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Bushfire season in Australian Indigenous seasonal calendars and associated drought trends

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ABSTRACT

Climate-induced changes in rainfall and temperature across Australia exacerbate drought and bushfire risk which have detrimental impacts on flora, fauna, and water quality. Indigenous Peoples across Australia have recorded climate, environment, and biotic patterns in seasonal calendars, of which five are used to delineate approximate time windows associated with bushfire to demonstrate the necessity of weaving non-colonial and colonial knowledge for better understanding modern climate challenges. The bushfire season (October–March) was examined for variability and trends in the Standardised Precipitation Evapotranspiration Index (SPEI), the Southern Oscillation Index (SOI), and the Indian Ocean Dipole (IOD) historical data from 1950 to 2021. SPEI is an integrative measure of local land-atmospheric conditions and affords physics-based monitoring of drought conditions across large spatial scales, using temperature, precipitation, and potential evapotranspiration to evaluate moisture content in a region. We found that drought indices showed moderate correlations with climate variables (SOI and sea surface temperatures). Taken together, this study illustrates overlapping scales of Indigenous and western knowledges in the context of bushfire risk and has the potential to enhance and inform climate adaptation efforts.

Key words: Australia, bushfire, climate change, drought, Indigenous, water deficits

HIGHLIGHTS

- Australian Indigenous seasonal calendars are used to delineate the bushfire season.
- SPEI integrates hydroclimatic variability and offers insights regarding drought risk.
- Spatial trend patterns show region wide and local patterns of variability.
- Moderately strong relationships present between SOI and leading patterns of SPEI.
- Integrative view provided through knowledge delineated from seasonal calendars and hydroclimatic data.

INTRODUCTION

Water security across Australia is being impacted by climate change, with increased severity of droughts and heavy rainfall events occurring across the continent (Steffen *et al.* 2018). Extreme dry and extreme wet events can be prepared for and managed through the measurement and monitoring of climate-related variables, such as atmospheric modelling, remote sensing, and standardised measurements for precipitation and temperature. However, these relatively modern methods are of Western colonial design and lack sufficient historical records to provide substantive insight into the boundaries of expected seasonal behaviour or the cumulative impact of deviations over multiple seasons. In comparison, Indigenous Peoples often have well-developed understanding of climate impacts on localised biota, such as the Indigenous Peoples of Australia who have been developing and cultivating their climate and environmental knowledge long before colonisation occurred and colonial methods were introduced to the continent (O'Connor & Prober 2010). The long historical awareness of seasonal cycles maintained by Indigenous Peoples can offer valuable insight into the boundaries for expected normal ranges of seasonal behaviour, as well as the potential impacts of deviations from these seasonal ranges over cumulative seasons (Thompson *et al.* 2020). This research demonstrates the necessity of weaving non-colonial and colonial knowledge together to better understand, mitigate, and adapt to the seasonal challenges brought by climate change.

According to colonial knowledge systems, the following are known to impact drought and bushfire seasons across Australia, and in turn affect flora, fauna, and water quality. More water can be held in the atmosphere as it warms, enabling the development of increasing heavy rainfall and flooding events. However, the intensification of the atmospheric subtropical ridge over the Australian continent acts to limit the movement of tropical water vapour laden air towards the more southern regions of Australia where declining rainfall trends are leading to drier conditions, particularly during the cool seasons in Southeast and Southwest Australia (Keywood *et al.* 2016; O'Donnell *et al.* 2021). These drying trends result in reduced streamflow which facilitates and exacerbates drought and bushfire conditions (Steffen *et al.* 2018). In these southern and eastern regions of Australia, droughts are anticipated to become more severe in intensity and duration (Kirono *et al.* 2020). Hotter conditions also contribute to drought and bushfire risk with declines in plant and soil moisture resulting in drier conditions (Steffen *et al.* 2018). Similar changes are also evident in historical and modelled records of streamflow across Australia (Coleman 2022; Coleman & Jain 2023).

The driving forces of drought and bushfire risk across Australia are associated with climate events related to sea surface temperature (SST) which is driven by the coupled ocean-atmospheric processes. SST conditions in the Pacific Ocean and the Indian Ocean modulate the seasonal climate across Australia. As such, two SST-based indexes, the Southern Oscillation Index (SOI) and the Indian Ocean Dipole index (IOD), are used in this study. These indexes perform as a measure of impact of climate cycles on precipitation and temperature across large regions of Australia. El Niño (a period of SOI with negative values) and positive IOD events reduce rainfall and increase temperatures, contributing to drought and bushfire conditions across Australia, particularly in the southeast (Cai *et al.* 2009; Wang & Cai 2020). Standardized Precipitation Evapotranspiration Index (SPEI) is an integrative measure of local land-atmospheric conditions and affords a physics-based monitoring of drought conditions across large scales, using temperature, precipitation, and potential evapotranspiration to evaluate moisture content in a region (Vicente-Serrano *et al.* 2015).

Extended and amplified hot and dry conditions contribute to bushfire risk (Climate Council of Australia 2019), and in turn bushfires pose risks to water quality, especially when drought and bushfires are increasingly followed by heavy rainfall (Steffen *et al.* 2018; King *et al.* 2020). The loss of vegetation from bushfires reduces soil permeability (Ruthrof *et al.* 2019), rainfall-runoff, and soil erosion, all of which increase the risk of flash flood events and facilitate the mass movement of ash into water bodies (Steffen *et al.* 2018; Kumar *et al.* 2020). Sudden and large influxes of nutrient-rich ash into water sources increase the risk of contamination of pathogens and algae which can drastically reduce water quality and pose health hazards (Steffen *et al.* 2018).

Indigenous Peoples have been living across Australia for thousands of years, during which they have adapted to periodic drought conditions and developed water management strategies (Jackson 2008). These adaptation methods are considered to be part of caring for Country, with Country representing the physical land, waterways, and seas, as well as other aspects including complex cultural and spiritual practices, law, language, family, and identity concepts (AIATSIS (Australian Institute of Aboriginal and Torres Strait Islander Studies) 2023). Relationships with Country and caring for its overall health are driving aspects of their interactions with environments and ecosystems, resulting in comprehensive holistic knowledge that defines the interconnectedness of seasonality, ecosystems, and cultural practices (e.g., Prober *et al.* 2011).

Colonisation has drastically impeded Indigenous knowledge processes and practices, reducing the transmission of knowledge processes and ability to apply their knowledge (Grewcock 2018). Efforts to improve the maintenance and transmission of Indigenous knowledge processes have included the development of Indigenous seasonal calendars which detail interlinkages of season-related climate, biota, and environmental knowledge to varying degrees (Bureau of Meteorology (BOM) 2016a; Woodward *et al.* 2020; CSIRO 2021). These calendars provide a glimpse into the relationship Indigenous Peoples share with Country, including recognition of patterns of regional stressors, such as wind, precipitation, and temperature conditions, how these stressors impact ecosystems and the humans and creatures within them, and how Indigenous Australians mitigate and adapt to the occurrence of these stressors. An example of this is the timing and techniques of lighting bushfires during ideal conditions to manage and develop landscapes for the maintenance of food and biodiversity (Vigilante *et al.* 2009) where slow moving and low intensity fires are typically relied on to reduce hazards, promote regrowth, and allow animals and insects to escape. This practice prevents the destruction of seeds, ground-level habitats, and can improve soil's ability to absorb moisture (Korff 2022). In comparison, lighting fires is avoided during seasonal periods of dangerous conditions where a fire could quickly become an uncontrolled hazard (McKemey & Banbai Rangers 2020; McKemey *et al.* 2020, 2022). Climate change mitigation and adaptation can benefit from the weaving of colonial and Indigenous Australian knowledge systems towards more comprehensive, inclusive, and equitable understandings of climate change impacts. The detailed environmental information contained within Indigenous seasonal calendars often includes hydrological conditions which may enable the calendars, as an initial step, to be used as catalogues documenting periods of increased drought risk.

Other work has considered a variety of techniques for drought forecasting (Dikshit *et al.* 2021; Sharafi & Ghaleni 2023; Wable *et al.* 2023), though few approaches have begun to consider the value of Indigenous knowledge (Leelavathy & Mekala 2023). Our study aims to demonstrate the value of acknowledging and weaving knowledge towards improving drought prediction and management through combining the drought knowledge contained in the seasonal calendars, with Western methods, including the SPEI index. The results of this study intend to provide an alternative approach to understanding the changing drought and bushfire risk in some example regions of Australia.

Positionality statement

This research draws on information contained in publicly accessible Australian Indigenous seasonal calendars. The first author acknowledges that they are a non-Indigenous Australian and the second author is a non-Indigenous, non-Australian citizen. They do not intend to violate the intellectual property rights or make assumptions of or for the Indigenous authors of the seasonal calendars or their nations and cultures. Only publicly available information is used in this research and this information is reduced to summary level across the calendars to prevent re-representation or appropriation of the information. Best practice guidelines of collaboration and co-design (David-Chavez & Gavin 2018; Woodward *et al.* 2020) have not been met in the production of this research due to time, distance, and financial constraints. A detailed acknowledgement at the end of this study details the guidance offered by the Commonwealth Scientific, Industrial, and Research Organisation regarding appropriate use of the publicly available Indigenous seasonal calendars. The authors firmly believe that they have respectfully adhered to the guidance.

METHODS

Data used in this study includes drought knowledge from five Indigenous seasonal calendars, as well as the SPEI drought index, SOI index, IOD index, and SST as Western measures of climate. Analysis methods included identification of the approximate bushfire season according to the calendars and multivariate statistical analysis and PCA of the SPEI data for the calendar locations and SOI, IOD, and SST.

Data and region

Indigenous seasonal calendars

Holistic regional knowledge of patterns in weather, environment, biota, and other events, including bushfires, have been recorded in Indigenous seasonal calendars with 25 nations across Australia granting public access to the calendars (BOM 2016a; CSIRO 2021). The contents across the seasonal calendars vary in diversity and level of detail due to resource limitations at the time of recording the calendars (e.g., lack of available knowledge, lack of translators) and Indigenous nations' and elders' rules and laws around sharing such information. Some seasonal calendars provide extensive details on plant or animal phenology, such as the approximate Gregorian months that a plant may flower or when certain snake species can be expected to emerge from hibernation, while others provide little information beyond meteorological observations, such as the approximate Gregorian months to expect hot temperatures, strong winds from a particular direction, or electrical storms. The majority of the available seasonal calendars are located across the north of Australia.

SPEI drought index

An index of monthly drought conditions through 1951–2021 at one-degree spatial resolution for each of the Indigenous seasonal calendar locations, extracted by selecting the closest gridpoint within the SPEI Global Drought Monitor database (Vicente-Serrano *et al.* 2015; Beguería *et al.* 2022). The index uses the Thornthwaite equation for estimating potential evapotranspiration through mean temperature and monthly precipitation (Vicente-Serrano *et al.* 2010). Positive SPEI values indicate water surpluses while negative values indicate water deficits. SPEI data cells were chosen based on the latitude and longitude of the approximate central region of each of the five Indigenous seasonal calendars with bushfire mentions (Figure 1). The SPEI data from these cells was limited to the range of months identified as the bushfire season from the Indigenous seasonal calendars.

Indigenous seasonal calendar	SPEI coordinates for approximate centres of Indigenous seasonal calendar region	
	Latitude	Longitude
A – Banbai	-30.25	151.75
B – D'harawal	-34.25	150.75
C – Gariwerd	-37.25	142.25
D – Ngadju / Marlpa	-32.25	121.75
E – Yanyuwa	-17.75	138.25

Figure 1 | Map of the approximate centre of seasonal calendar region used for SPEI gridded data.

SOI index

Rainfall across Australia is linked with El Niño and La Niña events, with rainfall reductions associated with El Niño, and rainfall increases associated with La Niña. The SOI is an indicator of the presence and strength of El Niño (negative values) and La Niña (positive values). Droughts are more common during El Niño events, making the SOI index a good comparator for SPEI. Monthly SOI data was downloaded from the Australian Bureau of Meteorology (BOM 2022b). The SOI data was restricted to the same time range as the SPEI data (1951–2021) and the months of data were also restricted to the bushfire season range identified by the Indigenous seasonal calendars.

IOD index

The Indian Ocean off the western coast of Australia goes through opposing patterns of warming and cooling in its eastern and western regions known as the IOD. These temperature differences between the east and west of the ocean influence climate across the Australian continent. A positive IOD is associated with reduced rainfall and higher temperatures, usually during the Australian winter and spring, while a negative IOD typically increases rainfall during the winter and spring period (BOM 2022a). Monthly Dipole Mode Index data for the IOD was available from 1951 through 2021 (National Oceanic and Atmospheric Administration (NOAA) 2022).

Sea surface temperature (SST)

SST is a more direct measure of SOI and IOD, since SOI and IOD are indexes of ocean temperature differences. The differences in SST temperatures at one region of an ocean compared to another are indicative of thermocline cycles within the ocean downwelling warmed surface water and upwelling colder deep waters. The atmosphere above these regional differences in SST within an ocean then responds with increased or decreased heat for convection which then translates into increased or decreased rainfall. The SST data was provided by NOAA and was subject to the same year and month restrictions as the SPEI data; 1951 through 2021, and the bushfire season of October through March (Kalnay *et al.* 1996).

Analyses

Indigenous seasonal calendars allowed the identification of an approximate bushfire season across five locations using qualitative methods, while R Studio was used for multivariate statistical analysis of SPEI data at the five locations provided to understand the differences and similarities between the locations. R Studio was also used for correlations between the SPEI principal components and SOI, IOD, and SST were used to reveal associations between drought values at the five locations and greater global circulation pattern trends.

Indigenous seasonal calendars

The approximate monthly presence of bushfires was gauged across 25 publicly accessible Indigenous seasonal calendars (BOM 2016a; CSIRO 2021). Each calendar was examined for explicit mentions of bushfires. The definition of bushfires was restricted to fires that were uncontrolled hazards and not intentionally lit or controlled fires used for cultural, preventative, and restorative purposes, such as managed grassland and wetland burning. This limitation resulted in bushfires being identified in five Indigenous seasonal calendars: Banbai, D'harawal, Gariwerd, Ngadju/Marlpa, and Yanyuwa (O'Connor

& Prober 2010; BOM 2016b, 2016c, 2016d; McKemey *et al.* 2022), shown in Figure 1. The small sample of calendars referencing bushfires is not representative of bushfire presence across Australia or Indigenous knowledge of bushfires. The authors of each seasonal calendar tailored the information in the calendars to what was relevant to their nation and culturally appropriate to share in a public document, so the inclusion of bushfire information was up to their discretion. The approximate months associated with bushfires within the five calendars were then used to identify the bushfire season.

SPEI drought index

Principal component analysis (PCA) (Lattin *et al.* 2003) was used on the SPEI drought index data to identify the presence of groups, ones that represent temporally uncorrelated spatial patterns, in the data that were not evident in the pre-analysis. It reduced the years of data into principal components that are representative of aspects across those years of data, such as climatic patterns. Changes in patterns for the bushfire season were assessed through the trend in unusually wet and unusually dry years.

The annual mean SPEI values for the bushfire season of each location were found and the correlations between locations were examined. PCA was then applied to the annual mean bushfire season SPEI values and locally weighted scatterplot smoothing was used on the first two components to reduce interannual variability below 10 years and examined over time.

The mean upper and lower quartiles ($\tau = 0.75$ and $\tau = 0.25$) for the SPEI means of the five locations from 1980 to 2021 were used to determine the wet (upper) and dry (lower) thresholds. The 30-year rolling mean SPEI values from October to March for each year were then evaluated for being above the upper threshold, and therefore unusually wet, or below the threshold, and therefore unusually dry for each location. This resulted in a count of the number of unusually wet and unusually dry years which was then plotted to demonstrate the range change for the drought index for the bushfire season.

Southern Oscillation Index (SOI)

SOI variability is anticipated to increase as climate change progresses (Power & Kociubo 2011). The association between SOI and rainfall suggests that rainfall patterns will be impacted by the SOI response to climate change. Long-term changes in SOI were assessed because of the association between SOI and rainfall intensity patterns.

Annual mean for the bushfire season was calculated for SOI and assessed for correlation with SPEI PC1 and PC2. Long-term changes in SOI were analysed using the mean values over time with locally weighted scatterplot smoothing used again to reduce interannual variability below 10 years. The 30-year rolling standard deviation from 1980 to 2021 was also found.

IOD index

The IOD is a major climate driver in Australia and as such was assessed for relevance to the principal component most associated with the western SPEI data location. Monthly IOD index data was restricted to 1951 through 2021 and split into the bushfire season (October through March) and the non-bushfire season (April through September). Each season was averaged and assessed for correlation with the SPEI PCA components.

Sea Surface Temperature (SST)

SST correlations with the two primary components from the principal analysis were assessed to further assess the impact of climatic features on the drought index. The x values for PC1 and PC2 were uploaded to the NOAA via FTP as a custom time series to enable correlation with their SST data. The maps were colour coded to indicate degree of correlation.

RESULTS

Indigenous seasonal calendars

Bushfires were associated across half of the Gregorian calendar months across the five Indigenous seasonal calendars, as shown in Table 1. The bushfire season increases in seasonal calendar presence from October until it reaches the maximum number of calendars in January and February, and then declines by one seasonal calendar in March. For this study, we chose a broad seasonal representation of the bushfire season across the five locations indexed during the October to March period. Interlinkages represented in the calendars demonstrate the connected aspects of ecosystems that are vulnerable to risk from bushfires. Examples of aspects of ecosystems that could be impacted by uncontrolled bushfires include plants that are key for anticipating and adapting to weather events and seasonal changes, medicinal plants, fruits, tubers, migratory birds and bats, many juvenile insects and animals, and water sources used for fishing (O'Connor & Prober 2010; BOM 2016b, 2016c, 2016d; McKemey *et al.* 2022).

Table 1 | Presence of bushfires across approximate months

	Approximate months											
	J	F	M	A	M	J	J	A	S	O	N	D
Banbai	■	■	■								■	■
D'harawal	■	■	■									
Gariwerd	■	■	■									
Ngadju/Marlpa	■	■	■								■	■
Yanyuwa	■	■								■	■	■
Counts of bushfire mentions	5	5	4							1	3	3

The 12 calendar months are listed sequentially and abbreviated using the initial letters, for example, January is noted as 'J'.

SPEI drought index

Annual mean SPEI cross-correlation was highest between Banbai and D'harawal (0.74), followed by Banbai and Yanyuwa (0.51) (Table 2). Banbai and D'harawal are both located on the southeastern coast and are the closest together out of all the stations so they may be subject to similar degrees of climate influence, resulting in the high correlation. Ngadju has the lowest correlations, likely due to being the farthest from the other locations. Climate variability stemming from the western oceanic region (e.g., linked to IOD) may have a greater influence on Ngadju than on the more eastern locations.

Another aspect of the SPEI variability is the relative incidence of arid and pluvial periods over the instrumental record. As such, a climatic baseline would entail year-to-year swings in SPEI, to which environmental systems and humans are well-adapted, and devise strategies to function effectively. However, in a changing climate, climatic baselines (mean and variability) may undergo shifts and SPEI may manifest as changes in the relative frequency of arid and pluvial periods, and associated extreme events, such as bushfires. This can be assessed using a representative time window (e.g., 30 or 50 years) and examining the number of years that exceed (or not exceed) a representative threshold for a pluvial (or arid) period, often corresponding to a quantile (Sen Gupta *et al.* 2011). For contiguous 30-year periods, we counted the number of years with SPEI values exceeding (not exceeding) the representative quantile threshold of 0.75 (0.25). The thresholds are indicators of unusually dry ($\tau = 0.25$) or wet conditions ($\tau = 0.75$). Mostly decreasing trends in unusually wet years and increases in unusually dry years were found (Figure 2). The exception to this was Ngadju, with the opposite occurring with clear increases in unusually wet years and decreases in unusually dry years. Banbai has the least increasing dry trend; however, the decreasing wet trend may indicate concern for water deficiencies. The other four eastern locations have more pronounced decreasing wet trends indicating reduced water surpluses, combined with increasing dry trends.

Table 2 | Correlation table for annual mean SPEI bushfire season ($n = 71$ years)

	Banbai	Gariwerd	Ngadju	D'harawal	Yanyuwa
Banbai	1	0.28	0.15	0.74	0.51
Gariwerd		1	0.12	0.32	0.31
Ngadju			1	0.13	0.06
D'harawal				1	0.32
Yanyuwa					1

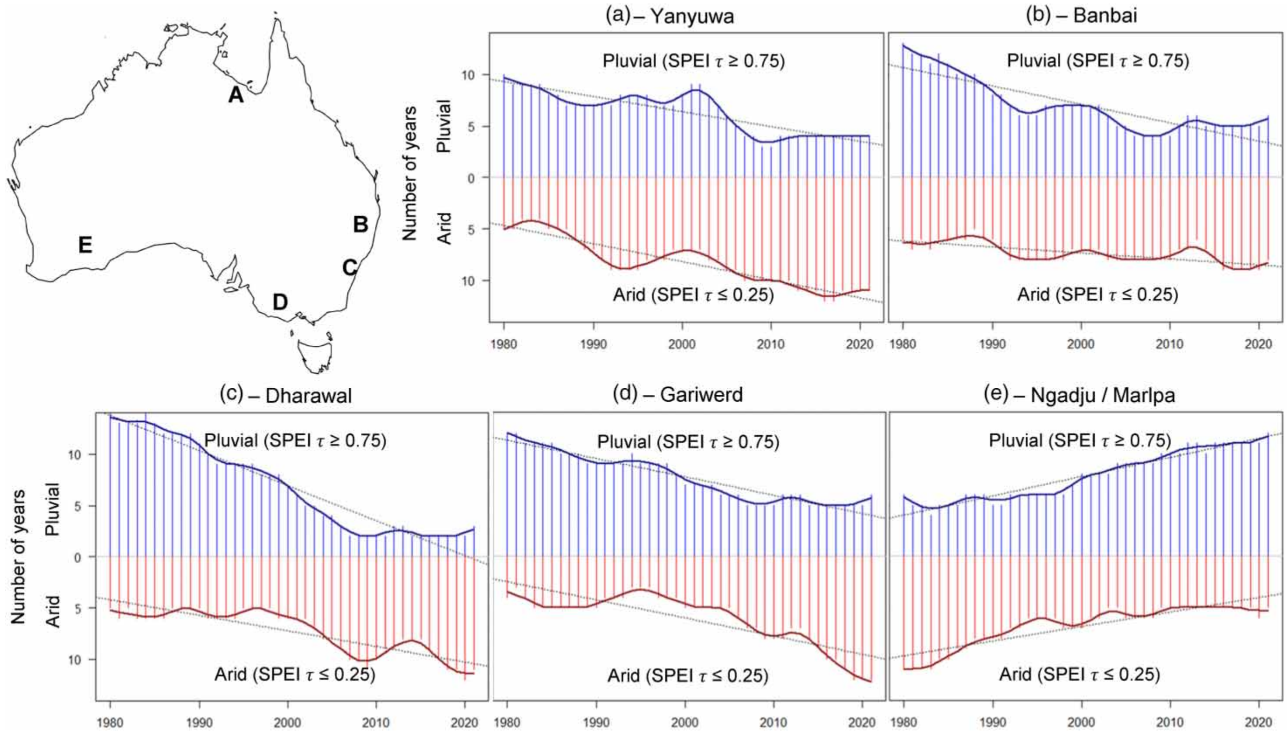

Figure 2 | Frequency of pluvial (wet) and arid (dry) years based on a 30-year moving window for SPEI index.

The first principal component of the SPEI drought index data, comprised of five time series corresponding to the October–March mean SPEI for the selected locations, accounts for 45.72% of variance and has negative associations with all five of the locations (Table 3), with Ngadju having the lowest strength association. The consistent sign indicates that PC1 primarily measures one factor influencing the SPEI data across all locations. The second component accounts for 19.36% of variance (Figure 3) and has a strong negative association with Ngadju, indicating a different factor to PC1 has a large influence on the SPEI values at this location. PC2, with the loading predominantly associated with Ngadju, represents interannual variability endemic to that location.

The trend for PC1 across 1951–2021 is overall negative with variance increasing slightly over time ($P < 0.01$). In comparison, PC2 has a slightly positive trend and lower variance ($P > 0.05$) (Figure 3).

SOI index

Correlations between annual mean SOI and SPEI PC1 were positive and moderate (0.56), while correlations with PC2 were positive but very weak (0.07), indicating that the leading pattern of SPEI PC covaries with the SOI (Supplementary Figure S1). The salience of the SPEI-based drought variability assessed in this manner is that SPEI is a proximate biophysical

Table 3 | Principal component loadings related to the SPEI principal components

	PC1 (45.7%)	PC2 (19.4%)	PC3	PC4	PC5
Banbai	0.52	−0.03	0.40	0.09	−0.5
Gariwerd	0.4	0.1	−0.78	0.47	−0.09
Ngadju	0.16	0.93	0	−0.33	0.04
D'harawal	0.49	0.04	0.44	0.42	0.62
Yanyuwa	0.23	−0.35	−0.2	−0.7	0.20

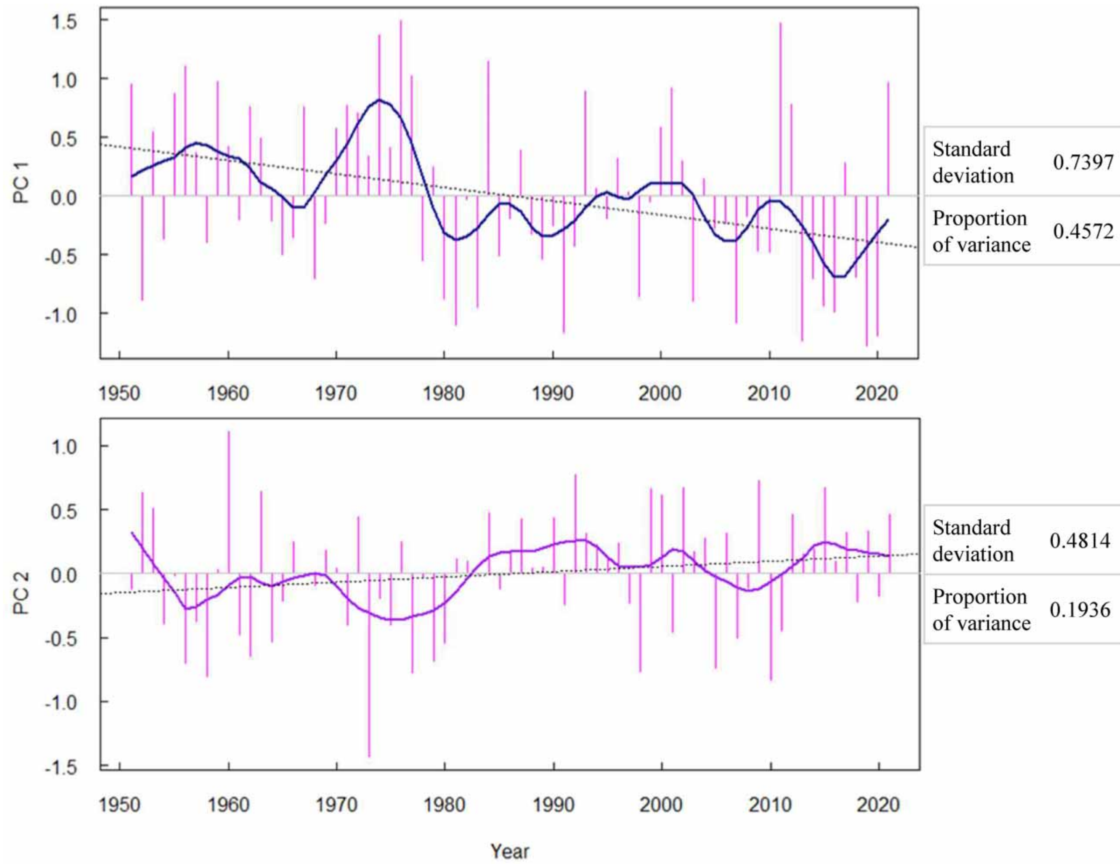

Figure 3 | The time variation in the SPEI PC1 and PC2 for the approximate austral spring and summer seasons (October–March) over the 1951–2021 periods. Long-term variability is assessed based on locally linear smoother with an 11-year window (shown in dark blue and purple). The linear trend of the period is shown by the dashed line.

index to bushfire risk, and given the seasonal to longer timescale predictability of El Niño/Southern Oscillation, there is a prospect of foreknowledge of an increased risk at the locations studied.

The annual SOI mean values are shown to be increasing in strength since 1990. The long-term variability in SOI is assessed based on rolling 30-year standard deviation estimates. Overall, there is a trend towards increase in variance of SOI; however, there appears to be a levelling off of variability during the past decade. These represent increasing variation in SOI, that is, increasing intensity in El Niño and La Niña events (Figure 4). Future trends in the frequency and amplitude of El Niño and La Niña events will likely be mirrored in climatic stress across Australia.

IOD index

The nature of SPEI variability along the western Australian region is reflected in the index for Ngadju. This location has a weak loading related to PC1. The PC2 is dominantly linked to Ngadju and to a lesser degree, and in an opposite sense to Yanyuwa. In general, we expect that southwestern Australian climate is modulated by the Indian Ocean climatic regime. This was assessed through correlations between the annual mean IOD bushfire season (October–March) and PC2 and the annual mean non-bushfire season (April–September) and PC2 (Supplementary Figure S2). The bushfire season had a weak positive correlation (0.13) with PC2 and the non-bushfire season had a slightly stronger positive correlation (0.2). Further analyses of PC and SST relationships are pursued next.

Sea surface temperature (SST)

Correlations between SST and PC1 are visualised in Supplementary Figure S3, with positive correlations of 0.1–0.5 hugging the northern, southeastern, and southern coasts of Australia. Stronger positive correlations up to 0.7 were also visible in the

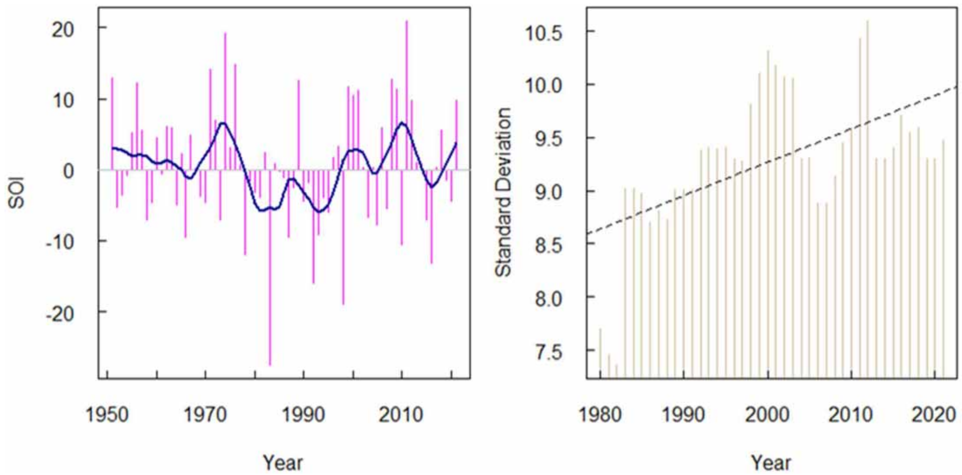

Figure 4 | (Left) Annual mean SOI and smoothed estimates of long-term variability (based on an 11-year lowess smoother) and (right) rolling 30-year standard deviation in annual SOI variability as a measure of the frequency of extreme events.

northwest region of the ocean, in the Bay of Bengal and Arabian Sea, with negative correlations from −0.1 to −0.5 extending off the east coast of Australia and scattered in the south with weak positive correlations below the continent. The results indicate that as SST increases in the northeast of the map (between Papua New Guinea and Tahiti), PC1 values also increase, which is supportive of increasing temperatures in this region causing El Niño conditions and associated reduced rainfall in Australia.

In comparison, correlations between SST and PC2 values are demonstrated in Supplementary Figure S4. The strongest correlations are seen in the southern Pacific Ocean (near 20S) and also qualitatively in the horseshoe-shaped region in the western tropical Pacific. This map displays negative correlations of −0.1 to −0.6 across the mid to northern regions and scattered through the southern region. Positive correlations of 0.1–0.4 were visible also in the southern region, in a small region off the mid-western coast of Australia, off the eastern tip of far north Queensland, and off the east coast of Australia. The pattern of strong correlations across the Indian Ocean presents an interesting possible pattern of regional co-variability in climate, however, the exact mechanisms are not clear.

DISCUSSION

Indigenous seasonal calendars offer a glimpse into extensive knowledge of environmental, ecological, hydrometeorological, and climatic patterns held by Indigenous Peoples. Weaving these knowledge methods with colonial knowledge methods can contribute to greater anticipation of and preparation for water shortages and drought conditions. This has been demonstrated using a bushfire season of October–March drawn from knowledge contained in the Banbai, D'harawal, Gariwerd, Ngadju/Marlpa, and Yanyuwa Indigenous seasonal calendars from across Australia. The two calendars on the eastern coast, Banbai and D'harawal, had highly correlated annual mean SPEI, indicating shared climate and interannual variability. PCA of the SPEI drought index data for all five approximated calendar locations during the October–March bushfire season indicated similarities in climate influence across locations, except for the Ngadju/Marlpa calendar in the southwestern corner of the continent. Additionally, during the bushfire season the four eastern locations had declining trends in water excesses and increasing trends in water deficits indicating an increased presence of bushfire risk conditions. Meanwhile, the southwest location demonstrated trends of increasing water excesses and decreasing water deficits, indicating a reducing likelihood of bushfires due to excess moisture over the bushfire season period.

There was a moderate positive correlation between SOI and the principal component most representative of the four eastern locations (approximately Banbai, D'harawal, Gariwerd, and Yanyuwa), and a very weak correlation between SOI and the second principal component which was most associated with the western location (Ngadju/Marlpa). This supports that the SOI influences climate and drought conditions across Australia, with effects strongest in the eastern and southern regions. Due to its proximity to the western coast and Indian Ocean, the western location was expected to have a stronger association with the IOD than the SOI. Correlations between the principal component most associated with the western location and each IOD bushfire season and non-bushfire season were positive and weak, but stronger than the correlation with SOI. These outcomes illustrate the historical and present complexity of climate interactions and drought prediction and management across Australia.

The increasing variance in the SOI indicates intensification of El Niño and La Niña events which contribute to periods of water excesses and deficits. This is likely contributing to the increasing trends in water deficits during the October–March bushfire season across the eastern four locations while other climate factors are driving an increase in water excesses in the western location. The tangible impact of these trends across all five locations is an increasing dislocation of the seasonal patterns beyond the normal variance. The positive trend in water excesses in the southwestern location and decreases in water deficits during the bushfire season is not representative of year-round trends, with rainfall declining in March through August (autumn and winter) since the 1970s (Keywood *et al.* 2016; O'Donnell *et al.* 2021). These climatic and weather findings are an example of colonial knowledge that can be woven with Indigenous knowledge of historic regional seasonal patterns for a greater holistic understanding of dynamic regional climatic processes and changes beyond the norm. Incorporation of Indigenous knowledge of biota can then further elucidate the effects of shifting climates and the risk they pose to the resiliency of human and ecological wellbeing, infrastructure, and economies at various scales.

The reliance of biota on seasonal patterns for regulation of phenology has extensive impacts on environment and biota when seasonal patterns are sufficiently and enduringly disrupted. The association between SPEI and hydrology has received a lot of attention, particularly for water quantity impacts. However, SPEI is linked with and is responsive to environment and biota, most obviously through its incorporation of potential evapotranspiration. The holistic impact of SPEI on environment and biota is less well researched though has been receiving more attention through increasing awareness of drought impacts on water quality and processes associated with water quality.

Reductions in observed rainfall during autumn and winter since the 1990s in southeastern Australia (March–August) (Keywood *et al.* 2016) combined with the increasing trends of water deficits in the eastern locations during bushfire season indicate a drying trend of urgent concern. The drying trend increases the risk of water stress occurring in the region, particularly since water deficits are less likely to be restored due to the decreasing trends in water excesses. A drier landscape makes colonial fire management methods for reducing fuel loads riskier, increasing the likelihood of bushfires of greater intensity and destructive ability. Indigenous seasonal calendars contain insight into the cultural burning practices used to manage diverse Australian landscapes for thousands of years (Vigilante *et al.* 2009; McKemey *et al.* 2020).

There is an urgent need for substantial investment into equitable and respectful collaborations with Indigenous nations to enhance resource management to improve resilience to water deficit and excess events, including droughts, bushfires, and floods. Collaborations will improve ongoing identification of the most at-risk bushfire areas and enable weaving of colonial and Indigenous land management methods for improved risk reduction. As an example, Indigenous land management burning methods are typically smaller, patchier in scope, more tailored to the environment, and have a greater focus on enabling rejuvenation than colonial methods. Whereas fires conducted through colonial methods usually burn larger areas at a time, burn taller and hotter, and have less regard for environmental diversity and how these fires have interlinkages with ecological rejuvenation (Vigilante *et al.* 2009). These greater intensity fires are more damaging to deeper roots and have higher reach into tree canopies which reduces overall vegetation and subsequent evapotranspiration. These then have the further negative impacts of increasing moisture evaporation from soil and increasing rainfall-runoff (Kumar *et al.* 2020), all of which can impact the quality of water sources post-bushfire event. In comparison, the holistic knowledge driving Indigenous fire methods poses less risk to water sources due to the smaller, cooler fires producing less ash to contaminate water sources and the lower fire intensity promoting vegetative regrowth which increases soil permeability, reduces the risk of soil erosion and flooding (Steffen *et al.* 2018; Ruthrof *et al.* 2019), and increases biodiversity (Vigilante *et al.* 2009).

CONCLUSION

Weaving colonial and Indigenous Australian climate monitoring methods enabled the identification of an approximate bushfire season of October through March. Similarities in climate influence during this bushfire season were indicated across all locations except for the location in the continent's southwest using the PCA of the SPEI drought index data. Declining trends in water excesses and increasing trends in water deficits were also found during the bushfire season. Trends of increasing water excesses and decreasing water deficits were found in the southwest location. Correlations between SOI and the principal components support the strong effect of SOI on climate in the eastern and southern regions. The IOD was weakly correlated with the western location, though more strongly correlated than with SOI.

Respectful and equitable collaboration with Indigenous Peoples can improve holistic understanding of interlinkages between fire, environment, biota, and climate while improving adaptation techniques to the increasing drying trends and changes in seasonal climate across Australia.

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DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories: SPEI: https://spei.csic.es/database.html, SOI: http://www.bom.gov.au/climate/enso/soi/, IOD: https://psl.noaa.gov/gcos_wgsp/Timeseries/DMI/.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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