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RESEARCH ARTICLE

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Wet season rainfall onset and flash drought: The case of the northern Australian wet season

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Abstract

In this paper, we report on the frequency of false onsets of wet season rainfall in the case of the Northern Australian wet season and investigate the role of large-scale tropical climate processes such as the El Niño–Southern Oscillation, Indian Ocean Dipole (IOD) and Madden–Julian Oscillation. A false onset occurs when a wet season rainfall onset criterion is met, but follow-up rainfall is not received for weeks or months later. Our analysis of wet season rainfall data from 1950 through 2020 shows a false onset occurs, on average, between 20 and 30% of wet seasons across all of northern Australia. This increases at a regional and local level such as at Darwin, the Northern Territory (NT), and parts of Queensland's north coast to over 50%. Seasonal climate influences, such as a La Niña pattern and a negative IOD that typically expedite the wet season rainfall onset, also increase the likelihood of a false onset over northern Australia. Our analysis also finds that periods of false onsets can sometimes, but not always, coincide with periods of rapid soil moisture depletion. The false rainfall onsets that develop into flash drought can be potentially disruptive and costly and are of potential significance for agriculture and fire management in northern Australia, and in other monsoonal climates that also typically experience a slow build-up to the seasonal monsoon. In conclusion, effective rainfall indicates that many seasons experience 'false onsets' with dry conditions after early rainfall. We propose that false onsets are a physical characteristic of the climate of northern Australia which occurs with relatively high frequency. In addition, these false onsets may sometimes co-occur with a flash drought.

KEYWORDS

El Niño–Southern Oscillation, Indian Ocean Dipole, Madden–Julian Oscillation, monsoon onset, rainfall

1 | INTRODUCTION

An estimated 50–60% of the world's population is impacted by the global monsoon system (Yancheva *et al.*, 2007; Wang and Ding, 2008; Qiao *et al.*, 2012). Variability in timing of the monsoonal rains has a significant impact on agriculture and economies across monsoonal climates (Fitzpatrick *et al.*, 2015; Pradhan *et al.*, 2017; MacLeod, 2018;

Parija, 2018; Bliefernicht *et al*., 2019; Ali *et al*., 2020; Lisonbee *et al*., 2020; Pirret *et al*., 2020). In many respects, delayed onsets, low seasonal precipitation totals, or prolonged breaks in monsoon precipitation can be considered a drought. Drought in tropical climates have similar impacts on agriculture and water availability as traditional droughts at higher latitudes (Duncan *et al*., 2013; Zhang *et al*., 2020). Monsoonal climates experience high temperatures, direct solar radiation, periods of high evaporation rates along with high rainfall variability, thus drought characteristics in tropical climates may include a rapid onset and/or a short duration (Zhang *et al*., 2019b; Yang *et al*., 2020). Short-duration tropical droughts may be similar to the '*verânicos*' of Brazil (Borges *et al*., 2018). The rapid onset of droughts in the tropics may also be similar to a 'flash drought' (Otkin *et al*., 2018b).

The aim of this study is to better understand some of the nuances of the northern Australian climate especially in regard to the wet season rainfall and monsoon onset. Northern Australia experiences a monsoonal climate (Zhang, 2010) with variability in the timing of the dry-to-wet season transition, and high variability in the timing of the monsoon onset (Lisonbee *et al*., 2020) and bursts and breaks in precipitation throughout the monsoon season (Drosdowsky, 1996). Lo *et al*. (2007) showed that the timing of the Australian wet season rainfall onset has high variability with a standard deviation that ranges from 10 days at the shortest over Australia's Top End Region (the region of the NT north of about 15°S) to over 30 days near the tropic of Capricorn. Lisonbee *et al*. (2020) showed that, by several definitions, in Australia the onset of the dynamical monsoon (e.g., the global-scale weather pattern, as opposed to the seasonal increase in precipitation) has a standard deviation of about 2 weeks and a range of almost 2 months from the earliest to the latest onset dates. This means that there could be times when the wet season rainfall begins early but the monsoon may be delayed (Lisonbee *et al*., 2020). Hence, we propose the following research questions: Are there times when the northern Australian wet season rainfall experiences a 'false onset', that is, the wet season begins but low rainfall or high evaporative demand dries the soils and creates a type of drought condition before the monsoon begins? Or, are there times when prolonged breaks in the monsoon create flash drought conditions? The focus of this research is to investigate periods of false onset in the Australian wet season, the frequency at which they occur, if their occurrence coincides with a flash drought, and if the frequency of occurrence is impacted by large-scale climate influences such as the El Niño–Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD; Saji *et al*., 1999) and the Madden–Julian Oscillation (MJO; Madden and Julian, 1971, 1972). To do so, we use precipitation and evaporation data at six locations across northern Australia and gridded rainfall and evaporation datasets to calculate how often a false onset to wet season rainfall occurs across northern Australia. We also use a gridded root-zone soil moisture dataset to investigate when these false onsets also coincide with a flash drought, as defined by a rapid reduction in soil moisture.

In the following, we review the key literature that characterizes northern Australia's wet season in Section 2.1 and flash droughts in Section 2.2. In Section 3, we describe the data and methodology used in our study, and Section 4 presents our results. Findings and implications for managing agriculture and other activities are discussed in Section 5 concluding with some key recommendations.

2 | BACKGROUND

2.1 | Wet season rainfall onset

In this paper, we draw a clear distinction between the Australian monsoon, the Australian wet season and the wet season rainfall onset. The monsoon is the global-scale weather pattern marked by a seasonal reversal of trade winds and an increase in precipitation (Ramage, 1971; Webster, 1981). The northern Australian wet season is defined as the months of October–April, and receives over 90% of the annual rainfall across tropical northern Australia (see Figure 1; Nicholls *et al*., 1982; Pope *et al*., 2009). Within the wet season, the seasonal rainfall usually begins slowly as isolated mesoscale thunderstorms. These increase in frequency and coverage as the season progresses until the onset of Australian monsoon, characterized by widespread and heavy rainfall. The monsoon usually begins in late December or early January (Keenan and Carbone, 1992; Drosdowsky, 1996; Pope *et al*., 2009; Lisonbee *et al*., 2020) with a mean onset date in the last week of December (Lisonbee *et al*., 2020). Although a large percentage (about 70%) of wet season rainfall comes from the monsoon (Nicholls *et al*., 1982) many potential users of long-range weather forecasts and historical weather information are primarily interested in the timing of the first rainfall of the season rather than the large-scale rearrangement of the troposphere. Thus, the research community has also defined a wet season rainfall onset (Nicholls *et al*., 1982; Nicholls, 1984; Cook and Heerdegen, 2001; Kullgren and Kim, 2006; Robertson *et al*., 2006; Lo *et al*., 2007; Balston and English, 2009; Drosdowsky and Wheeler, 2014; Berry and Reeder, 2016). After enduring 4–6 months with no rainfall, the first wet season rainfall is critical to replenish water supplies, reduce the fire risk and instigate grass growth in pasture

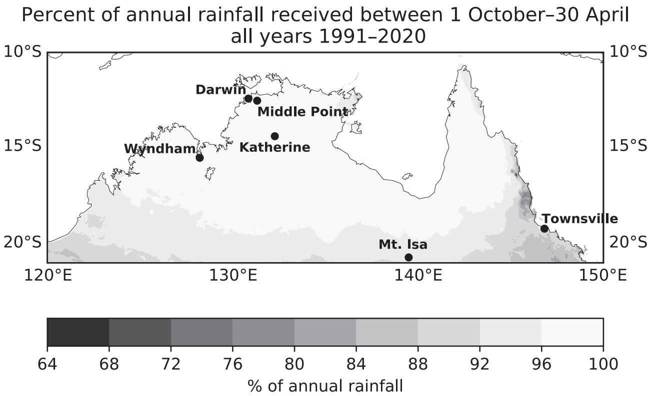

FIGURE 1 Locations used in this study and percentage of annual precipitation that falls within the wet season (October–April)

(McCown, 1981; McKeon *et al.*, 1990; Cook and Heerdegen, 2001; Lo *et al.*, 2007).

The northern Australian wet season rainfall onset has been defined in several ways (Lisonbee *et al.*, 2020). McCown (1981) used rainfall and a water balance model to define the commencement of a 'green season'. Nicholls *et al.* (1982) defined the wet season onset using varying accumulated rainfall thresholds. Nicholls (1984) defined wet season onset at a station in northern Australia when 15% of the mean annual rainfall was accumulated after September 1, the onset dates at 10 locations were then averaged to derive a northern Australia wet season onset. Cook and Heerdegen (2001) defined the 'rainy season' as the period when the probability of 10-day dry spells was less than 50%. Kim *et al.* (2006) calculated the seasonal (December–March) precipitation mean in mm/day; when the pentad rainfall anomaly first became positive relative to the seasonal mean at that location then the onset has occurred. Lo *et al.* (2007) defined a wet season onset as the date after September 1 when seasonal accumulated rainfall total exceeds 50 mm. Considering rainfall between September 1 to April 30, Smith *et al.* (2008) define the onset of a 'rainy season' as the date when 15% of the end of season total is accumulated and the end date as the date when 85% of the end of season total is accumulated. Balston and English (2009) use rainfall patterns in a plant growth model to find the 'green break of the season', or the transition from the dry to wet season relevant for pasture growth, for Ravenswood, Queensland (Qld), and surrounding rainfall stations; they defined the green date as 57 mm over 21 days after October 1. Berry and Reeder (2016) define the wet season rainfall onset as when the area-averaged rain transitions from at least 0.5 standard deviations below the seasonal average to at least 0.5 standard deviations above the seasonal average in less than a 7-day period (they call this a 'monsoon burst'). Berry and Reeder (2016) also made mention of 'false onsets' when the early season rainfall pattern is 'short-lived'.

The start of the wet season rainfall correlates well with ENSO indices (Troup, 1965; McBride and Nicholls, 1983; Lo *et al.*, 2007; Drosdowsky and Wheeler, 2014), but the onset of the dynamical monsoon does not correlate as well with ENSO with only a strong La Niña pattern correlating with an early onset (Lisonbee and Ribbe, 2021). The IOD has been shown to have a meaningful influence on rainfall totals in the early wet season (Risbey *et al.*, 2009; Taschetto *et al.*, 2011). A search of the literature for the influence of the IOD on the timing of the wet season rainfall onset did not yield any results, but the IOD has been shown to have only a small impact on the onset of the dynamical monsoon where a positive IOD correlates with a delayed monsoon onset at Darwin while a negative IOD did not show a statistically significant correlation (Lisonbee and Ribbe, 2021).

The MJO influences both rainfall rates and totals and the monsoon onset over northern Australia. Earlier research focused on the dynamical monsoon and a link was found between the active phases of the MJO over Australia and monsoon onset (Mcbride, 1983; Holland, 1986; Hendon and Liebmann, 1990; Drosdowsky, 1996; Hung and Yanai, 2004; Wheeler and Hendon, 2004; Pope *et al.*, 2009; Jackson *et al.*, 2018).

The present work, however, is focused on the wet season onset. Wheeler *et al.* (2009) and Risbey *et al.* (2009) focused on the impact of the MJO on rainfall rates across northern Australia and in various seasons. Wheeler *et al.* (2009) showed that September–November precipitation is slightly enhanced when the Realtime Multivariate MJO index (RMM; Wheeler and Hendon, 2004) is in Phases 6–7 (or over Australian longitudes) but suppressed in Phases 1–2, which may have implications on false onsets to the Australian wet season. When considering the wet season as a whole, Giangrande *et al.* (2014) showed that precipitation at Darwin during active MJO phases is twice that during suppressed phases. Berry and Reeder (2016) showed that, when averaged over northern Australia, sharp increases in rainfall rates are weakly modulated by the MJO where these rainfall bursts are more likely, but not exclusive to, when the MJO is active and in the vicinity of the Australian continent, consistent with previous studies. Ghelani *et al.* (2017) showed that the MJO increased rainfall in RMM Phases 5 and 6 and decreased it in Phases 2 and 3 and that this signal is enhanced during El Niño as compared to La Niña. Moron *et al.* (2019) found that early wet season weather patterns are not influenced by the MJO, but early bursts of the monsoon (occasionally in November and December) can be enhanced when the MJO is in RMM Phases 6–8. Murphy *et al.* (2016) showed regional variations in the effect of the MJO across northern Australia and also showed that November rainfall is the most variable of any month and that the MJO has a nominal impact on rainfall in November, a stronger impact in December and a strong impact on Monsoonal precipitation in January and February. Narsey *et al.* (2017) showed that the influence of the MJO on early wet season moisture bursts is secondary to the influence of a southerly moisture flux that is associated with higher latitude synoptic patterns.

2.2 | Flash drought

A 'flash drought' is usually considered to be 'an unusually rapid onset drought event characterized by a multiweek period of accelerated intensification that culminates in impacts to one or more sectors (agricultural, hydrological, etc.)' (American Meteorological Society, 2019; Otkin et al. 2018b). The application of the term *flash drought* has usually been applied to higher latitude drought events (Lisonbee *et al.*, 2021 and references therein), such as the major drought in the central United States in 2012 (Otkin *et al.*, 2016), the Murray Darling Basin, Australia, in 2017/2018 (Nguyen *et al.*, 2019), southern Africa in 2015/2016 (Yuan *et al.*, 2018), the Yellow River Basin, China, in 1991 (Liu *et al.*, 2020), Jiangxi Province, China, in 2003 (Zhang *et al.*, 2017) to name just a few. While at least one study examining flash drought intentionally defined the phenomena in a way that did not apply the term to monsoon onset (Mo and Lettenmaier, 2016), more recent research has investigated the frequency of flash droughts during the wet seasons of tropical locations around the world:

- Mahto and Mishra (2020) analysed the occurrence of flash drought during the Indian monsoon season;
- Zhang *et al.* (2020) examined the link between drought and monsoon variability over southern China;
- Stojanovic *et al.* (2020) examined flash droughts in Vietnam;
- Christian *et al.* (2019a, 2019b), while not the focus of their paper, suggest that a delayed monsoon onset may contribute to the development of flash drought in the southwest United States.

Only three previous studies have investigated flash droughts in Australia. Nguyen *et al.* (2019) used a standardized evaporative stress index (ESI) that depicts anomalies in the ratio of the actual to potential evapotranspiration (ET) to identify flash drought in Australia's northern Murray–Darling Basin in 2017/2018. Nguyen *et al.* (2021) used the ESI to examine large-scale climate drivers' influence on rapid intensification of drought conditions over eastern Australia in 2019. Finally, Parker *et al.* (2021) tested several methods to identify flash drought in Australia and compared these to a standardized soil moisture index (Ford and Labosier, 2017) to show that flash drought occurs relatively frequently in Australia and that northern Australia is among the more flash drought prone regions of the continent.

3 | DATA AND METHOD

False onsets to the wet season rainfall were identified using a combination of rainfall and evaporation data and periods of flash drought were identified using root zone (0–1 m) soil moisture data. These data were used to calculate the frequency of occurrence of false onsets and flash drought at a subset of locations across northern Australia using gridded precipitation, evaporation and soil moisture data. The frequency of occurrence was calculated for all wet seasons and for seasons when ENSO and IOD patterns were nonneutral. We also examined the phase of the MJO for seasons that experienced a flash drought.

3.1 | Data

Rainfall and evaporation data, both gridded and at point locations, were obtained from the Scientific Information for Land Owners (SILO) database of Australian climate data. SILO data products provide Australia-wide coverage with interpolated infills for missing data from 1889 to the present (Jeffrey *et al.*, 2001; State of Queensland Government, 2021). SILO is hosted by the Science and Technology Division of the Queensland Government's Department of Environment and Science. The rainfall and pan evaporation point data available from SILO originated from the Australian Bureau of Meteorology but with missing rainfall data infilled using a spatial interpolation method and evaporation data is derived where observations are not available (Jeffrey *et al.*, 2001; Beesley *et al.*, 2009 see also SILO documentation at https://longpaddock.qld.gov.au/silo/, last accessed June 30, 2021).

In this analysis, a La Niña event is defined as any year when the December to February mean NINO3.4 sea surface temperature anomaly is less than or equal to −0.8°C, and El Niño is when the same index is greater than or equal to +0.8°C. NINO3.4 values are from the National Oceanic and Atmospheric Administration's Climate Prediction Center (https://www.cpc.ncep.noaa.gov/data/indices/, last accessed March 17, 2022). Based on these criteria, 14 El Niño events and 17 La Niña events occurred between 1950 and 2021. The seasons used in this study are listed in Table 1.

IOD data using the Dipole Mode Index (Saji *et al.*, 1999; Verdon and Franks, 2005; Taschetto *et al.*, 2011) is from the

TABLE 1 Years when the ENSO and IOD criteria were met

El Niño years	1957, 1963, 1965, 1968, 1972, 1982, 1986, 1987, 1991, 1994, 1997, 2002, 2009, 2015
La Niña years	1950, 1955, 1970, 1973, 1975, 1984, 1988, 1995, 1998, 1999, 2005, 2007, 2008, 2010, 2011, 2017, 2020
Positive IOD years	1961, 1963, 1972, 1982, 1994, 1997, 2006, 2011, 2015, 2018, 2019
Negative IOD years	1954, 1955, 1956, 1958, 1959, 1960, 1964, 1968, 1974, 1975, 1980, 1981, 1984, 1992, 1996, 1998

Note: Where ENSO data are a 3-month average of December through February of the next year, for example, 1957 is the average NINO3.4 index for December 1957 through February 1958.

National Oceanic and Atmospheric Administration's Physical Science Laboratory (https://psl.noaa.gov/gcos_wgsp/Timeseries/DMI/, last accessed June 18, 2021; Saji and Yamagata, 2003). Dipole Mode Index thresholds used herein are ±0.4°C based on the September–November mean. From 1950 to 2021 there were 11 positive IOD events and 16 negative IOD events based on this criterion. The seasons used in this study are listed in Table 1.

MJO analysis was done using RMM phase and amplitude data from the Australian Bureau of Meteorology (http://www.bom.gov.au/climate/mjo/, accessed January 17, 2022). RMM data is available from June 1974.

3.1.1 | Station data

The locations for station data are shown in Figure 1, which also shows the percentage of annual precipitation that falls within the wet season (October–April). While data is available from 1889, the current analysis uses data beginning from the first year of record at each location, primarily due to concerns with data sparsity across northern Australia in the early part of the record. Darwin, NT, rainfall and evaporation data uses station number 14015, which has a consistent record beginning in 1941. Rainfall for the Katherine, NT, region came from Katherine Council station, station number 14902. The first full year of rainfall measurements in Katherine were taken in 1885. There are some gaps in the Katherine rainfall record in the decades of the 1980's, 1990's and 2000's, but the interpolated dataset fills in the gaps with nearby stations. Middle Point, NT, data are from Middle Point Rangers Station number 014090. Data at Middle Point Rangers Station began in 1959, with some gaps in the latter part of the record and modelled evaporation data. Mt. Isa, Queensland (Qld), rainfall and evaporation data is from station number 029127, the records are from 1966 to present. Data for northern Western Australia (WA) came from the town of Wyndham, WA, with station number 01013 where rainfall records began in 1968. Townsville, Qld, data came from Townsville Aero, station number 032040 where records began in 1941.

3.1.2 | Gridded data

The gridded precipitation and synthetic pan evaporation datasets from the 1950/1951 through 2020/2021 wet seasons were obtained through the SILO data portal. This data originated from the Australian Bureau of Meteorology's Australian Water Availability Project (Jones *et al.*, 2009). The data used in this analysis have a spatial resolution of 0.05° (or about 5 km) and a daily temporal resolution. There are caveats and limitations associated with any evaporation dataset; the gridded analysis used synthetic pan evaporation to approximate evaporative demand without making assumptions about vegetation type/height and with known limitations in the instrument record (Zajaczkowski and Jeffrey, 2020).

Soil moisture data is from the Australian Water Resources Assessment Landscape model (AWRA-L). AWRA-L is a daily, 0.05° grid-based, distributed water balance model (Frost *et al.*, 2018). Daily gridded soil moisture percentile data is available from 2000 to 2021. In this study, root-zone soil moisture data were used, which is an integration of soil moisture from 0 to 1 m depth.

3.2 | Method

The wet season rainfall onset date is defined as the date when 50 mm of rainfall is accumulated after September 1 as described by Lo *et al.* (2007) and further explored by Drosdowsky and Wheeler (2014) and Cowan *et al.* (2020). Lo *et al.* (2007) used this definition noting its simplicity and usefulness for northern Australian agriculture and showed that onset timing can be predicted using a statistical relationship with ENSO indices. Drosdowsky and Wheeler (2014) and Cowan *et al.* (2020) showed that there is skill in predicting this onset threshold using dynamical models at seasonal time scales. To capture both the accumulation and loss of water on the landscape, this study presents an adaptation of the 50-mm rainfall onset criteria by using the effective rainfall (precipitation minus evaporation) instead of the actual rainfall. A check of rainfall onset dates at Darwin Airport, for example, shows that in 20% of wet seasons the 50-mm threshold is accumulated within a single day and the accumulated total rainfall and accumulated effective rainfall are the same.

To identify false onsets, the total daily pan evaporation was subtracted from the total rainfall for that day to get an effective rainfall total. The daily effective rainfall was added to the previous day's total to find the accumulated effective rainfall amount. A false onset occurs when the accumulated effective rainfall reaches 50 mm at least once after September 1 and then returns to 0 mm at least once before the end of December of the same year (the average monsoon onset date at Darwin, NT).

An example of one wet season that experienced a false onset is shown in Figure 2. This example is from Darwin Airport for the 2018–2019 wet season. The accumulated rainfall reached the 50 mm threshold on October 26, 2018 (shown by the dashed line in Figure 2), the accumulated effective rainfall reached 50 mm on November 15, 2018 (shown by the solid line in Figure 2) but the accumulated effective rainfall returned to 0 mm by December 5, 2018. Thus, the 2018–2019 wet season was counted as a season with a false onset. The overall frequency of occurrence (FOC) of a false onset across the tropical north is calculated by:

$$\mathrm{FOC}=\frac{n}{N}\times 100,$$

where n is the number of seasons where a false wet season onset occurred and N is the total number of seasons considered. This method was applied to six locations across northern Australia. The method was also applied to gridded precipitation and evaporation data to calculate the frequency of occurrence of false wet season rainfall onsets across northern Australia.

The frequency of occurrence was also calculated using the rainfall and evaporation grids for only the wet seasons from 1950 to 2021 when ENSO and the IOD were nonneutral based on the threshold definition given in Section 3.1. The influence of the MJO was analysed by looking at the progression of MJO phases for seasons that experienced a false onset.

Flash drought was analysed following an adaptation of the methodology first introduced by Ford and Labosier (2017). The same approach has been used to investigate flash droughts in Australia (Parker *et al*., 2021) and India (Mahto and Mishra, 2020). A soil moisture flash drought is defined as when the pentad-average root zone (0–1 m) soil moisture percentile declines from at or above the 40th percentile to at or below the 20th percentile in four pentads (20 days) or less. Following Mahto and Mishra (2020), we further defined that a flash drought must have a minimum duration of four pentads, and we define the termination of a flash drought to occur when soil moisture rises to the 25th percentile. We did not apply a maximum duration criterion for a flash drought. Some flash droughts were short and lasted only for the four pentads needed to meet the minimum requirement for a flash drought while some droughts experienced a rapid onset near the end of the wet

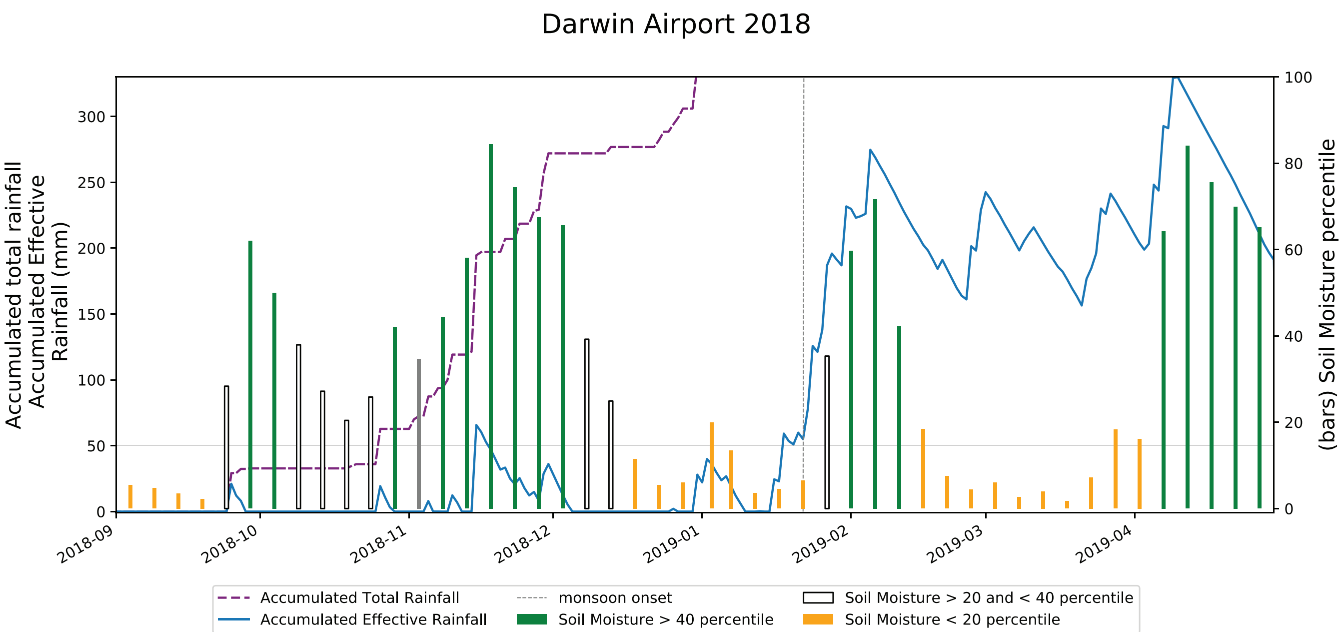

FIGURE 2 Accumulated effective rainfall (mm, solid), accumulated total rainfall (mm) for the same season (dashed) and root-zone soil moisture (bars) at Darwin airport for the 2018 wet season. Soil moisture bars are highlighted by value as soil moisture above the 40th percentile, soil moisture between the 40th and 20th percentile, and soil moisture below the 20th percentile. The 50 mm wet season onset threshold is marked by the horizontal line and the monsoon onset is marked by the vertical dotted line [Colour figure can be viewed at wileyonlinelibrary.com]

season and the drought continued throughout the dry season.

4 | RESULTS

4.1 | Analysis at point locations: Darwin, Katherine, Middle Point, Wyndham, Mt. Isa and Townsville

Figure 2 shows an example of a false wet season onset and was briefly mentioned in the Section 3.2 above. This example is from Darwin Airport for the 2018/2019 wet season; an especially dry season when the total monthly rainfall for December was only 67.2 mm, a quarter of the long-term monthly mean, and the January 2019 rainfall total was 362 mm, nearly 70 mm below the long-term average. The accumulated 50 mm wet season onset threshold (Lo *et al.*, 2007; dashed line in Figure 2) was met on October 26. When considering the accumulated effective rainfall, the onset threshold was met on November 15, 2018 when Darwin Airport received 73.2 mm of rainfall (solid line in Figure 2). Even with some small rainfall totals in the following days, the accumulated effective rainfall had returned to 0 mm by December 5. During this time the soil moisture declined from above the 60th percentile on December first to below the 20th percentile by December 15th and remained below the 20th percentile for eight pentads, when the monsoon began (as defined by Drosdowsky, 1996; the vertical dashed line in Figure 2) on January 23, 2019. This dry period qualified as both a false onset and a flash drought embedded within the wet season. The 2018/2019 wet season saw a second period in February and March that also met the flash drought criteria based on soil moisture percentiles alone, but due to this being a very wet time of year, the soils were 58% of saturation for February and 33% of saturation for March (not shown) and may highlight a limitation to using soil moisture as the defining feature of flash drought in monsoonal locations.

Calculating the frequency of occurrence for all years from 1941 (when records began at Darwin Airport) to 2020, a false onset to the wet season occurred at Darwin Airport in 52% of wet seasons, or about once every other year. Middle Point Rangers, Katherine, Wyndham and Townsville experienced a false onset in 36%, 34%, 33% and 30% of wet seasons, respectively, or about once every third year. Mt. Isa experienced a false onset to the wet season in 21% of wet seasons, or about once every 5 years, on average.

4.2 | Spatial analysis of wet season false onsets

To analyse the spatial distribution of the frequency of a false onset to the northern Australia wet season rainfall we analysed gridded data for every wet season from 1950 to 2020. For each wet season day, the effective rainfall was calculated at each grid point and added to the effective rainfall of the previous day. If the accumulated effective rainfall reached the 50 mm wet season onset threshold after September 1 and then reduced to at or below 0 mm before December 31 of that year then that grid point was counted as a false onset to the wet season for that year.

This analysis shows two regions in northern Australia where over 50% of the years experienced a false onset to the wet season rainfall (Figure 3). These are along the east coast of northern Qld, stretching from roughly Townsville, Qld, in the south to Cairns, Qld, in the north,

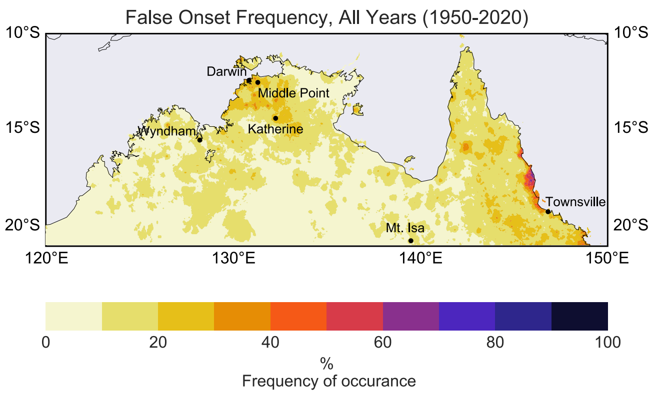

FIGURE 3 False onset frequency for all years from 1950 to 2020 [Colour figure can be viewed at wileyonlinelibrary.com]

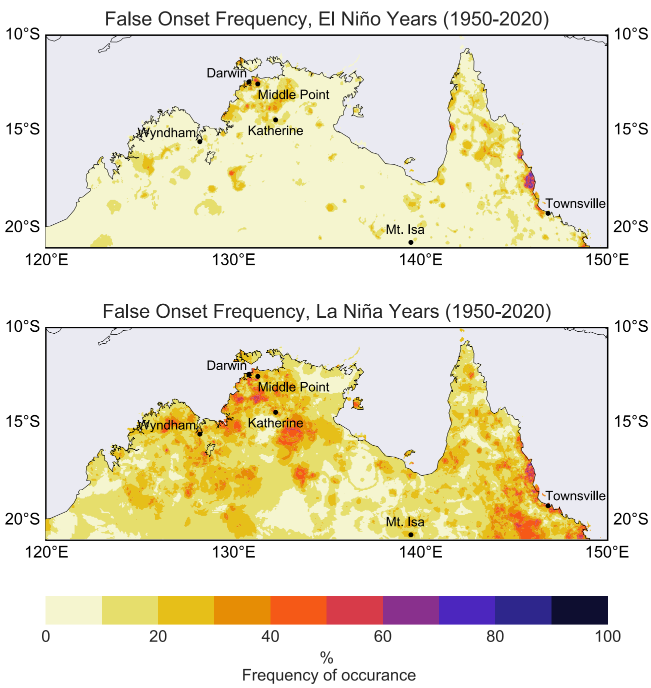

FIGURE 4 False onset frequency for all El Niño years (top) and all La Niña years (bottom) from 1950–2020 [Colour figure can be viewed at wileyonlinelibrary.com]

and the grid cells over Darwin, NT. It is worth noting that coastal Queensland experiences a different climate from the rest of northern Australia. The Queensland coast has been described as the 'wet tropics' (CSIRO and Bureau of Meteorology, 2015) where the rainfall is strongly influenced by the orographic effects of moist easterlies meeting the Great Dividing Range. As such, the region does not experience a distinct dry season in the same way that the rest of northern Australia does, but can still experience long periods without meaningful rainfall, as shown in this analysis.

Darwin Airport is located near the coast and experiences local coastal effects in the seasonal rainfall patterns. While the frequency of occurrence of false onsets exceeds 50% near Darwin, the frequency drops quickly to 30–40% just inland from Darwin, including at Middle Point (~50 km from Darwin Airport) and Katherine (~280 km). For most of the western Top End region, the frequency of false onsets is 20–30%. The frequency of occurrence for all years from 1950 to 2020 for all of northern Australia is shown in Figure 3.

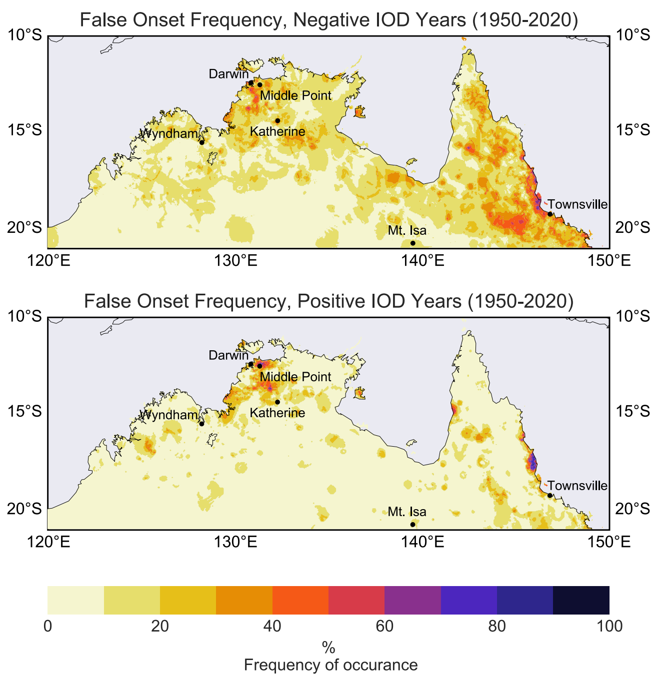

FIGURE 5 False onset frequency for all negative IOD events (top) and all positive IOD events (bottom) from 1950–2020 [Colour figure can be viewed at wileyonlinelibrary.com]

4.3 | The influence of seasonal climate patterns

Our analysis shows that false onsets are closely tied to seasons with below average rainfall (not shown). Across Cape York, the Top End of the NT, and the northern Kimberley region of WA all seasons that experienced a false onset from the years 1950 to 2020 occurred in a year with below average October–December total precipitation (based on the 1991–2020 average). When considering the opposite concurrence, between 5% and 35% of seasons when the October–December total rainfall was below average also experienced a false onset.

False wet season onsets are more prevalent during La Niña when compared to both El Niño (Figure 4) and all years (Figure 3) from 1950 to 2020. The prevalence of early wet season onsets in La Niña years and delayed onsets in El Niño years (Lo *et al.*, 2007) may explain this pattern. Lisonbee and Ribbe, 2021 showed that only strong La Niña patterns expedited the monsoon while weak La Niña, neutral and El Niño patterns did not have a statistically significant impact on the monsoon onset. The present analysis did not differentiate between weak and strong ENSO events. Therefore, one possible explanation for the increased occurrence of false onsets during La Niña events is that the time between the wet season onset and the monsoon onset in La Niña years would be longer than that of neutral or El Niño years, giving more time for a false onset to occur. A similar but opposite argument could be applied to El Niño years.

	1	2	3	4	5	6	7	8
Darwin Airport	-0.75	-0.88	0.95	0.59	1.75	1.45	1.61	-0.12
Middle Point Rangers	-1.08	-0.6	0.26	0.39	0.9	1.62	0.83	-0.5
Katherine Council	-1.27	-1.28	0.26	0.21	0.48	1.23	1.21	-0.74
Wyndham	-0.84	-1.21	-0.49	0.45	0.04	1.56	1.88	-1.11
Mt. Isa	-0.19	-0.3	-0.17	0.16	-0.32	-0.02	1.01	0.24
Townsville	-0.7	-1.11	-0.12	-0.28	-0.6	-0.2	0.54	0.41

FIGURE 6 Daily rainfall anomaly for RMM active phases and locations for the pre- and early-wet season months of September through December, inclusive. The anomaly is calculated as the difference between the mean daily rainfall during active (RMM amplitude > 1) and inactive or indiscernible (RMM amplitude < 1) periods [Colour figure can be viewed at wileyonlinelibrary.com]

Figure 5 shows the frequency of false wet season onsets during positive and negative IOD years over northern Australia. During a positive IOD event the north western NT sees an increase in frequency when compared to all years (see Figure 3) while most of the rest of northern Australia sees a decrease in the frequency of false onsets. In contrast, most of northern Australia generally sees a slight increase in the frequency during negative IOD years as compared to all years from 1950 to 2020.

The wet season onset is more likely when the MJO is active over Australian longitudes and the effective rainfall is less likely to return to zero while the MJO is active over Australia but can return to zero during any other phase of the MJO. Figure 6 shows the pre- and early-wet season (September–December) daily rainfall anomaly for each active MJO phase (RMM amplitude is >1) compared to all days when the MJO is weak or indiscernible (RMM amplitude is <1) for the six locations considered in Section 4.1, similar to the analysis done by Borges *et al.* (2018). Consistent with previous studies, we found that periods of increased rainfall are more likely in RMM Phases 5–7 while suppressed rainfall is more likely for Phases 1–2 with some differences by location. This alone would imply that the

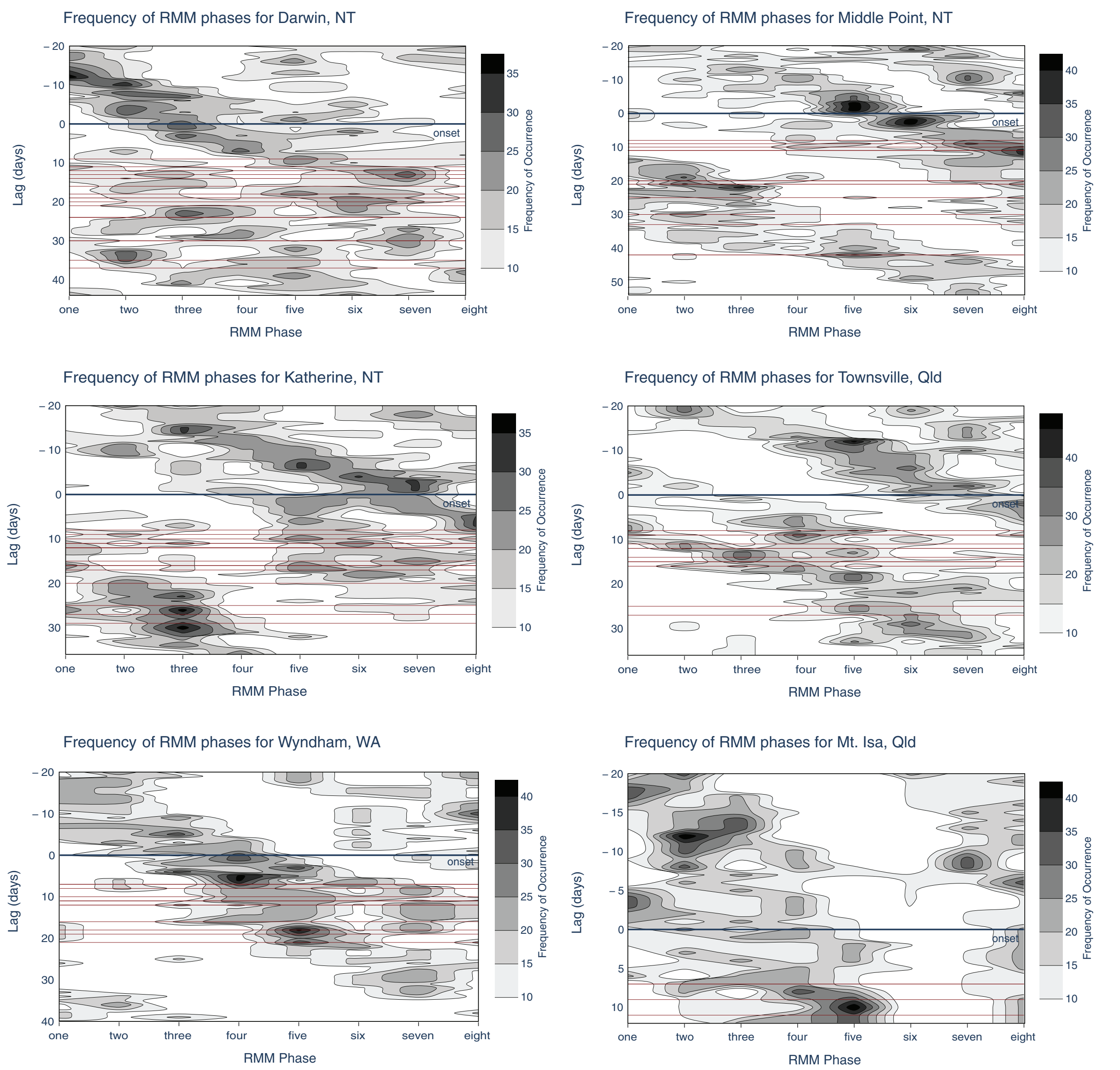

FIGURE 7 Frequency of occurrence (shading) of RMM phase (of any amplitude) and lag time in days for seasons that experienced a false onset of wet season rainfall. The zero-line represents the dates when the accumulated effective rainfall reached the 50 mm threshold and each subsequent horizontal lines denotes the dates when the accumulated effective rainfall returned to 0 mm after the onset [Colour figure can be viewed at wileyonlinelibrary.com]

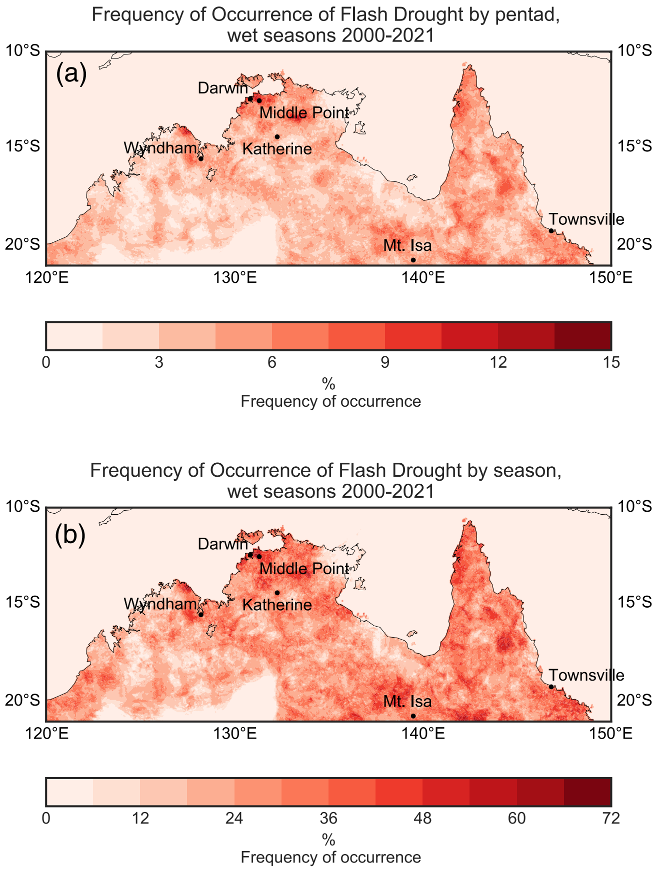

FIGURE 8 Frequency of occurrence of flash droughts within wet season months of October through April for the years 2000–2021: (a) calculated as the number of pentads that met the flash drought criteria per total pentads; (b) calculated as the number of seasons which met the flash drought criteria at least once per total seasons [Colour figure can be viewed at wileyonlinelibrary.com]

early wet season rainfall onset would be more likely when the RMM shows Phases 5–7 and that the effective rainfall would be more likely to return to zero in Phases 1–2. Figure 7 shows the frequency of RMM phases of any amplitude as a function of composite lag time relative to the wet season rainfall onset date for seasons that included a false onset at the same six location considered earlier, similar to an analysis done by Berry and Reeder (2016). The influence of the MJO on false onsets varies by location. Darwin and Katherine, for example, do not show a clear link between the MJO and false onsets while Townsville usually experiences an onset when the MJO is in Phase 7 and then the effective rainfall returns to zero when the MJO is in Phases 2–5.

4.4 | False onsets and flash drought

Parker *et al.* (2021) demonstrated that flash drought, as defined by a standardized soil moisture index (Ford and Labosier, 2017), occurred over Cape York and the *Top End* during 10–15% of days within their study period, which is relatively high when compared to other parts of the country but consistent with other studies of climate regions that experience high soil moisture variability (Pendergrass *et al.*, 2020). When focusing on just the wet season (October–April) and using pentad data from 2000 to present, we found a similar FOC (Figure 8a) as Parker *et al.* (2021) for Australia which is also similar to the FOC that Mahto and Mishra (2020) found for the Indian monsoon season. To align with the method used for the FOC for false onsets shown in Section 4.2, Figure 8b shows the FOC of wet seasons that experienced a flash drought at least once within the season. When considering the seasonal frequency of occurrence, the mean across all of northern Australia is 25% of seasons. On the higher end of the distribution, a few rare spots met the soil moisture flash drought criteria in over 60% of wet seasons. The relative high frequency of apparent flash droughts seems to provide some evidence that, despite the use in previous studies (e.g., Mahto and Mishra 2020), changes in soil moisture percentiles may not be a good flash drought indicator in tropical locations. If the flash drought criterion is met so frequently (every second or third year in some locations) then it is not a drought (i.e. climatological extreme), rather, it is evidence that frequent, rapid drops in soil moisture are part of the climatology of that location.

A false wet season onset and a soil moisture flash drought may coincide, but they do not always. Figures 9a–10c show examples from Townsville, Qld, that illustrate three scenarios: (a) flash drought without a false onset, (b) both a flash drought and a false onset, and (c) a false onset without a flash drought. Figure 9a is an example from the 2020–2021 wet season when there was a flash drought without a false onset. The wet season rainfall onset was delayed until the end of December, nearly 8 weeks later than average (Lo *et al.*, 2007), and the soil moisture dropped from above the 40th percentile on November 10, 2020 to below the 20th percentile by four pentads later on November 30, 2020, and remained low for five pentads in December. Figure 9b shows an example from the 2013–2014 season of a false wet season rainfall onset from a rainfall event on November 1, 2011, but without follow-up rainfall the soil moisture declined steadily through November and December followed by a rapid decline in the last two pentads in December that resulted in flash drought conditions through January 2014. Using an accumulated rainfall threshold alone would give the indication that the 2013–2014 wet season rainfall began early without any other indication of potential difficulties for agriculture or fire management in the region. The delay of a month or two between the

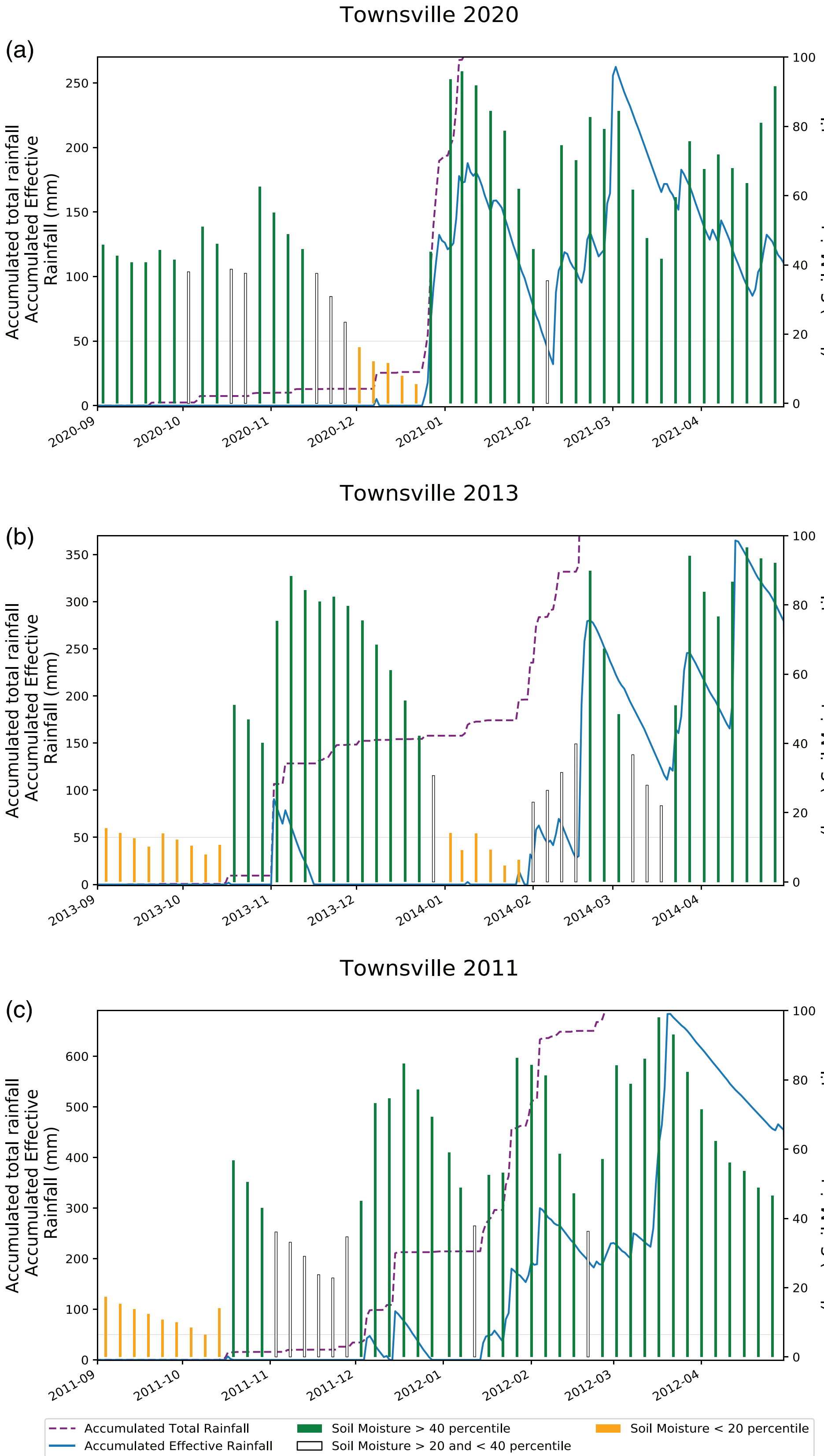

FIGURE 9 Accumulated effective rainfall (solid), accumulated total rainfall (dashed) and root-zone soil moisture percentiles (bars) at Townsville aero for the following wet seasons: (a) 2020–2021, (b) 2013–2014, (c) 2011–2012. Soil moisture bars are highlighted by value as soil moisture above the 40th percentile, soil moisture between the 40th and 20th percentile, and below the 20th percentile. The 50 mm wet season onset threshold is marked by the horizontal line [Colour figure can be viewed at wileyonlinelibrary.com]

false onset and the development of a flash drought was a common characteristic among all the sites considered in this analysis. Oftentimes the wet season rainfall onset criterion is met, causing high percentile soil moisture, but hot summertime temperatures, high evaporative demand and low follow-up rainfall depletes the soil

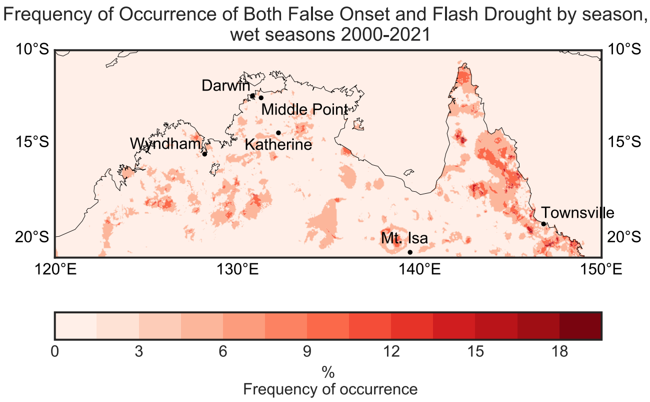

FIGURE 10 Frequency of occurrence of seasons that experienced both a false onset and a flash drought within the wet season months of October through April for the years 2000–2021 [Colour figure can be viewed at wileyonlinelibrary.com]

moisture and a flash drought develops several weeks later. Finally, Figure 9c shows an example from the 2011–2012 wet season when the rainfall showed a false onset in mid-December 2011, but the soil moisture remained above the 20th percentile.

From these examples at Townsville, Qld, a FOC can be calculated for how many seasons experienced a false onset, a flash drought and both a false onset and a flash drought within the same season. For all years from 2000 to 2020 (the years with available daily soil moisture data) Townsville experienced a false onset in 29% of the wet seasons considered, a flash drought in 24% of wet seasons, and both a false onset and a flash drought in 10% of wet seasons. Figure 10 shows the frequency of occurrence of seasons that experience both a false onset and a flash drought using gridded data from 2000 to the present for northern Australia. While both false rainfall onsets and soil moisture flash droughts occur with relative frequency across northern Australia, they only occasionally occur within the same season.

5 | DISCUSSION AND CONCLUSION

This analysis builds on the previously published concept first proposed by Lo *et al*. (2007) that the northern Australian wet season rainfall onset can be defined using a rainfall threshold of 50 mm accumulated rainfall after September 1. In this study, we do not dispute the merits of such an onset definition, but rather add to the understanding of the climate and physical characteristics of northern Australia during the early wet season and build-up to the monsoon. We find that there are times when the wet season experiences a 'false onset', that is, the wet season begins based on the accumulated rainfall criterion but low rainfall or high evaporative demand dries the soil before the monsoon begins. In these seasons, agricultural producers would experience a downward trend in soil moisture at a time of the year when they would expect an increase instead. The likelihood of false onsets is impacted by large-scale climate influences such as ENSO and the IOD, with La Niña and negative IOD patterns often coinciding with false onsets. This then provides the motivation for further analysis to investigate periods of false onset and flash drought and the frequency at which they occur. We find that not all false onsets are associated with or culminate in a flash drought.

In addition to the influence of seasonal-scale climate drivers, we also investigated the influence of the MJO on a subseasonal time scale. The literature shows that while the MJO is known to influence the timing of the dynamical monsoon onset, it is less of an influence on early wet season rainfall. Consistent with previous studies, we found that when the MJO is strong over Australian longitudes in October through December that it can also enhance precipitation and influence the timing of the wet season rainfall onset. While it is unlikely for the wet season to experience a false onset while the MJO is active over Australia, false onsets can occur during any other phase of the MJO progression.

Here, we have shown that a false onset to the wet season rainfall can occur frequently over northern Australia. The frequency of occurrence ranges from about 20% of wet seasons at places like Mt. Isa, Qld, up to around 50% of wet seasons near Darwin, NT, and north of Townsville, Qld. The concept of a false onset has not been thoroughly investigated previously, but was introduced by Berry and Reeder (2016). Previous studies have investigated flash droughts in Australia (Parker *et al*., 2021) and other tropical locations in the context of monsoonal and wet season rainfall variability (Zhang *et al*., 2019a; Christian *et al*., 2019a; Zhang *et al*., 2020; Mahto and Mishra, 2020; Yang *et al*., 2020; Stojanovic *et al*., 2020). We chose to investigate the concurrence of false onsets and flash droughts over tropical Australia to bridge potential impacts of drought-like conditions in the region. We have also shown that false rainfall onsets occasionally coincide with a soil moisture flash drought, but the two events are usually not related.

There are several limitations to this study that are considered in the interpretation of these results. This study followed previously published studies that used a change in soil moisture percentiles over a short time period to establish the occurrence of a flash drought (Ford and Labosier, 2017; Mahto and Mishra, 2020; Parker *et al*., 2021) including studies that applied this method in monsoonal climates (Mahto and Mishra, 2020). One of the limitations to using soil moisture percentiles in tropical climates during the wet season is that the soils are typically very wet even when the relative soil moisture percentile shows low values compared to the historical average. Notwithstanding this caveat, we showed that soil moisture flash droughts occur over northern Australia within about 25% of the seasons, on average. This frequency of occurrence, representing about once every fourth year, raises the question of should these events be considered a drought (i.e. a climatological extreme) or are they an inherent characteristic of the natural variability of tropical Australia? It also suggests that in regions with large temporal rainfall variability, that it may be better to use standardized change anomalies that account for the local climatology when determining if changes in absolute value over some period of time are truly unusual for that location (Otkin *et al.*, 2013, 2014, 2015). We used soil moisture as a step between false rainfall onsets and potential agricultural impacts, but from these results, it may be better to use a different indicator. ET-based drought metrics for flash drought detection have been effective at detecting mid-latitude flash drought because decreases in ET are a more direct indicator of vegetation impacts (Anderson *et al.*, 2007a, 2007b, 2013; Nguyen *et al.*, 2019). However, ET may not be more suitable for tropical locations; Otkin *et al.* (2018c) and Christian *et al.* (2019b) both suggest that an ESI may not work in monsoon regions (both referring to the southwest US monsoon) due to normally rapid changes in evaporative stress during monsoonal rains in the hot summer months. Notwithstanding the difficulty in selecting an appropriate flash drought indicator for tropical locations, we recommend that similar analyses are carried out for other regional monsoon systems where agriculture is often the most important sector of overall economic activity.

A final assumption made in this work is that the connection between false onsets and agricultural impacts can be drawn using soil moisture as an intermediate indicator between rainfall and agriculture (Otkin *et al.*, 2018a), thus the consideration of soil moisture changes is similar to previous research on flash drought (Ford and Labosier, 2017; Mahto and Mishra, 2020; Parker *et al.*, 2021). Considering that false rainfall onsets and flash droughts are usually not concurrent, it should not be assumed that wet seasons that experience a false rainfall onset will see drought-like impacts to agriculture in northern Australia; this connection should be tested in future research (i.e., the impacts of false wet season rainfall onsets and flash droughts should be documented and quantified).

It is concluded that the time between the wet season onset and the monsoon onset can be highly prone to false wet season rainfall onsets. We further conclude that La Niña and negative IOD—climate patterns that are usually associated with early onset and above average early wet season rainfall—are also associated with seasons with a false onset. We also found that wet seasons that experience a false rainfall onset only occasionally coincide with a rapid depletion of soil moisture and may not always have negative impacts on agriculture.

AUTHOR CONTRIBUTIONS

Joel Lisonbee: Conceptualization; data curation; formal analysis; investigation; methodology; writing – original draft. **Joachim Ribbe:** Supervision; validation; writing – review and editing. **Jason Otkin:** Writing – review and editing. **Christa Pudmenzky:** Writing – review and editing.

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