windy conditions and vice-versa for blue colours.

outbreak in Tasmania contrasting with torrential rainfall and flash floods in coastal Queensland. These contrasting conditions are clearly depicted in the ESI.

The corresponding 4-wk window standardized anomalies of rainfall, soil moisture, RO, VP, surface temperature and WS are shown in figure 4. The exceptionally hot anomalies largely exceed 2σ across the country, with minor exceptions along coastal Western Australia and Queensland. In the same time, strong negative PR and SM anomalies largely exceed -1σ. During this exceptionally hot and dry event, RO anomalies exhibit the same negative patterns as rainfall, but VP differs somehow. Although dominated by negative values collocated with dry conditions, the strong positive VP anomalies in the southeast including Tasmania, stand out. The WS pattern is dominated by negative anomalies over most of the country except the band of strongly increased WS exceeding 2σ stretching from coastal southern Queensland to inland New South Wales and Tasmania.

Therefore, variability in ESI appears to be mainly driven by precipitation and temperature for this event. However, the impact of WS, VP and SM also play a role in specific regions such as Tasmania where there is a more complex interplay between all the forcing factors.

3.2. Flash drought event in Eastern Australia in early 2018

Most of Eastern Australia suddenly changed from wet conditions in December 2017 to dry conditions in January 2018. This rapid drought development attracted media attention with the term flash drought used to describe the sudden character of the event. An anecdotal report from a sheep farmer (Pers. Comm. Mrs. Kym Thomas) in Cunnamulla located in the northern Murray Darling Basin in Queensland (see map in figure 1), affirmed they had to remove all their livestock from their property in early 2018. The sheep producer further indicated that the number of sheep in Cunnamulla was at its lowest early 2018 than it had been in the past 100 years, with numerous trees dying and little to no grass cover. By June 2018, they reported that all types of trees were dying, leaving a desert-like landscape of sand dunes replacing the normally vegetated scene. In figure 5, we show monthly evolution from October 2017 through to April 2018 of the 4-week window standardized anomalies of ESI and associated forcing factors (the last day of each month which also corresponds to the last day of the 4-week window, is shown), to capture this flash drought event. The evolution month-by-month is described below.

1. In October 2017, very wet conditions are apparent across most of Queensland and northern New South Wales as highlighted by strong positive PR, SM and RO anomalies. During this month, high TS, positive VP and negative WS anomalies are widespread across the country. The ESI is either positive or mildly negative, with no indication of drought conditions.

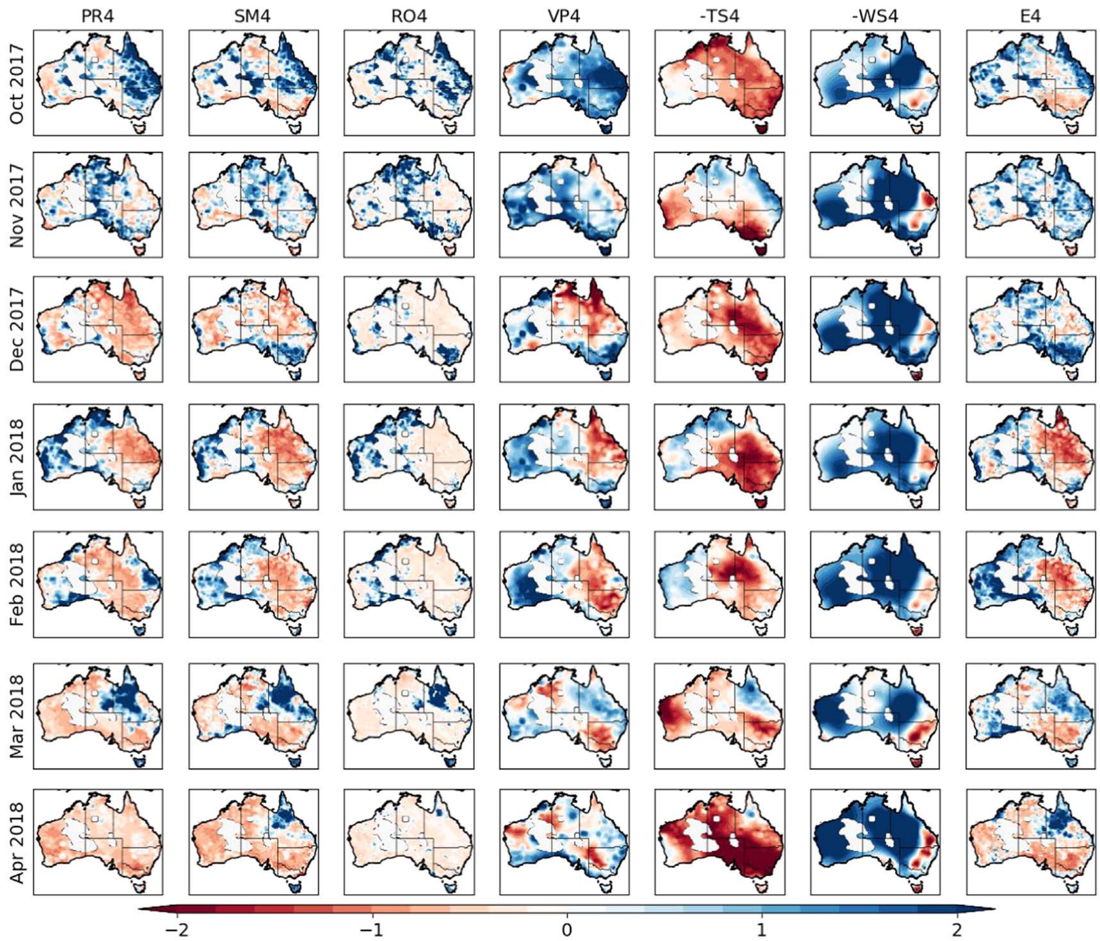

Figure 5. Monthly evolution of standardized anomalies of precipitation (PR4), root-zone soil moisture (SM4) runoff (RO4), actual vapour pressure (VP4), surface air temperature (TS4) and wind speed (WS4) and ESI (E4) averaged over 4-week windows from October 2017 to April 2018. The sign of TS and WS is reversed.

2. By November, the wet anomalies have shifted westward, leaving the east with mildly dry conditions (negative PR, RO and to a lesser extent VP). However, positive ESI persists in association with a slow change in SM.
3. In December, while most of the country had become dry and hot, persistent wet conditions in the south and west regions are indicative of above normal rainfall in November. The resulting ESI in those regions is positive where SM, RO and VP remain strongly positive, while in Queensland the ESI is weakly negative in association with combined dry and hot indicators.
4. In January 2018, dry and hot conditions have strengthened in most of Eastern Australia, except in eastern Victoria where wet conditions persist. The ESI captures the hot and dry anomalies with negative values exceeding -1σ in Queensland.
5. In February, most of Eastern Australia remains dry and hot, except for Tasmania and eastern Queensland where positive rainfall anomalies exceed 2σ, which dominate the SM and TS anomalies. Consequently, the ESI flips sign in these two regions. However, New South Wales and most of Queensland are still dominated by negative ESI exceeding -1σ.
6. In March, intense positive rainfall anomalies largely exceeding 3σ occur over northwest Queensland resulting in strong positive SM, RO and VP and cool anomalies. The same behaviour is observed in Tasmania. As such, ESI became positive all over Queensland and Tasmania. In contrast, New South Wales, Victoria and South Australia remain dry and hot and so ESI remains moderately negative.
7. In April, most of the country is marked by hot and dry conditions as indicated by negative PR and strongly positive TS anomalies. However, both SM and ESI remain negative in Queensland and Tasmania, stemming from the positive PR anomalies in March. Through the seven months shown here, WS shows little change. It mainly features positive anomalies near the east coast and negative anomalies elsewhere.

This evolution shows that ESI accurately captured the flash drought event across Eastern Australia in January

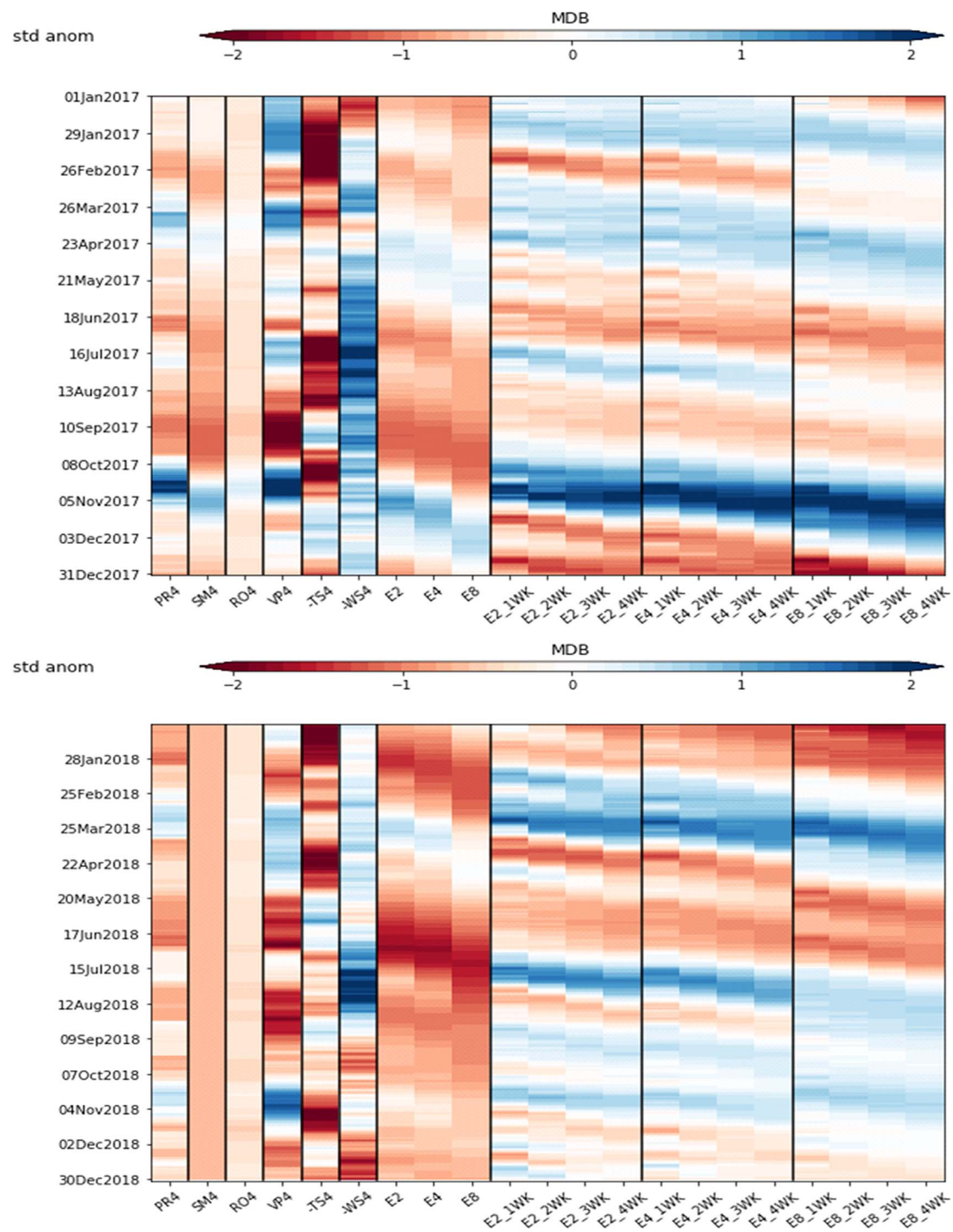

Figure 6. Daily evolution of (columns 1–6) standardized anomalies over 4-wk windows of precipitation (PR4), root-zone soil moisture (SM4) runoff (RO4), actual vapour pressure (VP4), surface air temperature (TS4) and wind speed (WS4), (columns 7–9) ESI over 2-, 4- and 8-wk windows and (columns 10–22) their change anomalies at 1-, 2-, 3- and 4-wk intervals, respectively. These anomalies are averaged for the northern MDB that lies within QLD as shown in figure 1.

2018 which is mainly driven by rapid change over the course of one month in TS, PR and SM. In contrast, WS shows little impact on ESI variability during this period.

3.3. Monitoring flash drought over Northern Australia

The time evolution of the standardized anomalies of PR, SM, RO, VP, TS and WS averaged over 4-wk windows and ESI at 2-, 4- and 8-wk windows along with ESI change anomalies at 1-, 2-, 3- and 4-wk intervals is shown in figure 6 for the northern part of the Murray Darling Basin that lies in Queensland (see figure 1). The time evolution spans over the 2017–18 period. This representation offers a more detailed evolution at daily intervals of the variables compared to the spatial view described in figure 5.

The flash drought event in January 2018 is clearly marked by a rapid change towards strongly negative ESI. Prior to this flash drought episode, very intense positive PR and VP anomalies started in early October 2017 and lasted for a month. This wet event is preceded by hot anomalies by about a week and followed by positive SM and RO by about 2 weeks. These conditions result in positive ESI through November–December, with a delay caused by the length of the averaging window (i.e. longer delay as the window length increases).

The rainfall anomalies start reversing sign from mid-November and increasing markedly (exceeding -1.5σ) through to February 2018. SM and VP follow the same behaviour with about a 1-week delay, however RO remains positive throughout the period. TS remain positive from mid-December 2017 to mid-May 2018, becoming markedly hot in January and April (exceeding largely 2σ). WS anomalies are negative throughout most of the period. E2 is the first ESI to become negative from mid-December followed by E4 about 1 week later and E8 about 2 weeks later. E2 reaches the maximum negative magnitude at the end of January followed by E4 and E8 with the same delay. This rapid change in ESI from a positive anomaly in November 2017 to a strongly negative anomaly in January 2018 qualifies for a flash drought event when applying the definition proposed by Otkin *et al* (2018).

The occurrence of positive rainfall anomalies following this flash drought event at the end of February 2018 and lasting a month marks a transition to a flash recovery (Otkin *et al* 2019) before leading to yet another flash drought event at the end of May 2018. As measured by the ESI, this later drought is most intense at the end of June and more protracted as it only shows signs of weakening at the end of October when another wet period occurs.

Otkin *et al* (2013) suggested that large negative ESI change anomalies are a good precursor for flash drought monitoring. Here we verify this by showing the ESI change anomalies at different intervals in the 12 right-hand columns of figure 6. Taking the evolution of E2 change anomalies at a 1-wk interval (E2_1WK), we note that E2_1WK becomes negative from mid-November 2017 until the end of January 2018. However, the two maxima seen in mid-November and mid-December did not give an indication for a flash drought to occur. This absence of a flash drought occurrence could be due to a too short of an interval (1-week) and perhaps too short of an averaging window (2-week). This hypothesis is confirmed when looking at ESI change anomalies at longer intervals. For example, the E4_4WK became negative in early December 2017 leading negative E4 by about 2–3 weeks and increasing to a maximum just one month later, when the first flash drought event of 2018 began. It again became negative in mid-April, again leading negative E4 for more than 4 weeks. In a case study, Otkin *et al* (2015) suggested that a combination of these Ei_jWK were necessary to monitor and predict flash drought more accurately. The results here are consistent with their conclusions.

4. Concluding remarks

This study aimed at applying the ESI method that has been extensively used in the US by Otkin *et al* 2018 (and refs. therein) to monitor flash drought in Australia. The novelty is that here we use high resolution ET and PET outputs from the Bureau of Meteorology's land surface water balance model AWRA-L v6 which is driven by high resolution station based and satellite-based observations (Frost *et al* 2018). The outputs are long term gridded data at 5 km horizontal resolution and at daily timescale over the period of 1911 to present day. However, we constrain our study back to 1975, the year when climatological wind data were replaced by real wind observations in AWRA-L, which still ensures a climatological base state of 44 years and the potential for realtime flash drought monitoring across Australia.

A disadvantage of using the ESI method is that it requires a sufficiently long term database for the standardisation process and daily timescale data. However, this is true for all drought monitoring datasets, and may be even more important for precipitation-based metrics given that the precipitation distribution is often non-normal. This should be less of a problem for the ESI because anomalies in the ET–PET ratio follow more of a Gaussian distribution.

Through a case study that highlights the exceptionally fast build-up of hot and dry conditions between December 2017 and January 2018 that occurred over most of Eastern Australia, the results presented here suggest that ESI might be suitable for monitoring flash drought in Australia. The flash drought event across Eastern Australia that occurred in January and June 2018 was also well represented in the ESI, confirming anecdotal evidence from a local sheep producer in southern Queensland. Further, the ESI change anomalies tend to lead a flash drought event by up to one month, consistent with results shown by Otkin *et al* (2013, 2015) over the US. In addition, this case study shows that even if rainfall and temperature are the main ingredients for any type of drought, including flash drought, certain regions can be strongly affected by other factors such as soil memory, soil capacity to store water and plant types, VP and WS. These factors may be playing a role in accelerating the build-up of a drought event leading to the type of drought discussed here.

The results presented here enable us to expand the ESI analysis to detect flash drought events for the entire period of 1975–2019 and at grid scale across Australia. More importantly, this will allow us to better understand flash drought characteristics in a climatological context. For example, it can be used to assess whether and how large-scale modes of variability may be related to this phenomenon, and whether there are any trends in terms of frequency of occurrence, seasonality, and factors influencing drought intensity and extent. Given the strong impact of such phenomenon on agriculture it is crucial to understand what drives Australian flash droughts and to improve their predictability.

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References

Anderson M C, Cammalleria C, Hain C R, Otkin J A, Zhan X and Kustas W 2013a Using a diagnostic soil-plant-atmosphere model for monitoring drought at field to continental scales *Procedia Environ. Sci.* **19** 47–56

Anderson M C, Hain C, Otkin J A, Zhan X, Mo K, Svoboda M, Wardlow B and Pimstein A 2013b An intercomparison of drought indicators based on thermal remote sensing and NLDAS simulations *J. Hydrometeorol.* **14** 1035–56

Anderson M C, Hain C, Wardlow B, Pimstein A, Mecikalski J R and Kustas W P 2011 Evaluation of drought indices based on thermal remote sensing and evapotranspiration over the continental United States *J. Clim.* **24** 2025–44

Anderson M C, Zolin C, Sentelhas P, Hain C, Semmens K, Yilmaz M T, Gao F, Otkin J A and Tetrault R 2016 Assessing correlations of satellite-derived evapotranspiration, precipitation, and leaf area index anomalies with yields of major Brazilian crops *Remote Sens. Environ.* **174** 82–99

Bureau of Meteorology 2019a Summer 2019 sets new benchmarks for Australian temperatures (http://media.bom.gov.au/social/blog/2020/summer-2019-sets-new-benchmarks-for-australian-temperatures/?fbclid=IwAR1SB1fzlCXX-y-XeZ8VLuJhzfxEkHxqhMkKnRL5IOuoR3gUTqFt5MXBS2M) (Melbourne, Australia: Bureau of Meteorology)

Bureau of Meteorology 2019b Widespread heatwaves during December 2018 and January 2019. Special Climate Statement 68 (http://bom.gov.au/climate/current/statements/scs68.pdf) (Melbourne, Australia: Bureau of Meteorology)

Doyle K 2018 What you need to know about droughts: Why they happen and how they are defined. ABC news/weather (https://abc.net.au/news/2018-08-01/what-you-need-to-know-about-droughts/10051956)

Ford T W and Labosier C F 2017 Meteorological conditions associated with the onset of flash drought in the eastern United States *Agric. Forest Meteorol.* **247** 414–23

Ford T W, McRoberts D B, Quiring S M and Hall R E 2015 On the utility of *in situ* soil moisture observations for flash drought early warning in Oklahoma, USA *Geophys. Res. Lett.* **42** 9790–8

Frost A J, Ramchurn A and Smith A 2018 The Australian landscape water balance model (AWRA-L v6). Technical description of the Australian water resources assessment landscape model version 6 *Bureau of Meteorology Technical Report* (Melbourne, Australia: Bureau of Meteorology)

Frost A J and Wright D P 2018 Evaluation of the Australian landscape water balance model: AWRA-L v6 *Bureau of Meteorology Technical Report* (Melbourne, Australia: Bureau of Meteorology)

Hobbins M T, Wood A, McEvoy D J, Huntington J L, Morton C and Verdin J 2016 The evaporative demand drought index: I. Linking drought evolution to variations in evaporative demand *J. Hydrometeorol.* **13** 1195–214

Hunt E, Svoboda M, Wardlow B, Hubbard K, Hayes M J and Arkebauer T 2014 Monitoring the effects of rapid onset of drought on non-irrigated maize with agronomic data and climate-based drought indices *J. Agric. Forest Meteorol.* **191** 1–11

Hunt E D, Hubbard K G, Wilhite D A, Arkebauer T J and Dutcher A L 2009 The development and evaluation of a soil moisture index *Int. J. Climatol.* **29** 747–59

Jones D A, Wang W and Fawcett R 2009 High-quality spatial climate data-sets for Australia *Aust. Meteorol. Oceanographic J.* **58** 233–48

McVicar T R *et al* 2008 Wind speed climatology and trends for Australia, 1975-2006: capturing the stilling phenomenon and comparison with near-surface reanalysis output *Geophys. Res. Lett.* **35**

Mo K C and Lettenmaier D P 2015 Heat wave flash droughts in decline *Geophys. Res. Lett.* **42** 2823–9

Mo K C and Lettenmaier P D 2016 Precipitation deficit flash droughts over the United States *J. Hydrometeor.* **17** 1169–84

Otkin J A, Anderson M C, Hain C, Mladenova I, Basara J and Svoboda M 2013 Examining flash drought development using the thermal infrared based evaporative stress index *J. Hydrometeor.* **14** 1057–74

Otkin J A, Anderson M C, Hain C and Svoboda M 2015 Using temporal changes in drought indices to generate probabilistic drought intensification forecasts *J. Hydrometeorol.* **16** 88–105

Otkin J A, Anderson M C, Hain C, Svoboda M, Johnson D, Mueller R, Tadesse T, Wardlow B and Brown J 2016 Assessing the evolution of soil moisture and vegetation conditions during the 2012 United States flash drought *Agric. Forest Meteorol.* **218–219** 230–42

Otkin J A, Haigh T, Mucia A, Anderson M C and Hain C R 2018 Comparison of agricultural stakeholder survey results and drought monitoring datasets during the 2016 U.S. Northern Plains flash drought *Weather, Climate, Soc.* **10** 867–83

Otkin J A, Svoboda M, Hunt E D, Ford T W, Anderson M C, Hain C and Basara J B 2018 Flash droughts: a review and assessment of the challenges imposed by rapid onset droughts in the United States *Bull. Am. Meteorol. Soc.* **99** 911–9

Otkin J A, Zhong Y and Hunt E E 2019 Assessing the evolution of soil moisture and vegetation conditions during a flash drought–flash recovery sequence over the south-central US *J. Hydrometeor.* **20** 549–62

Penman H L 1948 Natural evporation from open water, bare soil and grass *R. Soc.* **193** 120–45

Shuttleworth W J 1992 Evaporation *Handbook of Hydrology* ed D R Maidment ch 4 pp 4.1–4.53

Svoboda M *et al* 2002 The drought monitor *Bull. Am. Meteorol. Soc.* **83** 1181–90