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Changes in Antecedent Soil Moisture Modulate Flood Seasonality in a Changing Climate

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Key Points:
- Timing of streamflow annual maxima is more closely linked to the timing of antecedent soil moisture maxima than rainfall maxima
- The more extreme a flood event, the weaker the dependence on antecedent soil moisture relative to rainfall occurrence
- Using circular regression, streamflow annual maxima timing is found to be nonstationary, consistent with shifts in soil moisture

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Abstract Due to difficulties in identifying a climate change signal in flood magnitude, it has been suggested that shifts in flood timing, that is, the day of annual streamflow maxima, may be detectable. Here, we use high-quality streamflow, largely free of snowmelt, from 221 catchments across Australia to investigate the influence of shifts in soil moisture and rainfall timing on annual streamflow maxima timing. In tropical areas we find that flood timing is strongly linked to the timing of both rainfall and soil moisture annual maxima. However, in southern Australia flood timing is more correlated with soil moisture maxima than rainfall maxima. The link between flood, soil moisture, and rainfall timing is confounded by event severity: For less extreme events flood timing is more likely to correspond to soil moisture timing, whereas rainfall timing becomes increasingly important as flood severity increases. Using circular regression to investigate nonstationarity, we find that flood timing is shifting to earlier in the year in the tropics and later in the year in the southwest of the continent, consistent with changes in mean and extreme rainfall and shifts in soil moisture timing due to tropical expansion. In southeast Australia, there is evidence that the mechanisms controlling flood seasonality are changing with a reversal of trends post Millennium Drought. Overall, changes in soil moisture timing, compared to changes in rainfall timing, are found to have a greater influence on changes in annual maxima streamflow flood timing.

1. Introduction

Understanding drivers of flood seasonality (or flood timing) is important not only for understanding catchment dynamics (Black & Werritty, 1997; Magilligan & Graber, 1996) but also for understanding how flood risk may change in a future climate. If we understand how the drivers of flood risk are changing, then we may also be able to infer how flood risk will change (Berghuijs et al., 2019; Do et al., 2020). As small shifts in the seasonality of climatic variables have large consequences on ecosystems (Diehl, 2018), changes to flood timing are not just important from a flood risk perspective but could also reduce farming productivity (Klaus et al., 2016) and impact the reliability of water supplies (Barnett et al., 2005).

The argument that shifts in flood seasonality could be used as an indicator of climatic change has existed for over half a century (Schwarz, 1977). However, the number of studies simultaneously investigating changes in flood seasonality and the hydroclimatic drivers of change remain limited and localized (Blöschl et al., 2017). A recent manuscript investigating change in flood seasonality across Europe (Blöschl et al., 2017) points to the great difficulty in identifying climate change signals in flood responses and the attribution of changes in flooding to climatic change (Pall et al., 2011; Seneviratne et al., 2012). Attributing and identifying changes in flooding is extremely difficult due to several factors: the large uncertainty in the flood signal (Apel et al., 2004; Hall et al., 2014), the multiple factors that drive nonstationarity in the flood response (Sharma et al., 2018), the fact that those drivers of flooding are catchment specific (Guo et al., 2017; Whitfield, 2012), and the lack of a standardized terminology for what is considered an extreme event (Pendergrass, 2018).

Assuming catchment stationarity (Ajami et al., 2017), flood timing will depend on the rainfall immediately prior to the flood event, the degree of antecedent catchment wetness, and any snowmelt (Berghuijs et al., 2016; Blöschl et al., 2017). As temperatures increase we may expect greater snowmelt and less precipitation falling as snow and preferentially as rain (Lettenmaier & Gan, 1990) causing a shift to earlier snowmelts (Trenberth, 2011) and possibly earlier flooding (Matti et al., 2017) with decreased magnitude (Vormoor et al., 2016). This may also increase the prevalence of rainfall-driven floods (Arheimer & Lindström, 2015) or floods due to rain on snow (Musselman et al., 2018).

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In Australia, the primary drivers of flooding are the rainfall prior to the flood event and the catchment soil moisture state (Bennett et al., 2018; Ivancic & Shaw, 2015; Kuczera et al., 2006; Stephens, Johnson, & Marshall, 2018; Wasko & Nathan, 2019) as few catchments are driven by snowmelt. A flood event can result from a small depth of rainfall on a wet catchment, or a large rainfall on either a dry or wet catchment (Wasko & Nathan, 2019). Hence, although rainfall is a necessary condition for a flood to occur and floods are generally driven by rainfall, the magnitude of rainfall alone is not necessarily an indicator of flood severity. For example, despite increases in extreme precipitation intensities across many parts of the world (Alexander et al., 2006; Donat et al., 2013; Westra et al., 2013), these increases have not necessarily translated to increases in annual flood maxima (Do et al., 2017) due to decreases in antecedent soil moisture (Sharma et al., 2018; Wasko et al., 2019; Wasko & Nathan, 2019). The seasonality of flood timing has been linked to soil moisture amount (Berghuijs et al., 2019; Black & Werritty, 1997; Collins, 2019; Ganguli et al., 2019; Parajka et al., 2010) and changes in snowmelt and associated changes in antecedent soil moisture (Parajka et al., 2010).

Using nonparametric Mann-Kendall tests, statistically significant shifts in the timing of daily rainfall maxima across the United States have not been detected (Mallakpour & Villarini, 2017), and no spatially consistent trends are reported in the timing of annual maxima rainfall or streamflow over China (Gu et al., 2017; Zhang et al., 2017). Though locally, a shift toward earlier rainfall maxima in the boreal autumn in Maine has been identified using nonparametric circular statistics (Dhakal et al., 2015). Climate models suggest that historical decreases in the vertically integrated saturation specific humidity on the day of annual maximum precipitation can be interpreted as a shift in the timing of precipitation maxima to lower temperatures, that is, toward the cold season (Pfahl et al., 2017). This is supported by a local model study for Switzerland where, using linear regression, it was found annual maxima are less frequent in late summer and more frequent in early summer and early autumn, resulting in a shift in timing to when it is cooler (Brönnimann et al., 2018). Marelle et al. (2018) found that, by the end of the 21st century, extreme precipitation could shift from summer and early autumn toward autumn and winter, with this shift strongest in northern Europe and Northeastern America.

Using the Sens slope estimator, Blöschl et al. (2017) identified spatially coherent shifts in annual flood maxima across Europe using 4,262 gauges over a 50-year period from 1960–2010. Flooding is shifting to earlier in the year in western Europe and along the Atlantic coast due to earlier soil moisture maximum. But in other regions, such as the North Sea, later winter storms are resulting in later flooding (Blöschl et al., 2017). Using 84 natural rivers in Canada, a consistent shift to an earlier peak for spring snowmelt runoff was found, consistent with anthropogenic climatic change (Burn, 1994). A similar shift to earlier flood peak occurrence due to snowmelt has been observed across Scandinavia (Blöschl et al., 2017; Matti et al., 2017) primarily due to increased temperatures (Arheimer & Lindström, 2015; Wilson et al., 2010) with similar trends observed in the United States due to earlier snowmelts in the central United States (Hamlet & Lettenmaier, 2007). While increases in warm-season flooding in the Northeast United States have been attributed to the apparent annual shift in flood timing (Collins, 2019; Frei et al., 2015). The strength of seasonality has been shown to vary across the contiguous United States where those catchments that have strong seasonality in flooding appear to inherit this behavior from rainfall seasonality and those catchments with less strong seasonality inherit behavior from the soil moisture storage, with flood seasonality strengthening with increasing soil moisture storage (Ye et al., 2017).

As discussed, flood timing is investigated for multiple reasons, including understanding flood generating mechanisms (Berghuijs et al., 2019; Black & Werritty, 1997) and identifying climatically homogenous regions (Burn, 1997; Formetta et al., 2018; Ouarda et al., 2006; Yang et al., 2019). Here, our focus is on detecting shifts in flood timing with climatic change (Burn, 1994). With very few exceptions (Blöschl et al., 2017; Villarini, 2016; Ye et al., 2017) studies which investigate changes in flood timing do not explicitly consider the timing of hydroclimatic drivers of flood response. This study addresses a gap in the literature of (large-scale) continental studies and investigates the timing of floods jointly with the timing of rainfall and soil moisture maxima. Changing antecedent soil moisture has been shown to modulate flood magnitude across Australia, with increasing soil moisture increasing flooding in the north, while decreasing soil moisture elsewhere has resulted in smaller annual maxima in the south (Wasko & Nathan, 2019). Here, we build on these findings to investigate shifts in flood timing across Australia to answer the following questions:

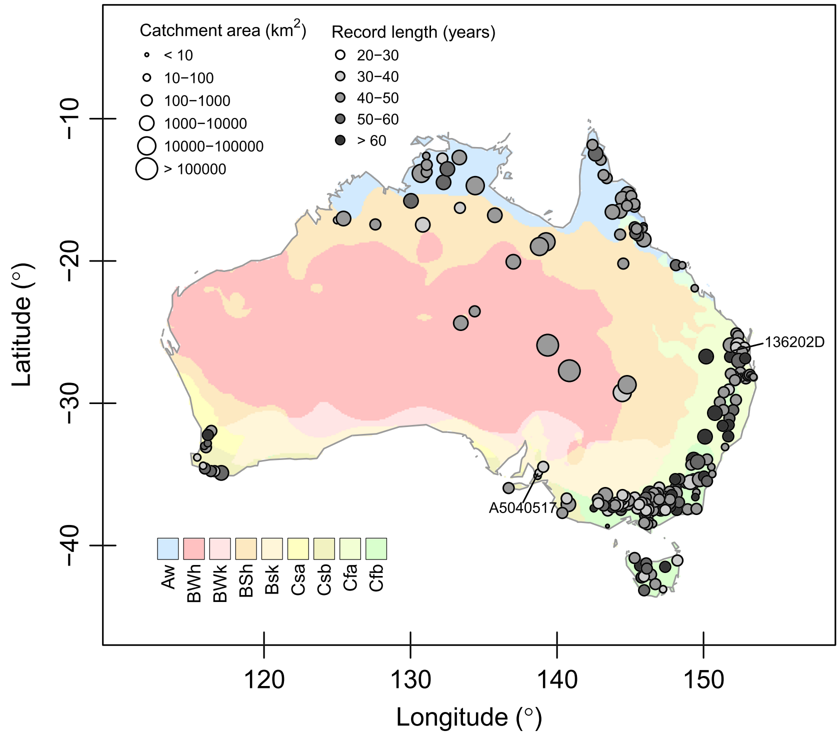

Figure 1. Streamflow gauging locations, catchment areas, and length of record. There are 221 catchments with a median record length of 46 years. The gauging stations are underlain by the Köppen climate classification (Peel et al., 2007).

1. Does annual maxima flood timing correspond more to the timing of rainfall maxima or soil moisture maxima, and does this vary with flood magnitude?
2. Is historical flood timing, rainfall timing, and soil moisture timing stationary?
3. Are changes in flood timing linked more to changes in rainfall timing or soil moisture timing, and can these changes be related to large-scale climatic changes such as mean rainfall and soil moisture changes?

To answer these questions, we use a national high-quality streamflow data set largely free of snowmelt with catchment average observed rainfall and modeled soil moisture. Circular statistics are employed to investigate the timing of streamflow, rainfall, and soil moisture maxima. Nonstationarity in the timing of each of the variables is investigated, for what believe is the first time, using circular regression.

2. Data and Climate

Daily streamflow are obtained for 221 catchments from the Australian Bureau of Meteorology's Hydrologic Reference Stations. The location of these catchments with their length of record is presented in Figure 1. The original data set consisted of 222 stations, but since its creation, one of the sites has been removed. The Hydrologic Reference Stations are considered the highest-quality, unimpacted, streamflow stations for the continent of Australia and are recommended by the Australian Bureau of Meteorology for use in detection of climatic trends (Zhang et al., 2016). The record lengths vary from 27 to 64 years with 1950 the first year of record and 2014 the last. The median record length is 46 years. Streamflow sites are predominately located in areas of high mean rainfall and population, and as a result, few long high-quality stations exist in the arid regions in the west and inland. The catchment areas vary in size from 4.5 to 232,846 km^2. The majority (180) of the catchments are less than 1,000 km^2 in area, a size range which is often referred to as being hydrologically small.

With reference to the Köppen climate classification presented in Figure 1, the climate of Australia broadly shifts from tropical (A) in the north to temperate (C) in the south and is arid (B) inland. The north is broadly tropical savannah (Aw) with strongly summer dominant rainfall. The northeast coast of Australia has

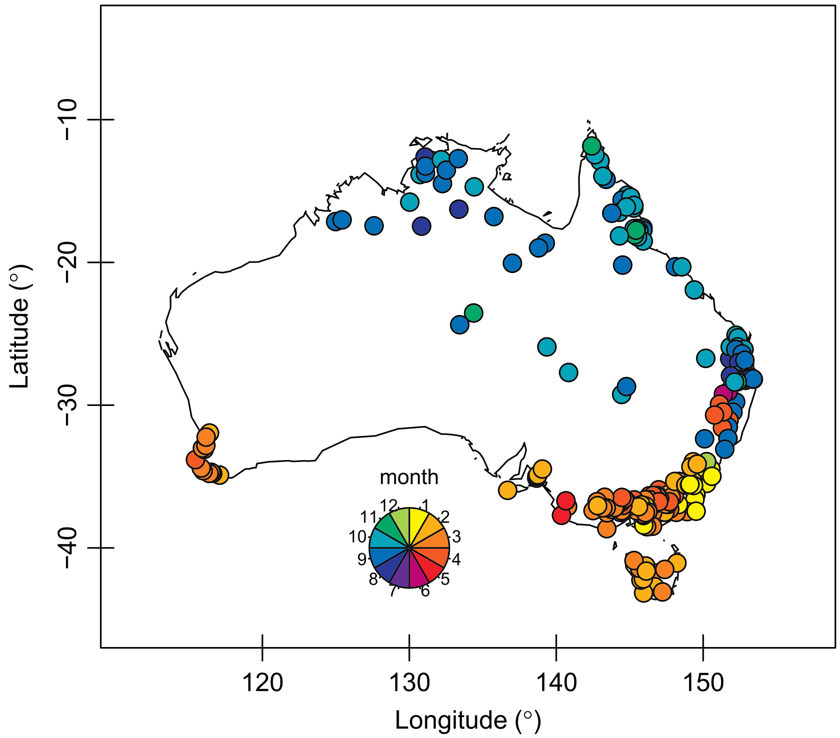

Figure 2. Month with the lowest average streamflow. The water year is defined as beginning in the month of lowest mean monthly streamflow. The legend is the month number of the calendar year.

greater mean rainfall than the central north largely as a result of advection of moisture via southeast trade winds. Southern coastal areas are temperate; the southwest is temperate with a dry summer (Cs), whereas the southeast has no dry season (Cf). The result is a strongly winter dominant rainfall in the southwest and a weakly winter dominant rainfall in the southeast. Rainfall seasonality varies systematically north to south so that along the temperate east coast it transitions through a seasonally uniform rainfall at approximately −30° latitude.

To ensure a sequence of dependent flood events is not counted in two successive years (e.g., Gumbel, 1941), annual flood maxima were extracted using a local water year that was defined as starting in the month with the lowest average streamflow (Figure 2). The water year begins in the austral spring in the tropics (before the start of the "wet" season) and toward late austral summer or early austral autumn in the south of Australia. For consistency, annual maximum rainfall and soil moisture were also extracted using the same definition of water year. Annual maxima for rainfall, soil moisture, and streamflow were extracted using a 7-day moving average. Note that all results were repeated without averaging over a 7-day period and the conclusions remained the same, which is consistent with Blöschl et al. (2017) who found that multiple-day precipitation timing statistics were almost identical to the characteristics of maximum daily amounts.

The rainfall is a catchment average calculated from the Australian Water Availability Project (AWAP) using the R package "AWAPer" (Peterson et al., 2020). AWAP is a high-quality daily gridded rainfall on a grid size of 0.05° or approximately 5 km (Jones et al., 2009), which is recommended for use in calculating catchment average extremes (Nathan et al., 2016; Nathan & McMahon, 2017). Catchment average soil moisture was extracted from the Australian Bureau of Meteorology Australian Water Resources Assessment Landscape (AWRA-L), a daily distributed water balance model that uses the same grid as AWAP to produce soil moisture and streamflow estimates across Australia (Viney et al., 2015). AWRA-L has been extensively evaluated against in situ soil moisture observations with correlations similar to, or exceeding, those found for remotely sensed products (Holgate et al., 2016). Here, soil moisture from the upper 1 m of the soil profile was used as it has been found to be most correlated with flood response (Hill et al., 2016; Hill & Thomson, 2016).

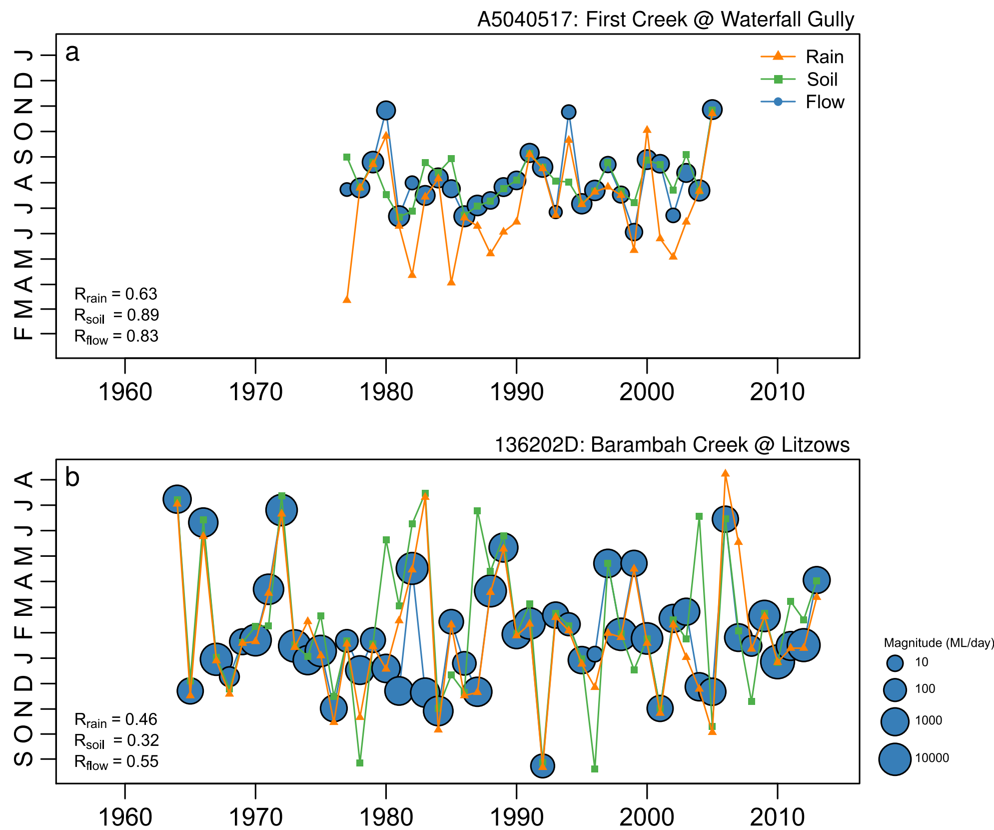

Figure 3. Time series of annual maximum rainfall (rain), soil moisture (soil) and streamflow (flow) for (a) First creek at Waterfall Gully and (b) Barambah Creek at Litzows. Site locations are presented in Figure 1. Only streamflow symbols indicate the magnitude of the event. Streamflow circle size (area) is proportional to the logarithm of flow magnitude. The *y* axis begins at the start of the water year for each site. The strength of the seasonality of each variable as indicated by the mean resultant length (*R*, see equation (4)) is presented for reference.

Illustrative time series are presented for two sites highlighted in Figure 1. First Creek is a small (5.3 km^2) dry summer temperate catchment, which shows a pronounced seasonality of all variables around winter (Figure 3a). Barambah Creek (647 km^2) is also a temperate catchment but, due to a more uniform monthly rainfall distribution, exhibits a greater spread in the timing of annual maximum rainfall, soil moisture, and streamflow, with a tendency toward a timing centered on the austral summer (Figure 3b). From here on, the rainfall, soil moisture, and streamflow are abbreviated to flow, rain, and soil.

3. Methods

Circular statistics are traditionally used to analyze timing of annual maxima as the first and last day of the calendar or water year are not linearly adjacent but are temporally continuous (Bayliss & Jones, 1993; Magilligan & Graber, 1996). Extensive evidence exists that streamflow and rainfall follow cyclical distributions (Gumbel, 1954; Villarini, 2016), and, although linearity can often be assumed for streamflow maxima originating from a single flood mechanism (e.g., Court, 1952), studies generally assume circular statistics due to the complications of ensuring unimodality where multiple flood causing mechanisms are present (Burn, 1994; Gumbel, 1954). Here, the seasonality (i.e., timing) of event maxima are investigated using circular statistics (Fisher, 1993).

With circular statistics, the chosen day of origin does change the statistics calculated. The ordinal day of the calendar year j_i for rain, soil, and flow timing is adopted. The ordinal day is converted to an angular value θ_i, where m is the number of days in the year t_i and $i = 1 \ldots n$, where n is the number of years of record (equation (1)):

$$\theta_i = \frac{j_i}{m} \times 2\pi \tag{1}$$

The mean direction $\overline{\theta}$, or timing (in radians), is calculated by (Fisher, 1993)

$$C = \sum_{i=1}^{n} \cos\theta_i \quad S = \sum_{i=1}^{n} \sin\theta_i \tag{2}$$

$$\overline{\theta} = \begin{cases} \tan^{-1}\left(\frac{S}{C}\right) & S>0, C>0 \\ \tan^{-1}\left(\frac{S}{C}\right) + \pi & C<0 \\ \tan^{-1}\left(\frac{S}{C}\right) + 2\pi & S<0, C>0 \end{cases} \tag{3}$$

where n is the number of observations, which in this case is the number of years. The strength of the seasonality is described by the *mean resultant length* R, which varies between 0 and 1, where 1 implies all values are coincident and a tendency away from 1 implies a more uniform distribution (equation (4)).

$$R = \frac{1}{n}\sqrt{C^2 + S^2} \tag{4}$$

An example of the interpretation of the mean resultant length is presented in Figure 3. First Creek at Waterfall Gully (Figure 3a) is strongly seasonal with both soil moisture and streamflow maxima almost exclusively observed in winter months; hence the values of R approach 1 and are equal to 0.89 for soil and 0.83 for flow. Rainfall maxima are more uniformly spread throughout the year (though still highly seasonal) and hence have a lower mean resultant length value of 0.63. In contrast, the seasonality of the hydroclimatic variables at Barambah Creek is more uniform, and hence, the values of R are lower; the flow maxima are the most seasonal of the three variables and hence have a mean resultant length of 0.55, but the soil maxima appear to almost occur at any time of the year (though a little more in the winter) and hence the R is closer to 0 (0.32). Although not a universal observation, the stronger the seasonality, the more likely that all the hydroclimatic variables exhibit the same timing (cf. Figure 3a to Figure 3b). Figure 3 will be referred to throughout the manuscript to aid interpretation of results. It needs to be noted that although a uniform distribution will have an R of 0, so to can a distribution with two perfectly antimodal (opposite) peaks on the unit circle, so a value of 0 does not necessarily imply a uniform spread around the unit circle.

Nonuniformity of seasonality is tested using the Rayleigh test. Uniformity is rejected if R is too large with the significance probability P calculated:

$$Z = nR^2 \tag{5}$$

$$P = \exp(-Z)\left[1 + \frac{2Z - Z^2}{4n} - \frac{24Z - 132Z^2 + 76Z^3 - 9Z^4}{288n^2}\right] \tag{6}$$

For example, soil moisture maxima at First Creek at Waterfall Gully (Figure 3a) have a high mean resultant length (0.89) and the p value (P) is equal to 3.4×10^{-10} indicating statistical significance and rejection of the null hypothesis that the distribution of soil moisture maxima is uniform. However, for Barambah Creek at Litzows, the soil moisture maxima have a smaller R and a p value of 0.005. Although the null hypothesis is rejected at the 1% level of significance, this distribution, even with its relatively large spread, can still be approximated as nonuniform.

Previous studies have generally used linear methods such as Mann-Kendall trend test and Sen's Slope estimator, after standardization of the circular timing data into a linear space, to investigate temporal trends. Here, temporal trends in the mean direction are analyzed using circular regression (Fisher, 1993; Jammalamadaka & Sengupta, 2001; Presnell et al., 1998) with the predictor, year (t), standardized by the mean ($\overline{t}$):

$$\hat{\theta}_i = \theta_0 + 2\tan^{-1}(\beta(t_i - \bar{t})) \quad (7)$$

The regression coefficient β (after transformation) corresponds to the temporal trend, and θ_0 corresponds to the mean direction. Circular regression is undertaken using the R package "circular" (Agostinelli & Lund, 2017). Referring to the example from Figure 3, the trend for First Creek is toward later soil maxima at 7.6 days per decade (Figure 3a), with a similar trend of 6.7 days per decade for Barambah Creek (Figure 3b). Visually, we may infer a stronger trend for First Creek (Figure 3a), but this is an artifact of plotting in a linear space. This highlights how circular regression considers, for example, the June/July soil moisture timing at the start of the record for Barambah Creek (Figure 3b) as possibly an early timing in circular space, despite it appearing as later timing in the linear space. Unless specified, all significance is presented as global (field) significance at the 1% level based on the false discovery rate (Benjamini & Hochberg, 1995), which is robust to spatial dependence (Wilks, 2006).

4. Results

4.1. Timing of Hydroclimatic Variables

Rainfall maxima timing (Figure 4a) in the tropical north of Australia generally occurs in February. The mean resultant length is greater than 0.8 (Figure 4d) indicating very strong seasonality. Correspondingly the maximum soil moisture (Figure 4b) and maximum streamflow (Figure 4c) have very strong February seasonality with $R > 0.8$ (Figures 4e and 4f). As demonstrated in Figure 4, the stronger the seasonality, the more likely the rainfall and soil moisture maxima timing coincide with the flood timing. Along the northeastern coast, the soil moisture and streamflow maxima exhibit March seasonality indicating that the streamflow maxima occur after the rainfall and the streamflow maxima correspond to the soil moisture maxima (additional illustration presented later in Figure 5).

As discussed, the Australian climate shifts from summer to winter dominant mean rainfall north to south, but the seasonality of rainfall maxima does not necessarily exhibit this climatic shift. For the tropics, the rainfall maxima generally occur in summer as expected, but the rainfall maxima also generally occur in the summer months for much of the east coast of Australia, even where the mean monthly rainfall are largely uniform. In the southeast there is little evidence of unimodality in the annual rainfall maxima (Figure 4d) and extreme rainfall is likely to occur at any time of the year. But soil moisture timing has a strong seasonality (Figure 4e) around August and September (Figure 4b), approximately at the same time as streamflow (Figure 4c). In the southwest of Australia all hydroclimatic variables exhibit strong seasonality but the rainfall maxima generally occur in June before the soil moisture (July) and flow (August).

Throughout the tropics there is a strong correspondence in the rainfall, soil moisture, and streamflow maxima occurrence, but along the east coast the flow peak more closely coincides with the soil moisture peak. This is also true for the southwest where the streamflow maxima lag the rainfall maxima by 1 to 2 months; streamflow maxima occur in either the same month or the month following the soil moisture maxima. In the southeast, while the timing of soil moisture and streamflow maxima are coincident, there is little or no correspondence to the timing of rainfall maxima. This is analogous to the example presented in Figure 3a where the green soil moisture squares overlay the streamflow (blue circles) more often than the rain (orange triangles), suggesting that, except for the tropics, flood timing is more modulated by soil moisture timing than rainfall timing.

4.2. Dependence of Timing to Flood Magnitude

To further inspect differences in timing between rainfall, soil moisture, and streamflow, Figure 5 presents a heat map of the difference between the timing of streamflow and rainfall and between streamflow and soil moisture. The differences in timing are plotted against a nondimensional measure of flow magnitude, the annual maxima flows at the site divided by the mean of annual maxima, which facilitates comparison of data across sites. The seasonality of flood timing can aid in identifying homogenous regions (Figure 4). The southwest, central north, and southeast of Australia are identified as regions of strong flood seasonality. The left column presents the difference between flow and rain timing, with the right column between flow and soil timing, with the rows representing each of the regions presented in Figure 5. The final (bottom) row presents all the data across Australia.

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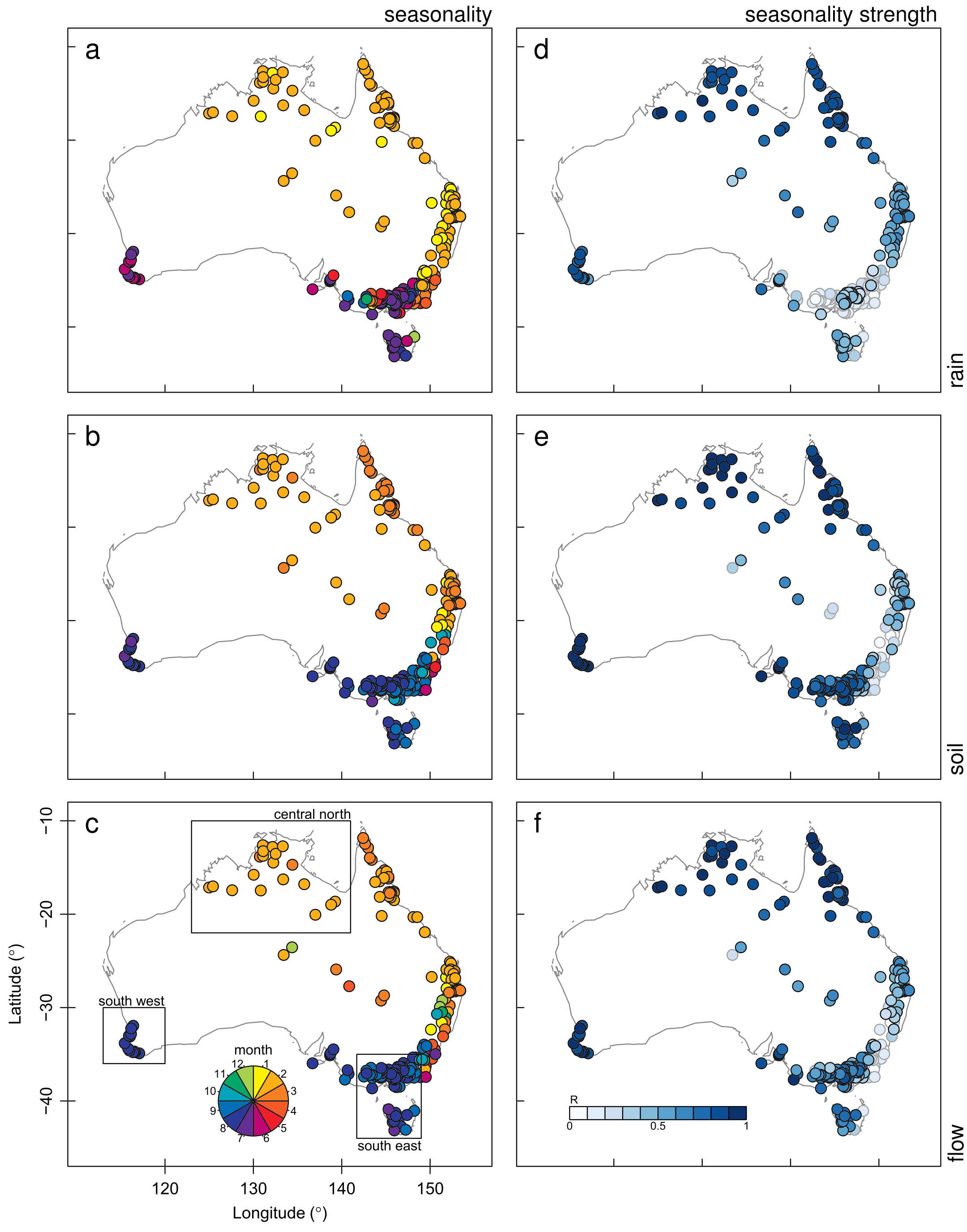

Figure 4. Seasonality and strength of seasonality (as measured by mean resultant length) for rainfall, soil moisture, and streamflow across Australia. The first column presents the seasonality for (a) rainfall, (b) soil moisture, and (c) streamflow. The second column presents the mean resultant length (R) for (d) rainfall, (e) soil moisture, and (f) streamflow. Sites where uniformity is rejected at the 1% level of field significance are colored using black outlines. Largely homogenous regions of streamflow timing are identified by rectangles.

As discussed in section 1, a flood of a given magnitude may result from either a relatively small rainfall event on wet ground or from a large rainfall event on a dry catchment. Figure 3a showed an example where the timing of the soil moisture maxima is generally coincident with streamflow, but for large events in particular, streamflow maxima coincide with both soil moisture and rainfall maxima. This tendency toward joint

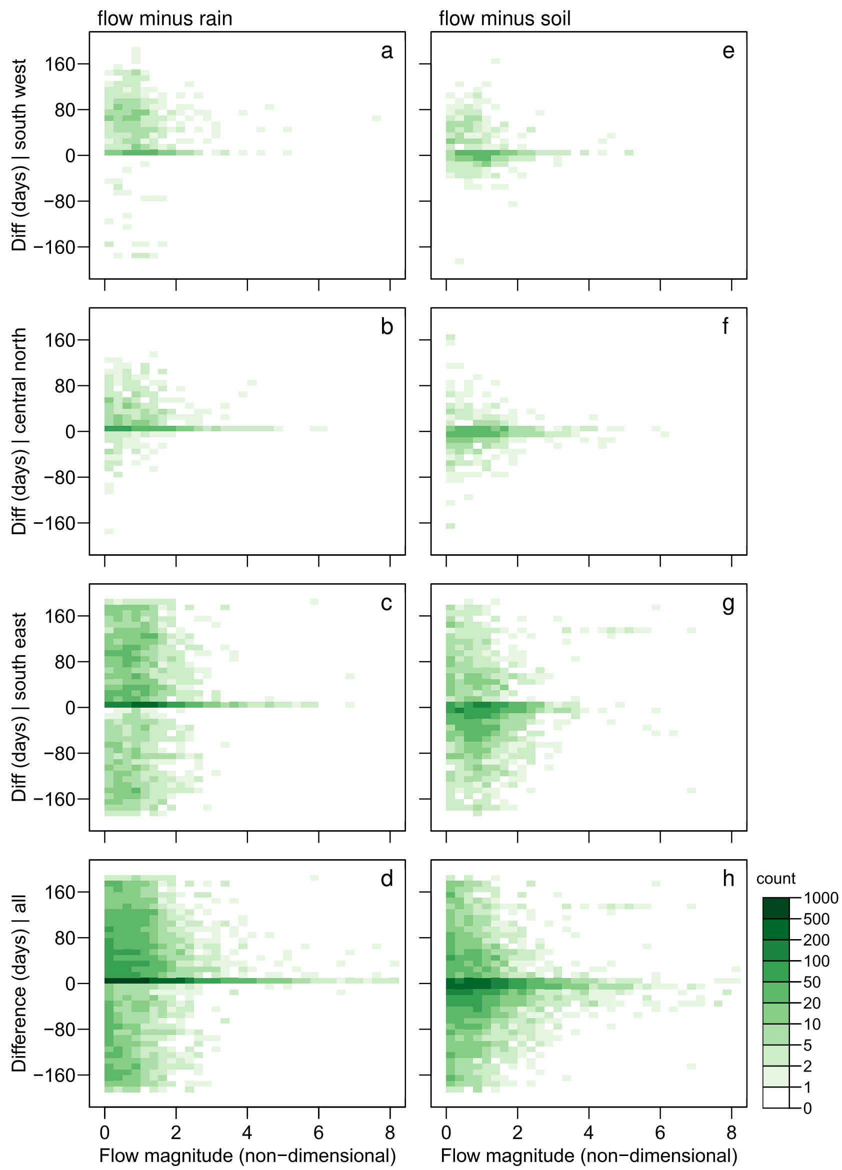

Figure 5. Heat map of difference in timing against the magnitude of the streamflow for (a–d) streamflow and rainfall and (e–h) streamflow and soil moisture. Rows represent the different regions depicted in Figure 3 (a, e) southwest, (b, f) central north, (c, g) southeast, and (d, h) all data. The color represents the number of occurrences. The streamflow has been normalized by the mean annual maximum streamflow for each site. Positive values indicate the rainfall or soil moisture maxima has occurred before the flow maxima.

occurrence suggests that the largest flood events are likely to be a result of both wet antecedent moisture conditions and large rainfall. Figure 3b showed an example with less correspondence between rain, soil, and flow maxima, but still, on average, the soil moisture timing corresponded more closely to the streamflow maxima timing. However, for the largest flow events (largest blue circles), the rainfall maxima are coincident with the streamflow maxima whereas the soil moisture maxima are not necessarily so. It is this variation in timing correspondence with flow magnitude that is summarized in Figure 5.

For the southwest, the flood timing corresponds to the rainfall timing for most events (Figure 5a). But there are a large number of instances of rain timing occurring almost randomly up to half a year prior to the streamflow maxima with almost no instances of rainfall maxima post the streamflow maxima. In contrast, although occasionally soil moisture peaks before the streamflow, the soil moisture timing corresponds

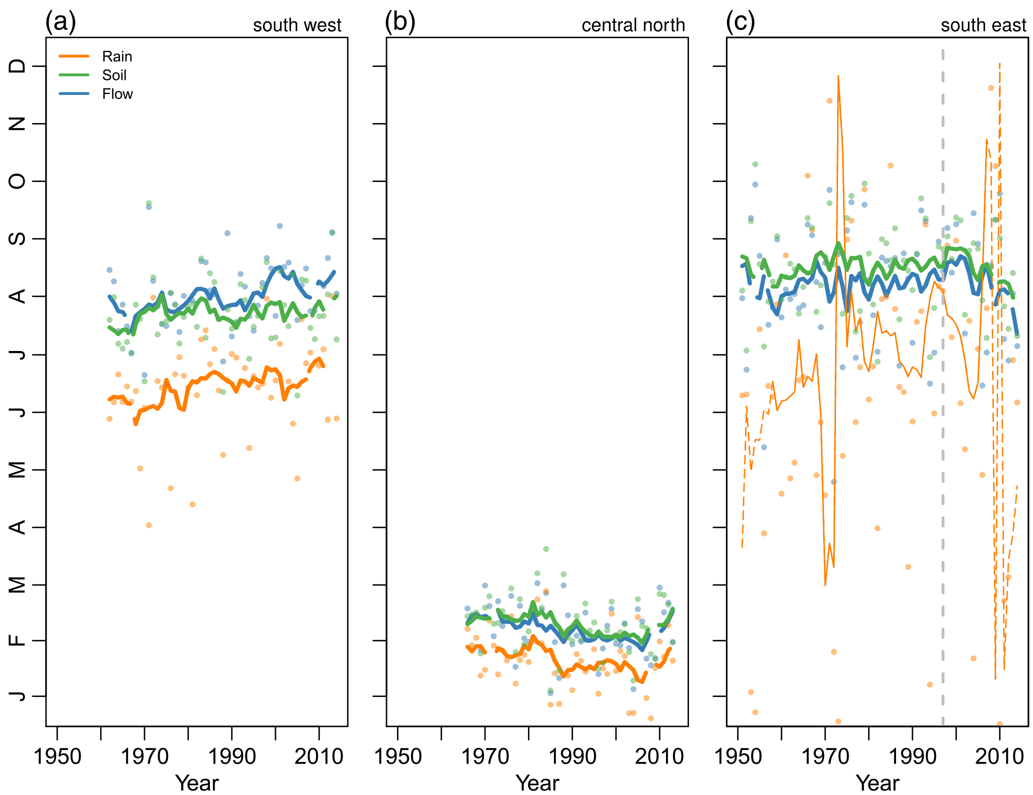

Figure 6. Rainfall, soil moisture, and streamflow timing for (a) southwest, (b) central north, and (c) southeast Australia. Each point is an average of all sites with records within the bounded regions in Figure 4. The thick line is a 7-year moving average. The broken line represents seven years from the end of the time series. Note that at least five sites had to be operating for the year to be included. The vertical gray dashed line represents the start of millennium drought in 1997.

more closely to the flow timing (Figure 5e). Although this presents only the timing of maxima, the results point to the hydrologic pattern of a catchment becoming increasingly saturated until a rainfall event occurs which results in a large flood and confirms that soil moisture timing is a dominant driver of flood timing in southwestern Australia.

In contrast, for central north the differences between the flow and rain timing (Figure 5b) look more similar to the difference between the flood and soil timing (Figure 5f). For the most part, flood events correspond to the peak rainfall and soil moisture timing, and this is particularly the case for those events of higher magnitude. For more frequent events there is still some evidence of moisture buildup due to rainfall maxima occurring before flow maxima, but this is not as pronounced as for the southwest. In this region there are more soil moisture maxima after the flow maxima suggesting that rainfall maxima are possibly driving flood response and the soil saturates as part of the large rainfall event.

The southeast of Australia encompasses a large proportion of gauging stations, and hence, there are more events. For rare events, say, those greater than twice the average annual maxima, there is a very strong dependence of the flood timing on the rain timing (Figure 5c) with fewer soil moisture maxima corresponding to these large flood events (Figure 5g). However, for more frequent events, say, those less than twice the average annual maxima, there are many occurrences of rainfall maxima timing uniformly distributed throughout the year (Figure 5c), which is not the case for soil maxima (Figure 5g). In southeast Australia, soil moisture maxima are more likely to coincide with flow maxima for less extreme events.

When we consider all the sites across Australia the relative importance of rain and soil timing on flow timing becomes clearer (Figures 5d and 5h). For the more frequent events, with magnitude varying between the smallest event up to twice the average annual maxima, there is little correspondence between the rainfall and streamflow timing (Figure 5d) with the heat map showing a wide range of differences between the timing of the streamflow and rainfall maxima. There is a high count of rainfall event timing almost uniformly

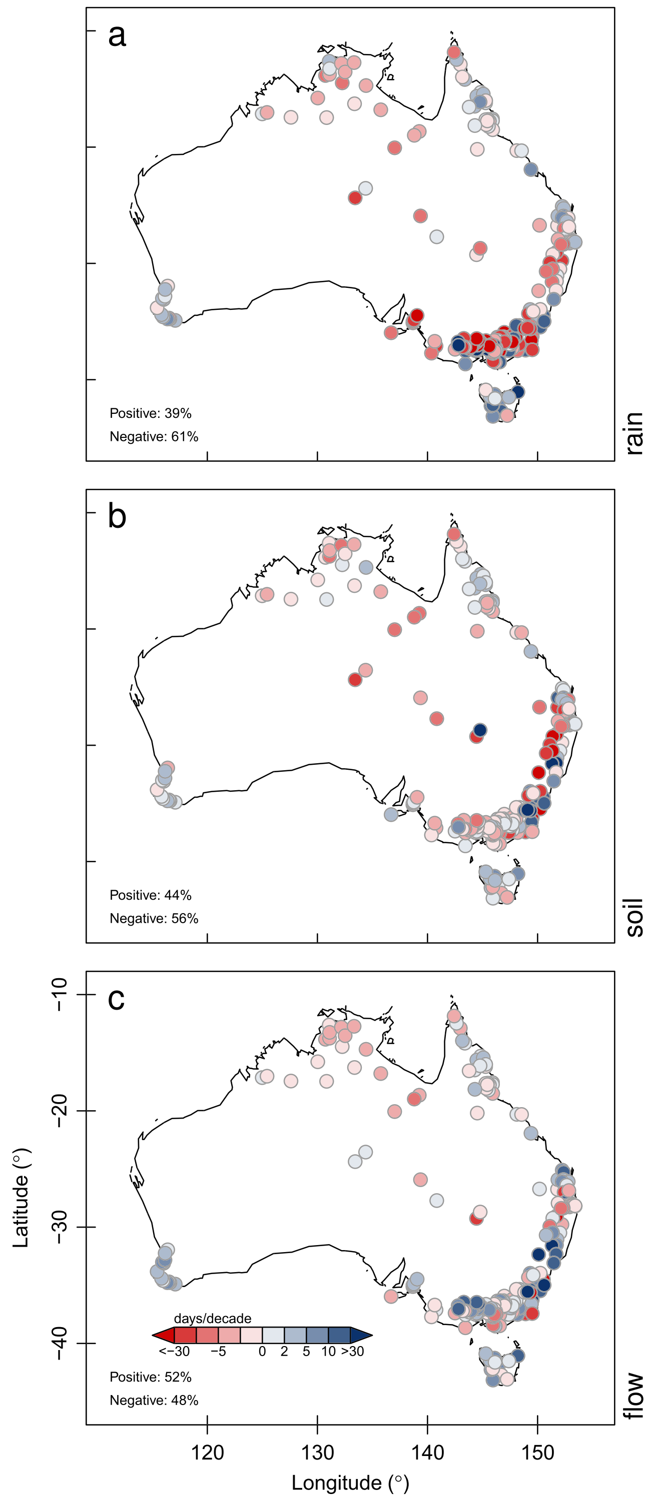

Figure 7. Historical trends in timing of the maxima for (a) rainfall, (b) soil moisture, and (c) streamflow. Red (negative) is a change in the number of days to earlier in the year, and blue (positive) is a change in the number of days to later in the year. No sites were statistically significant at 1% field significance.

distributed up to approximately 120 days prior to the flood event indicating that frequently rainfall maxima occur several days (or months) before streamflow maxima. However, for these more frequent events, the heat map for the difference in timing between the soil moisture maxima and streamflow maxima is more centrally tended, with the peak converging to coincidence of both variables (Figure 5h). There are much fewer soil moisture maxima prior to the streamflow maxima, with the majority of soil moisture peaks occurring at the same time (or just after) the streamflow maxima. This confirms that, on average, for more frequent flood events of the order of annual maxima, streamflow maxima timing is more related to soil moisture timing (as presented in Figure 4), suggesting antecedent moisture conditions are the driver of flood timing, whereas, for more extreme events, rainfall timing corresponds more with flood timing, so extreme rainfall is the primary driver of more extreme flood timing.

4.3. Nontationarity of Hydroclimatic Variables

To investigate nonstationarity, a time series of rainfall, soil moisture, and streamflow timing is presented in Figure 6 for each of the homogenous regions presented in Figure 5. For the southwest, rainfall and streamflow maxima are trending to later in winter (Figure 6a). The soil moisture timing precedes the flow timing with the seasonal pattern of the flow timing corresponding more closely to the soil moisture timing than rainfall timing (cf. Figure 5). But the soil moisture timing exhibits only a very weak trend toward occurring later in the year. Although it appears that soil moisture has a greater modulating effect on flood seasonality than rainfall, it is not necessarily clear what is driving the nonstationarity in flood timing.

In contrast to southwestern Australia, in the tropical center north there is a shift to earlier rainfall, soil moisture and streamflow maxima up to 2010 by 2–5 days earlier per decade, with a possible shift to later floods in the last few years (Figure 6b). It is evident, on average, streamflow peaks before soil moisture in the tropical north suggesting that, on average, there is a contribution from the rainfall that results in the streamflow maxima, which wets the soil to its maximum. The temporal trend of flow, rain, and soil moisture is all closely related, which suggests that changes in both rain and soil moisture timing are modulating flood timing in the central north. Similar temporal evolution is present for the northeast of Australia also, but little earlier or later trend is observed (results not shown).

Figure 6c presents the rainfall, soil moisture, and streamflow maxima for the winter rainfall dominant southeast Australia. The temporal evolution of the flood timing follows the soil moisture timing, with little correspondence to rainfall timing. The soil moisture and streamflow maxima timing were either stationary or shifting toward later in the year from 1970 to 1997. In 1997 one of the worst droughts on record occurred in southeast Australia (Van Dijk et al., 2013). This event is referred to as the Millennium Drought and ended in 2009, though we note that rainfalls have continued to be well below average in the years following the drought ending years of 2010/2011. Prior to the Millennium Drought beginning in 1997, the streamflow varies in concert with soil moisture. There is a distinct lack of seasonality in rainfall maxima, and hence, the shift in flood timing cannot be attributed to a shift in rainfall timing; rather, it is likely a result of a shift in soil moisture timing. After 1997 there is a large shift to earlier

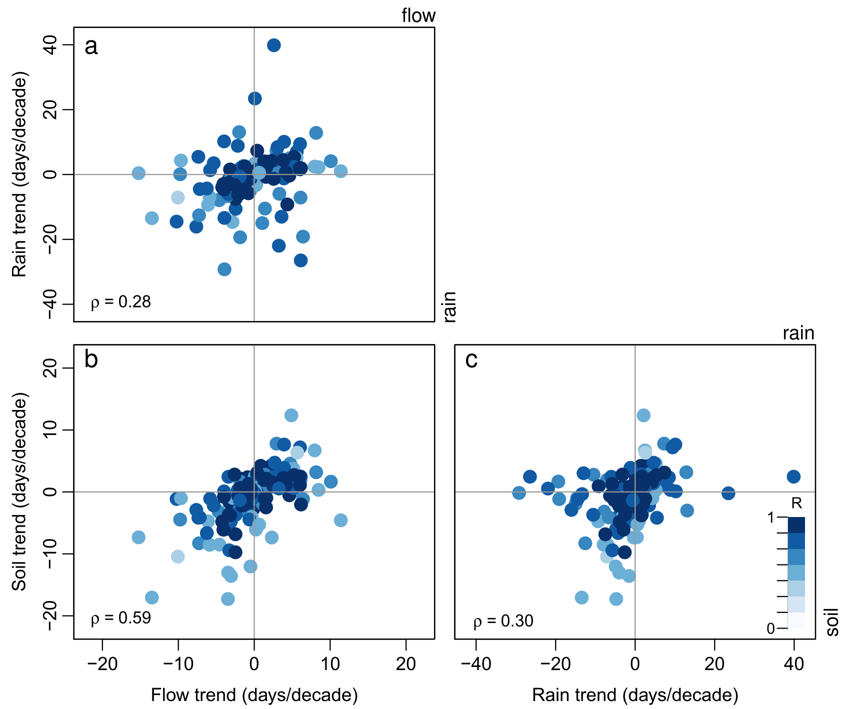

Figure 8. Correlation (ρ) of at site trends in timing of maxima for rainfall, soil moisture, and streamflow (a) correlation between trends in rainfall and streamflow, (b) correlation between trends in soil moisture and streamflow, and (c) correlation between trends in rainfall and soil moisture. Each dot represents a trend presented in Figure 7 for sites where uniformity was rejected at the 1% field significant level for all three variables (Figure 4).

flooding and soil moisture timing suggesting that the Millennium Drought has caused a large disruption in these catchment, which supports the findings Saft et al. (2015) that rainfall-runoff mechanisms in catchments in southeast Australia may have changed during the Millennium Drought.

4.4. Trends in Timing of Hydroclimatic Variables

Figure 7 presents the circular linear trend of timing in rainfall, soil moisture, and flood maxima. With possibly the exception of the Millennium Drought, the assumption of linearity in time trend appears valid (Figure 6) and inspection of the residuals for the fitted relationships (not shown) confirms the assumption of linearity is valid. Although none of the trends are statistically significant at the 1% field significance level, some spatial consistency exists and is discussed below. Trends in rainfall maxima are mixed, with 39% of sites trending to later in the year and 61% trending to earlier in the year (Figure 7a). A strong annual rainfall maxima seasonality in the tropics (Figure 4a) does not transfer to spatially consistent trends in rainfall maxima timing (Figure 7a). Rainfall maxima are trending to earlier in the year in the central north, but on the east coast the trends are mixed in direction. For compatibility with Figure 4, trends are calculated and presented for all sites regardless of whether the assumption of uniformity was rejected (Figures 4d–4f). We note that if a site has a uniform distribution, which is true for the southeast coast, then the calculated trend is more likely to be random, and unlikely to be meaningful. Tasmania, the southeastern island off the coast of mainland Australia, exhibits a trend to later annual rainfall maxima, as does the southwest of Australia.

The soil moisture maxima (Figure 7b) show broadly similar trends to the rainfall maxima (Figure 7a) with shifts to earlier in the year in the central tropics, later in the year in the southwest and mixed elsewhere (with no trends statistically significant). There is little spatial consistency in the soil trends across Australia with 44% of sites trend to later in the year and 56% of sites trending earlier. The streamflow maxima trends exhibit the strongest spatial coherence. For the central north there is a clear shift toward flooding earlier in the year of 2–5 days per decade. Along the east coast the trends are very mixed with only some spatial coherence in limited regions in the southeast. In the far southeast below −40° latitude (Tasmania) there is a shift to flooding later in the year. The southwest shows a shift to flooding later in the year of approximately 5–10 days per decade.

We note that not considering at site serial correlation can result in artificially lower statistical significance (*p* value) than if serial correlation were considered. But, since the field significance results indicated none of the trend tests were significant, the degree of artificial lowering of the *p* value by serial correlation must be small and any reduction in effective sample size minimal. Regardless, rain, soil, flow timing, and flow magnitude were checked for serial correlation using the Durbin-Watson test for autocorrelation (Durbin & Watson, 1950) with the number of sites found to have significant autocorrelation approximately equal to the number of sites that could be expected to be significant by chance.

Due to the large variability in the trends in timing of rainfall, soil moisture, and streamflow maxima (Figure 7), the cross correlation between trends are presented in Figure 8 for sites that did not have uniform distributions at the 1% field significance level (Figure 4). The trend in rainfall timing does follow the flow timing trend (Figure 8a), but overall, the correlation between the trends (0.28) is similar to the correlation (0.30) between the rainfall and soil moisture maxima (Figure 8c). Soil moisture and rainfall are coupled (Holgate et al., 2019), but we can expect the strength of this relationship to be less than that between annual rainfall maxima and streamflow maxima (Wasko & Nathan, 2019). In contrast, there is a stronger correlation (0.59) between the trends in soil moisture and streamflow maxima timing. This confirms that the primary driver of nonstationarity in annual flood maxima across Australia is the change in soil moisture timing.

5. Discussion

5.1. Climate Changes Influencing Flood Timing Across Australia

From the results presented it is evident that changes in soil moisture timing, as well as changes to rainfall seasonality, are driving nonstationarity of flood timing across Australia, with changes in soil moisture timing of more importance for more frequent events. Little literature exists on changes to the seasonality of rainfall, in particular changes in the rainfall prior to a flood event. An evaluation of why soil moisture antecedence is changing is beyond the evidence presented here, but some general inferences are possible.

There are large increases in mean rainfall in the central tropics and decreases elsewhere (CSIRO and Bureau of Meteorology, 2018; Head et al., 2014), particularly in the southeast and southwest of Australia (Risbey et al., 2013). This has been linked to a tropical expansion due the Earth's Hadley cells expanding poleward (Grise et al., 2018; Staten et al., 2018) and intensifying (Mitas & Clement, 2005). The result is that more of Australia's southern climate is trending toward dry subtropical with reduced autumn and winter rainfall (Cai & Cowan, 2013; Mathew & Kumar, 2019; Turton, 2017), corresponding to the seasons in which flooding generally occurs in the south of Australia. Changes in mean rainfall are broadly consistent with extreme rainfall decreases in the autumn months, and increases in the summer months (Zheng et al., 2015).

Understanding the impact of changed rainfalls on soil moisture is difficult due to, for example, coupling of rainfall to soil moisture (Holgate et al., 2019) and changing vegetation responses in response to climate change (Klamerus-Iwan & Błońska, 2018; Mankin et al., 2019). Evapotranspiration and evaporation historically show mixed trends across Australia. For example, for the period 1998–2008 a decrease in evapotranspiration was primarily driven by moisture limitations (Jung et al., 2010). Prior to 1999 decreasing pan evaporation across Australia was attributed to declining wind speeds (Johnson & Sharma, 2010). But subsequently, it has been found many sites around Australia are showing an increase in evaporation due to increasing vapor pressure deficit (Stephens, McVicar, et al., 2018).

It has been shown that antecedent soil moisture has decreased in the south of Australia and increased in the north (Wasko & Nathan, 2019). The reasons for changing antecedence soil moisture could be several, but the drivers are generally linked to the changing temporal pattern of rainfall (Sharma et al., 2018). For example, large-scale circulation pattern changes have been linked to changing rainfall occurrence (Huang et al., 2018) and antecedent rainfall related to flooding (Lu et al., 2013). However, broadly, changes in antecedent soil moisture across Australia prior to flood events follow changes in mean rainfall, creating a link from the tropical expansion through to soil moisture trends across Australia via a change in mean rainfall (Wasko & Nathan, 2019).

5.2. Relationship of Climatic Changes to Shifts in Flood Timing

A change in the average seasonal (or annual) rainfall does not necessarily explain a shift in the seasonality of flooding, but, all other factors being equal, if mean rainfall depth is reducing, it will take longer for soil moisture to increase, delaying the onset of flooding where soil moisture conditions modulate flooding. This may be the case in southwest Australia where rainfall timing often precedes flood timing by days if not months (Figure 5a) suggesting a soil moisture buildup prior to the onset of a flood event (Figure 5e). Drier antecedent soil moisture conditions and later rainfall maxima are consistent with a shift to later flood timing in southwest Australia (Figure 6a).

In the center north there is less evidence of a soil moisture buildup prior to a flood event with soil moisture peaking at or after the flood event (Figure 5f). As a result, flood timing appears to correspond closely to both soil moisture and rainfall timing. Wetter antecedent soil moisture conditions and earlier rainfall maxima are physically consistent with earlier flood timing on average, or at least up to the last decade (Figure 6b). The lack of consistent directions in the trends in flood timing on the northeast coast of Australia is broadly consistent with mixed rainfall maxima and soil moisture maxima timing trends (Figure 7b) and antecedent moisture conditions becoming both drier and wetter (Wasko & Nathan, 2019).

The direction of rainfall maxima timing trends in the southeast of Australia is mixed. However, the broad trend to earlier flood timing (Figure 7c) is consistent with the strong temporal correlation to changes in soil moisture maxima timing (Figure 6c) and drier antecedent conditions due to reduced rainfalls. But, as presented in Figure 6c, the direction of trend has reversed in recent years, coinciding with a large drought event. This change in direction is not substantial enough to reverse the direction of the overall linear trend presented in Figure 7c due to the small number of years toward the end of the record. But this example does serve to demonstrate that the above generalizations concerning large-scale climatic changes may not be applied on a catchment by catchment basis, and individual catchment characteristics and their changes remain an important consideration (Whitfield, 2012).

6. Conclusions and Implications

The timing of rainfall, soil moisture, and streamflow maxima is strongly seasonal (nonuniform) for the tropical north of Australia occurring in the austral summer, while only soil moisture and streamflow are strongly seasonal for the temperate south coinciding with the austral winter. In the southeast, the annual maxima rainfall timing shows little seasonality with the timing of extreme events being equally likely throughout the year. This questions the prevailing school of thought that rainfall from midlatitude cyclones (known as east coast lows), which occur in the cooler months, is the primary driver of extreme events such as flooding (Callaghan & Power, 2014; Johnson et al., 2016; Pepler et al., 2016). The results here suggest that the accumulation of soil moisture is the primary driver of flood timing for southeast Australia, in agreement with a recent study which classified flooding in the south of Australia as being caused by excess rainfall on saturated ground (Stein et al., 2019). Consistent with trends in flood magnitude across Australia being more modulated by changes in rainfall for more extreme events (Wasko & Nathan, 2019), the timing of a flood is more likely to correspond to the timing of the rainfall maxima for more extreme events. For less extreme events the reverse is true, with the timing of the soil moisture maxima more likely to correspond to the timing of streamflow maxima.

It is often assumed that changes in extreme rainfall will result in changes in flooding (Bates et al., 2008; Seneviratne et al., 2012), but changes in antecedent conditions will also modulate future flooding (Ivancic & Shaw, 2015; Sharma et al., 2018) and flood timing (Berghuijs et al., 2019). In the tropical north flood timing is shifting to earlier in the year consistent with earlier soil moisture maxima due to an increase in mean rainfall and earlier rainfall maxima. In the southwest of Australia, flood timing is shifting to later in the year consistent with later soil moisture maxima associated with decreasing mean rainfalls and later rainfall maxima. Changes in mean rainfall are consistent with shifts in large-scale atmospheric circulations where the tropics are expanding, resulting in mean rainfall increases in tropical regions and decreases in the extra tropics. In the southeast of Australia, streamflow and soil moisture maxima are trending to later in the year, consistent with the rest of the extratropics of Australia. The 1997 Millennium Drought caused a change in the direction of streamflow and soil moisture timing to earlier in the year for which we do not find evidence of a subsequent reversal, suggesting a change in the runoff mechanisms for catchments in this region (Saft et al., 2015). Overall, trends in flood timing are more spatially homogeneous and more consistent with changes in soil moisture timing than with changes in rainfall maxima. We conclude soil moisture is the dominant driver of annual maxima flooding across Australia.

Acknowledgments

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Erratum

In the originally published version of this article, Figure 6 was incorrect. The figure has since been corrected and this version may be considered the authoritative version of record.