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Session J02 – Invited speaker

Abrupt Drought-To-Flood Transitions in Australia

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Abstract: This study examines historical abrupt drought-to-flood transition (ADFT) events (Figure 1) across Australia using the Standardized Precipitation and Evapotranspiration Index (SPEI) at 1-, 3- and 6-month scales, representing short-, mid-, and long-term transitions. On average, more than 18 ADFT events occurred per location during 1965-2024, with northern and southwestern regions emerging as hotspots, each experiencing more than 20 events. These events typically lasted about six months while can persist up to nine months. The intensity of ADFT events generally falls within the range of 2.6–3.2, as measured by the cumulative absolute SPEI over the drought and ensuing wet phases, with similar intensity for drought and subsequent wet phases. We detected statistically significant increasing trends in the frequency and intensity of ADFT events in short-term transitions. Although event durations have not lengthened, drought phases have intensified more than the wet phase, indicating more polarised hydroclimatic extremes. These findings highlight the need to account for compound climate risks in national and regional strategies, including water security, agricultural adaptation, and resilient infrastructure planning, to better navigate Australia's evolving climate reality.

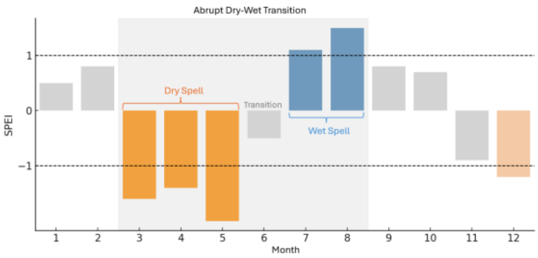

Figure 1 Schematic of ADFT event determination

Keywords: *Drought, Flood, Compound Events, Water Security, SPEI*

1. INTRODUCTION

Abrupt drought-to-flood transitions (ADFT), where prolonged dry conditions are suddenly followed by intense wet extremes, are increasingly documented worldwide (De Luca et al., 2020, He & Sheffield, 2020; Chen & Wang, 2022). Unlike the gradual wetting typically associated with drought recovery, ADFT events involve rapid swings between hydroclimatic extremes. Such sharp transitions can cause greater damage than isolated droughts or floods, posing substantial challenges to conventional risk frameworks that treat dry and wet extremes as separate hazards and often overlook the cascading risks of compound events (Zscheischler et al., 2018; Chiang et al., 2022, Fang and Lu, 2023, Götte and Brunner, 2024).

ADFTs disrupt hydrological and agricultural systems, with far-reaching economic and social consequences. Prolonged droughts deplete groundwater reserves and alter soil structure, leaving soils compacted and less permeable (Teuling et al., 2013). When intense rainfall follows extremely dry antecedent conditions, catchments tend to generate rapid surface runoff rather than replenishing subsurface storage, triggering flash floods instead of facilitating hydrological recovery (Grillakis et al., 2016, Staudinger et al., 2025). Such extremes also create operational challenges for reservoirs, where the need to conserve water for drought mitigation conflicts with the necessity of releasing excess flows during floods. Poorly timed decisions under fast shifting swings can destabilize allocation systems and undermine long-term water security.

The agricultural sector is particularly vulnerable in this situation, as irrigation during drought followed by flooding can inundate fields and kill crops. When such events coincide with optimal planting or harvesting windows, they disrupt germination, reduce yields, and threaten farmers' livelihoods fundamentally (Hochman et al., 2017, Furtak and Wolińska, 2023). Furthermore, ADFTs can accelerate land degradation through erosion, sediment transport, nutrient leaching, and vegetation dieback, leading to long-term declines in ecosystem functions, water quality, and community resilience (Pizzorni et at., 2024).

Understanding the dynamics of ADFT events is therefore essential for improving risk assessment, enhancing infrastructure resilience, and informing adaptive water resource management strategies. Evidence from the United States (Götte and Brunner, 2024), China (Shi et al., 2021), Asia (Fang & Lu 2023), and multi-regional analysis (De Luca et al., 2020, He & Sheffield 2020, Chen &Wang 2022) indicates accelerating abrupt shifts across multiple scales. Australia, as the driest inhabited continent, is well-known for being highly exposed to hydroclimatic extremes, including the Millennium Drought (1997–2009), the Tinderbox Drought (2017–2019), and the Eastern Australia floods (2022). While considerable research has examined individual drought or flood events (van Dijk et al., 2013; Abram et al., 2021), the compound dynamics between drought and subsequent floods remain poorly understood, despite growing evidence of their co-occurrence and cumulative impacts. Previous work, such as Chen et al., (2021), has investigated long-term drying and wetting across the continent, but has primarily focused on water storage rather than event-scale dynamics.

To address this gap, the present study provides the first continent-wide assessment of the ADFT events in Australia. Using a standardized SPEI-based framework, we quantify the historical frequency, duration, intensity and spatial distribution. The findings offer insights to early warning systems, improve risk mapping, and support the design of adaptive water resource strategies under increasing hydroclimatic volatility.

2. DATA AND METHODS

2.1. Meteorological Data

Grided daily precipitation and potential evapotranspiration data from 1889–2024 were obtained from the SILO database (Scientific Information for Land Owners https://www.longpaddock.qld.gov.au/silo/gridded-data/). The Morton's wet environment areal potential evapotranspiration (Mwet) is used to represent the atmospheric water demand under non-water-limited conditions (Wang et al., 2001, Zajaczkowski & Jeffrey, 2020). Daily precipitation (P) and potential evapotranspiration (PET) were aggregated to monthly totals, after which monthly water balance was calculated as P-PET. These were then used to compute standardized climatic indices and conduct drought–flood transition analyses.

2.2. Standardized Climate Indices

Among the various standardized climate indices, the Standardized Precipitation-Evapotranspiration Index (SPEI; Vicente-Serrano et al. 2010) was adopted in this study to identify and characterize abrupt transition events. Unlike univariate indices such as the Standardized Precipitation Index (SPI; McKee et al. 1993), SPEI incorporates both precipitation and potential evapotranspiration, providing a more comprehensive measure of atmospheric water balance across adjustable timescales.

SPEI was computed by subtracting potential evapotranspiration from monthly precipitation, followed by standardization using a probability distribution function. Consistent with Vicente-Serrano et al. (2010), a three-parameter log-logistic distribution was adopted in this study. A minimum baseline period of 30–50 years is typically recommended for robust standardization. The 72-year period from 1889 to1960 was hence used for fitting the distribution, which was then applied to the full time series to derive SPEI values at grid level.

To capture drought and wet conditions across multiple temporal scales, SPEI was calculated at 1-, 3-, and 6-month timescales (hereafter SPEI-1, SPEI-3, and SPEI-6), based on moving windows same as that of SPI. These represent short-term, mid-term and long-term responses, which roughly align with agricultural, meteorological, and hydrological responses respectively. Thresholds of ±1.0, ±1.5, and ±2.0 were used to define mild, moderate, and severe anomalies for extreme dry and wet conditions across all timescales.

2.3. Event Identification and Characteristics

Based on SPEI-1, SPEI-3 and SPEI-6, short-term, medium, and long-term ADFT events were defined at each temporal scale as sequences in which a dry spell (SPEI ≤ -1) is immediately followed by a wet spell (SPEI $\geq +1$). We allow a transition window of up to three months (Figure 1) to capture abrupt hydroclimatic shifts from dry to wet conditions within a short temporal interval.

The frequency of ADFT events was quantified for specified analysis intervals (e.g., decadal or 60-year periods) to examine patterns and variability of event occurrence. Event duration was measured as the total number of months spanning both the dry and subsequent wet spells. The intensity of each dry or wet spell was calculated as the mean SPEI value during the respective phase. Overall event intensity was quantified as the sum of the absolute SPEI magnitudes of the dry and wet phases. To further assess the relative influence of each extreme phase, the durations and intensities of the dry and wet spells were analysed separately.

It is noted that isolated dry or wet extremes (e.g., single-phase events, Figure 1, month 12) were excluded from this analysis. Likewise, transitions from extreme wet to dry conditions were not considered, as the study focused exclusively on dry-to-wet transitions relevant to drought recovery processes.

3. RESULTS

3.1. Historical Event Characteristics

Over the past six decades, ADFT events have been frequent across Australia. Short-term events (SPEI-1, Fig. 2a) occurred ~18 times, while mid-term (SPEI-3, Fig. 2b) and long-term (SPEI-6, Fig. 2c) events were nearly twice as common, at 36 and 29 times, respectively—equating to a recurrence of once every 2–3 years at all scales. Spatially, mid-term events were the most widespread, except along the eastern coast. Short-term events clustered in northern and southeastern coasts, whereas long-term events showed the opposite pattern, concentrated in the south and west but rare in the southeast.

The average duration of ADFT events lengthened with SPEI scale: 5.8 months for SPEI-1, 6.6 months for SPEI-3, and 7.0 months for SPEI-6. At SPEI-1, dry spells lasted slightly longer than wet spells (3.0 vs. 2.8 months), whereas SPEI-3 showed balanced contributions (3.3 months each). SPEI-6 events were generally longer (3.5–3.6 months). Some events persisted up to 9 months, with longer durations concentrated in the south and west (SPEI-1), central interior (SPEI-3), and north and east (SPEI-6).

Short-term ADFT events were generally the most intense, with values up to 2.8 and mean dry/wet phase intensities of –1.38 and 1.44, respectively. Mid- and long-term events were slightly weaker, consistent with the smoothing effect of the 3–6 month SPEI windows and subsequent phase averaging.

Interestingly, regions with high ADFT frequency also show high intensity, indicating a compounding effect where transitions are both more frequent and more severe. In contrast, the longest durations occur in low-frequency regions, suggesting frequent events are intense but not necessarily prolonged.

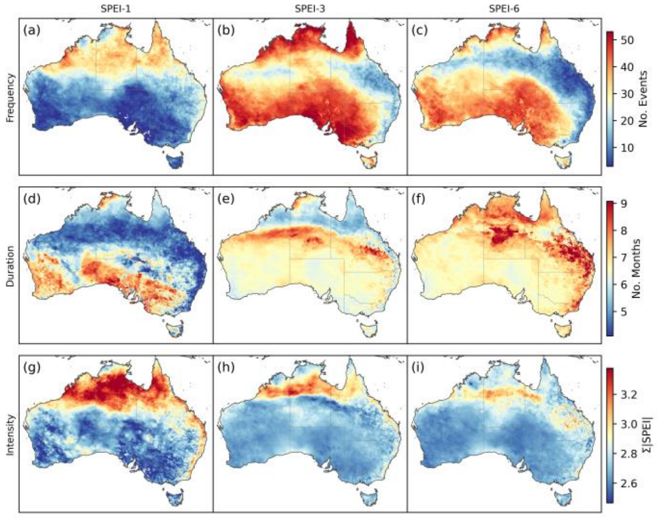

Figure 2. Characteristics of ADFT events across Australia during 1964-2024, including total number of events, average duration in months, and average SPEI-based intensity.

3.2. Continental Trend

By dividing the study period into decadal windows, we assessed temporal trends in ADFT frequency across Australia. The results reveal scale-dependent patterns: short-term events increased significantly over time (0.06 events per decade, $R^2 = 0.50$, $p < 0.05$), indicating a strengthening tendency for abrupt transitions at finer temporal scales. Mid-term events showed no clear trend, while long-term events declined significantly (−0.04 events per decade, $R^2 = 0.22$, $p < 0.05$), suggesting reduced persistence of prolonged transitions (Fig. 3a).

Both event duration (Figure 3b) and intensity (Figure 3c) demonstrated an increasing tendency. The increase in intensity was more pronounced than duration, suggesting that such extreme events have become more severe rather than simply last longer.

Further, analysis of the dry and wet spells of the ADFT events revealed that increases in intensity were more evident in the dry than in the wet spell (Figure 3e, f compared to h, i). The intensity of dry spells

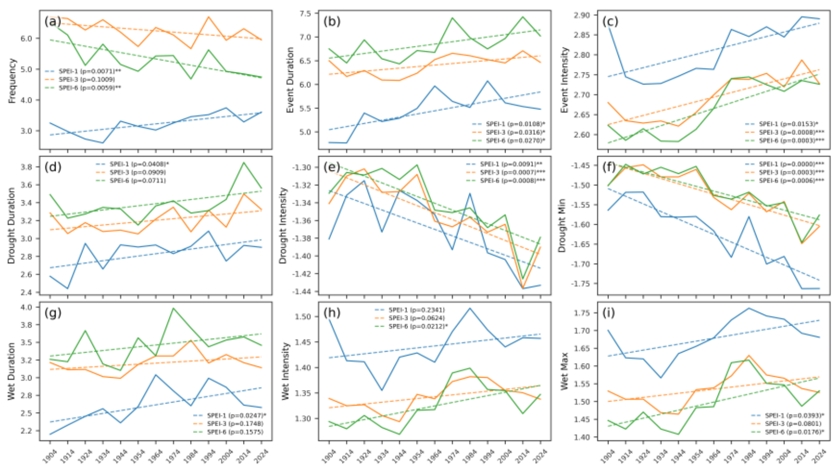

Figure 3. Trends in ADFT event characteristics from 1895 to 2024. Each variable is averaged across Australia with geospatial weights within decadal windows. The x-axis indicates the final year of each decade.

increased at a rate of approximately 0.01 per decade, with R^2 values ranging from 0.42 for short-term to 0.71 long-term events, indicating a consistent and concerning intensification of drought conditions relative to the floods that follows.

3.3. Trend Distribution

Trend analysis at the grid level (Figure 4) reveals substantial spatial heterogeneity in the evolution of ADFT event. For occurrence, statistically significant upward trends (red shading) were found in short-term event frequency (Figure 4a), especially in the central and western Australia, whereas opposite patterns (blue shading) are observed for mid- (Figure 4b) and long-term (Figure 4c) frequencies in the same regions. This spatial divergence suggests an intensification of hydroclimatic variability and a possible shift toward shorter-term fluctuations in water availability in these regions. Frequency increases are also observed across eastern Australia for all SPEI timescales, yet these trends are generally not statistically significant. On a continental scale, short-term events have increased by an average of 0.35 events per decade (Figure 5a). In contrast, mid- and long-term events tend to decline by -0.08 and -0.2 events per decade, respectively (Figures S2a and S3a).

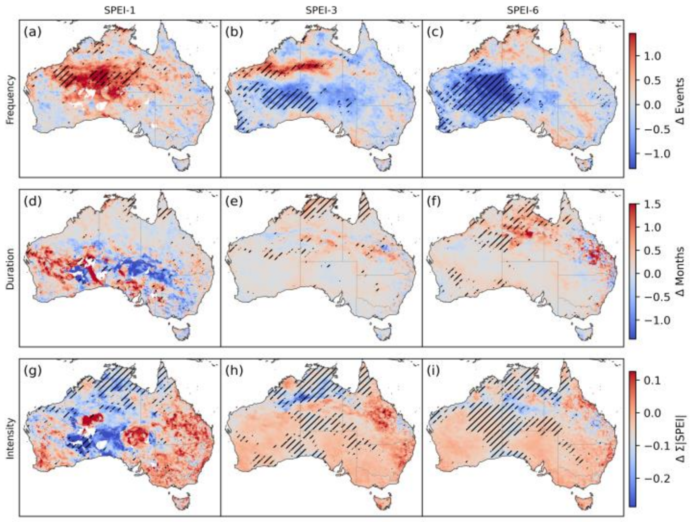

Figure 4. Spatial distribution of decadal changes in ADFT event characteristics, calculated as the difference between 2015–2024 and the baseline average (1895–1964). Shaded areas indicate grid cells with statistically significant trends ($p < 0.05$) over the study period.

Changes in mid- and long-term event durations are more uniformly distributed compared to short-term events across space but generally lack statistical significance (Figure 4d, e, f). Notable exceptions include significant increases detected in the Northern Territory and parts of Queensland and Western Australia. On average, duration has increased 0.06, 0.13, and 0.19 months for SPEI-1, -3, and -6, respectively.

On the contrary, increase in event intensity shows stronger spatial coherence and statistical significance across much of the continent (Figure 4). Most regions exhibit increasing intensity, particularly during the dry spell (Figure S1g-l). For short-term events, the mean SPEI during dry spells has decreased by 0.03 (Figure 5e), with minimum SPEI values decreasing by twice that magnitude (Figure 5f). Similar changes have been found for wet spell. These trends are less pronounced for mid- and long-term events, indicating that the most substantial intensification in fluctuation is occurring at shorter temporal scales (Figure S1g-l, S2, S3).

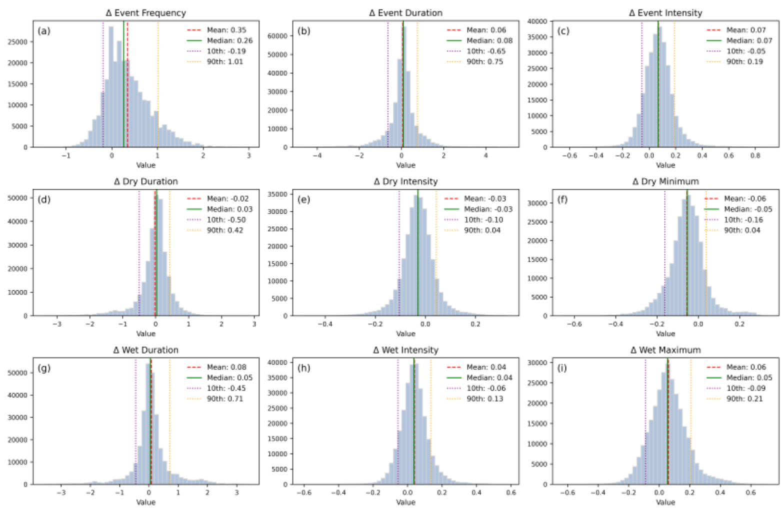

Figure 5. Frequency distributions of decadal changes in SPEI-1 ADFT event characteristics across Australia (see spatial patterns in Figure 3). Each panel represents the distribution of changes in event metrics, calculate as the difference between the most recent 10-year period (2015–2024) and the baseline (1895–1964). Vertical lines indicate the mean (red dashed), median (green solid), and 10th and 90th percentiles (purple and orange dotted, respectively).

4. DISCUSSION AND CONCLUSION

This study presents the first continent-wide assessment of abrupt drought-to-flood transition events in Australia over the past six decades, analysing their frequency, duration, and intensity across multiple timescales. Historical ADFT events are found to be widespread and recurrent, with mid- and long-term events occurring more frequently than short-term events. Spatial patterns vary with timescale, likely reflecting differences in atmospheric drivers and land–atmosphere feedbacks. Short-term events are concentrated along the northern and southeastern coasts, whereas mid- and long-term events dominate inland regions, broadly consistent with the SPEI-3 patterns reported by Chen & Wang (2022).

Short-term ADFT events show significant increases in both frequency and intensity, while mid- and long-term events remain stable or decline. Grid-level analyses reveal that regions with frequent ADFT events often also experience higher intensities, particularly in central and western Australia, indicating elevated compounding risk. However, more frequent events are not necessarily longer in duration. This behaviour aligns with the Clausius–Clapeyron relationship, whereby a warmer atmosphere enhances evaporation (intensifying drought) and increases moisture-holding capacity (amplifying flood potential), thereby driving more volatile hydroclimatic variability (Allan & Soden, 2008; Seneviratne et al., 2012; Pendergrass, 2020).

A key finding is that intensification is primarily driven by worsening drought phases, while subsequent wet spells show comparatively weaker trends. This indicates that although drought–flood sequences are not necessarily lengthening, their extremes are becoming sharper. The increasing severity of the dry phase across all SPEI timescales highlights the role of antecedent drought in amplifying flood risk—a pattern consistent with global evidence on compound extremes and hydrological memory. In many cases, normal or moderately wet periods fail to provide sufficient recovery, aligning with the 'dry-gets-drier' paradigm but diverging from the 'wet-gets-wetter' (Greve et al., 2014). Given that event duration exhibits only minor changes, it is plausible that the rapid swings between opposing anomalies are driven primarily by synoptic-scale atmospheric processes and land–atmosphere feedbacks, rather than by longer-term climate modes alone.

These dynamics have important implications for drought recovery and water management. When prolonged drying is followed by insufficient recharge, streamflow regimes are disrupted, and hydrological recovery becomes less likely. This challenges the assumptions of stationary catchment response models, which presuppose that infiltration can adequately replenish soil and groundwater stores before generating flow. As a result, current management frameworks may underestimate the persistence and severity of drought-dominated transitions.

In light of ADFT hazards, it may be beneficial for risk assessment frameworks to consider droughts and floods in a more integrated way, recognising their compounding and sequential nature. Efforts could include further development of early-warning systems, refinement of risk mapping, and exploration of flexible water management approaches, particularly in regions identified as ADFT hotspots. It is noted that the physical drivers of these abrupt transitions are not yet fully understood, highlighting the value of targeted research to better quantify the atmospheric, oceanic, and land-surface processes involved. Advancing such understanding could support more informed planning and the design of strategies that are responsive to compound drought–flood risks.

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APPENDIX

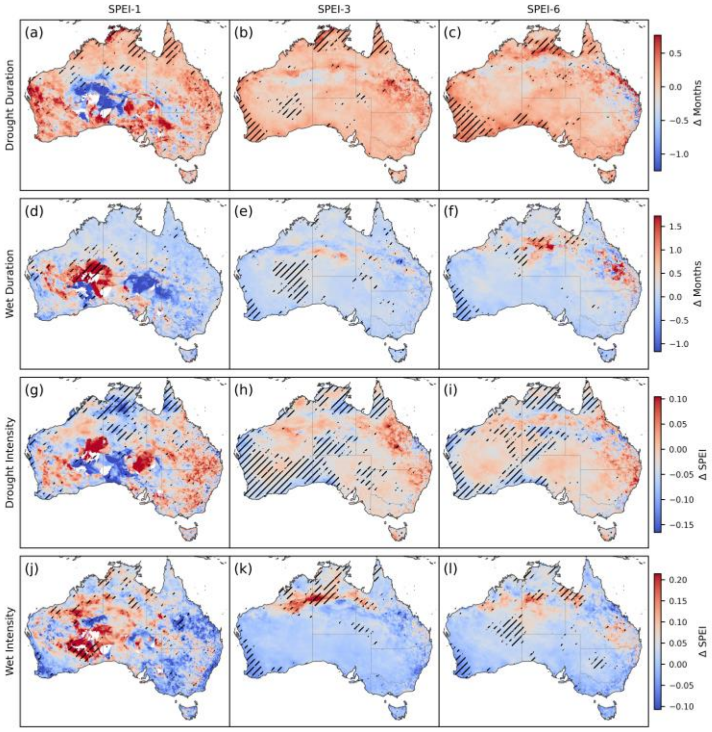

Figure S1. Map of decadal changes in dry and wet spells of ADFT characteristics (2015-2024 minus the average of 1895-1964). Shade as decadal trend detected at each grid with p<0.05).

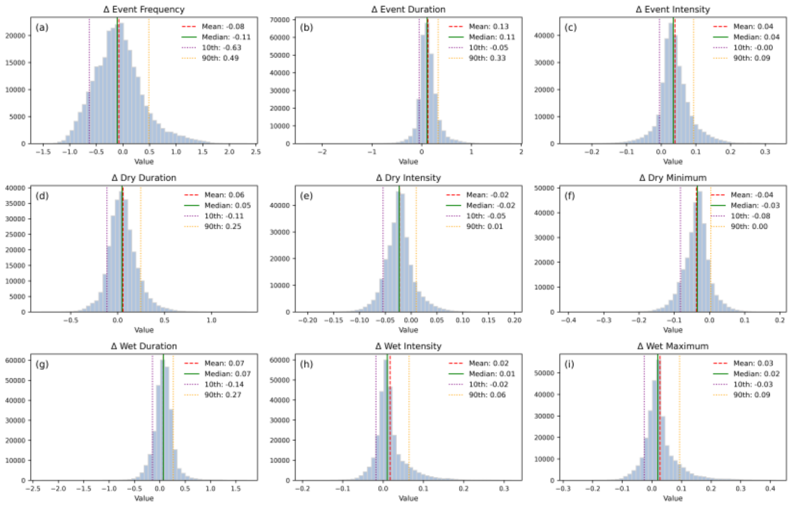

Figure S2. Frequency distributions of decadal changes in SPEI-3 ADFT event characteristics across Australia (see spatial patterns in Figure 3). Notes are consistent with those in Figure 5.

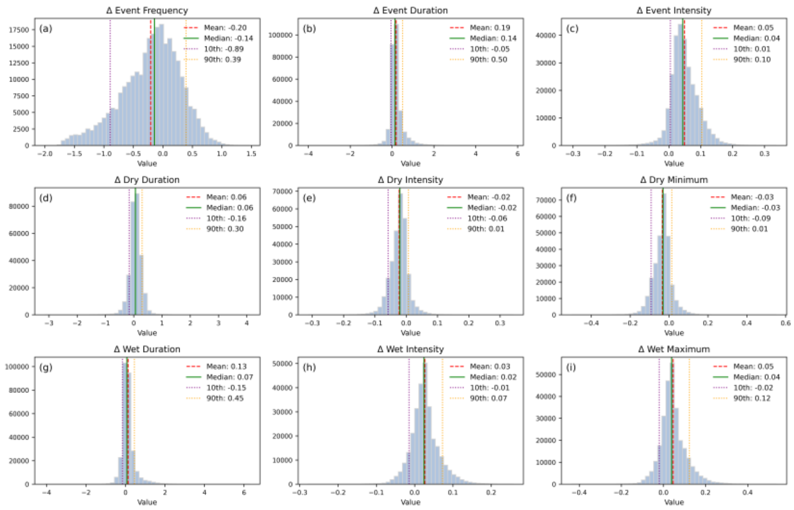

Figure S3. Frequency distributions of decadal changes in SPEI-6 ADFT event characteristics across Australia (see spatial patterns in Figure 3). Notes are consistent with those in Figure 5.

