Rethinking Hydroclimatic Extremes: Occurrence of abrupt Drought-to-Heavy-Precipitation transition events

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Abstract
Drought-to-heavy-precipitation abrupt transitions (sometimes called dry-to-wet extremes, whiplash events, or drought–flood transitions) are an emerging research focus. These are rapid shifts from a period of sustained drought (rainfall deficits, soil moisture stress, low streamflow) to intense precipitation or flooding over short timescales. Also described as climate whiplash events, they reflect the increasing volatility of the hydroclimate system. Unlike droughts, there's no universally agreed metric for identifying drought-to-heavy precipitation abrupt transitions. In this study, we developed a precipitation-based dry-to-wet flip-flop event identification framework. The framework was applied to Australia and Europe to identify and study these events, along with answering the question: Are droughts and heavy precipitation mutually exclusive? Results showed that regions in mid-latitudes often have higher frequency and magnitude of these events, suggesting greater temporal variability in precipitation/weather processes in those regions. Further, these events are more likely to occur during austral summer and autumn (in Australia) and boreal spring (in Europe). While such flip-flops can have detrimental impacts through giving rise to flash flooding and blackwater events, they also facilitate seasonal recovery in meteorological drought conditions and hence are potentially important in meteorological drought breaking. There is a need to support adaptation initiatives to better protect human society from the losses caused by these events, as well as to move towards more compound event-resilient designing.

1 Introduction

Hydroclimatic extremes such as droughts and heavy precipitation events are among the most consequential climate hazards affecting ecosystems, water resources, and human societies. Traditionally, droughts and floods have been studied as independent phenomena; however, recent research increasingly highlights the importance of interactions between different extremes, particularly when they occur in close succession. Such compound or sequential extremes can amplify impacts beyond those associated with individual hazards (AghaKouchak et al., ,). Rapid transitions between dry and wet conditions have emerged as a particularly important class of compound hydroclimatic events. These abrupt shifts—often referred to as drought-to-flood transitions, dry-to-wet extremes, or hydroclimate whiplash—describe situations in which a prolonged period of precipitation deficit is followed by intense rainfall within a relatively short timescale (DeFlorio et al.,). Such transitions reflect increasing volatility in the hydrological cycle and may represent a key feature of climate variability in many regions.

Recent studies suggest that climate change may increase the likelihood and intensity of these abrupt hydroclimatic swings. As global temperatures rise, the atmosphere's capacity to hold moisture increases, intensifying precipitation when favourable conditions occur, while simultaneously enhancing evaporative demand and drought risk. This combination can lead to more pronounced oscillations between dry and wet states, often described as increasing hydroclimatic volatility (Davenport et al.,). Consequently, many regions may experience longer dry spells punctuated by more intense rainfall events. Observational analyses have documented drought–flood alternation events across several parts of the world. For example, (Liu et al.,) conducted a global analysis of drought–flood abrupt alternation events and showed that such transitions occur across a wide range of climatic regimes, particularly in regions characterised by strong precipitation variability. Similarly, (Liu & Sheffield,) demonstrated that large-scale hydroclimatic variability can lead to alternating wet and dry extremes across many regions globally.

At the basin scale, hydrological studies have shown that abrupt transitions from drought to flood can occur in many river systems. (He & Sheffield,) identified drought-to-flood transitions in multiple major basins worldwide, highlighting their implications for hydrological predictability and water resource management. However, evidence also suggests that meteorological and hydrological transitions may not always be strongly linked. For example, (Brunner et al.,) found that meteorological and hydrological dry-to-wet transition events are only weakly related in many European catchments, reflecting the complex processes that mediate the translation of rainfall anomalies into hydrological responses.

Atmospheric circulation patterns also play a critical role in facilitating abrupt wet–dry transitions. Recent studies show that spatially compounding drought–flood events in Europe are often associated with persistent atmospheric blocking patterns that maintain drought conditions before rapidly shifting to storm-favourable circulation regimes (Brunner et al.,). Such circulation-driven regime shifts can produce rapid changes in regional precipitation patterns and contribute to the occurrence of abrupt hydroclimatic transitions. The impacts of these events can be particularly severe when intense precipitation occurs shortly after drought conditions. Drought-affected soils and ecosystems may be less capable of absorbing sudden rainfall, increasing the likelihood of rapid runoff and flash flooding. In addition, water management systems and infrastructure that are adapted to drought conditions may be poorly prepared for sudden heavy rainfall. Empirical analyses suggest that compound drought–flood events can produce larger socio-economic losses than standalone events, highlighting the importance of understanding these interactions (Deng et al.,).

Despite growing interest in drought–flood transitions, important methodological challenges remain. Different studies use varying drought indices, precipitation thresholds, and temporal windows to define transitions, leading to substantial differences in the number and characteristics of detected events (Zhao et al.,). Moreover, many existing studies focus on hydrological drought–flood transitions based on streamflow records (He & Sheffield,), whereas fewer studies examine precipitation-based transitions that capture the meteorological processes initiating such events. Developing consistent frameworks for identifying drought-to-wet transitions is therefore essential for improving our understanding of their occurrence and impacts. In particular, precipitation-based approaches may offer advantages for detecting these events across large spatial domains where hydrological observations are limited.

In this study, we propose a precipitation-based framework to identify abrupt *dry-to-wet flip-flop events*, defined as heavy precipitation events occurring shortly after severe meteorological drought conditions. We apply this framework to Australia and Europe—two regions characterised by diverse climate regimes and precipitation drivers—to investigate the occurrence, spatial distribution, and seasonal characteristics of these transitions between 1950 and 2022. Specifically, this study aims to (a) Develop a precipitation-based framework for identifying drought-to-heavy-precipitation flip-flop events. (b) Quantify the probability and timing of heavy precipitation events following severe drought conditions. (c) Characterise the spatial distribution, magnitude, and seasonality of these events across Australia and Europe. (d) Assess the role of these transitions in short-term recovery from meteorological drought. By providing a consistent framework for identifying abrupt drought-to-wet transitions, this study contributes to a growing body of research on compound hydroclimatic extremes and helps improve understanding of the risks posed by rapid shifts in hydroclimatic conditions.

2 Data and Methodology

2.1 Study Regions and Data

This study focuses on Europe and Australia, two regions characterized by diverse hydroclimatic regimes and substantial variability in precipitation patterns. Europe spans a wide range of climatic zones, from Mediterranean climates in the south to temperate and continental climates in central and northern regions. Australia exhibits strong precipitation variability influenced by large-scale climate drivers. Such climatic conditions and vast spatial variability of precipitation make the two regions suitable for examining abrupt transitions between dry and wet conditions.

For this study, daily precipitation data were obtained from gridded observational datasets covering the period 1950–2022. The precipitation data for the European region was obtained from EOBS (10 km spatial resolution), while that for Australia was obtained from ERA5 reanalysis (25 km spatial resolution). These datasets provide spatially continuous precipitation fields and have been widely used in previous hydroclimatological studies of drought and extreme precipitation.

2.2 Identification of Drought-to-Heavy-Precipitation Events

To facilitate the identification of drought and subsequent precipitation extremes, precipitation data were aggregated to pentad (five-day) timescales. The use of pentad data helps reduce high-frequency noise while preserving the temporal resolution necessary to capture rapid hydroclimatic transitions. The identification of drought-to-heavy-precipitation events included three main steps, as detailed below.

(1) **Drought Identification** Meteorological drought conditions were identified using the Standardized Precipitation Index (SPI), a widely used drought indicator that quantifies precipitation deficits relative to the climatological distribution (McKee et al.,). The SPI transforms precipitation anomalies into standardized units, enabling comparison across regions with different climatic characteristics. SPI values were calculated using aggregated pentad precipitation totals. A severe drought condition was defined when SPI values fell below a threshold of -1.5. This threshold corresponds to substantially below-normal precipitation conditions and is commonly used to identify severe meteorological drought events.

(2) **Heavy Precipitation Events** Heavy precipitation events were defined based on percentile thresholds derived from the local precipitation distribution. Specifically, 5-day accumulated precipitation exceeding the 95th percentile of daily precipitation value at each grid cell was classified as a heavy precipitation event. This percentile-based approach accounts for regional differences in precipitation climatology and ensures that extreme rainfall events are identified relative to local conditions.

(3) **Detecting their abrupt occurrence in succession** Dry-to-wet flip-flop events were defined as occurrences in which a heavy precipitation event follows a severe meteorological drought within a short temporal window. Thus, after having identified drought and heavy rainfall event as described above, a flip-flop event was identified when the 5-day accumulated rainfall was above the heavy rainfall threshold and the SPI-3 for the previous month was below -1.5. Such a temporal window to detect transitions was selected to capture rapid hydroclimatic shifts while avoiding unrelated events separated by longer timescales. The drought and heavy precipitation threshold as well as the choice of indicators for the two were chosen so that the framework could identify potentially impactful events.

Spatial patterns of the characteristics of the flip-flop events were analysed by calculating the frequency of the weather whiplash events at each grid cell. Seasonal characteristics were examined by aggregating events according to meteorological seasons. This analysis enables identification of regions and seasons where rapid drought-to-wet transitions occur most frequently. We also computed the average (relative) magnitude of the precipitation event following the drought. The magnitude was defined as the maximum of all 5-day accumulated rainfall total above the threshold. However, to be able to compare impact of the whiplash events across regions, instead of looking the at absolute average magnitude of the whiplash events for a grid, we derived relative magnitude. This was done by dividing the average magnitude by the 95th percentile of precipitation at that grid.

3 Results

3.1 Case study examples

To demonstrate the ability of the proposed framework described in Section 2.2 to detect abrupt drought-to-heavy-precipitation events, we examined known impactful cases in both study regions. In Europe, a notable example of such an event occurred in September 2017 in Zadar, Croatia, where a mesoscale convective system produced approximately 300 mm of rainfall within 24 hours—around three times the average monthly precipitation. This event followed a period of relatively dry conditions and triggered severe flash flooding in the region. Figure xyz shows the weather whiplash event of the September 2017 Zadar flash floods in Croatia. The proposed framework is able to capture the flip-flop. In Australia, the region of Gippsland in the southeastern state of Victoria experienced intense rainfall in September 2023, which was preceeded by months of drought conditions. Figure 1 shows that the framework captures abrupt transitions consistent with documented hydroclimatic reversal events.

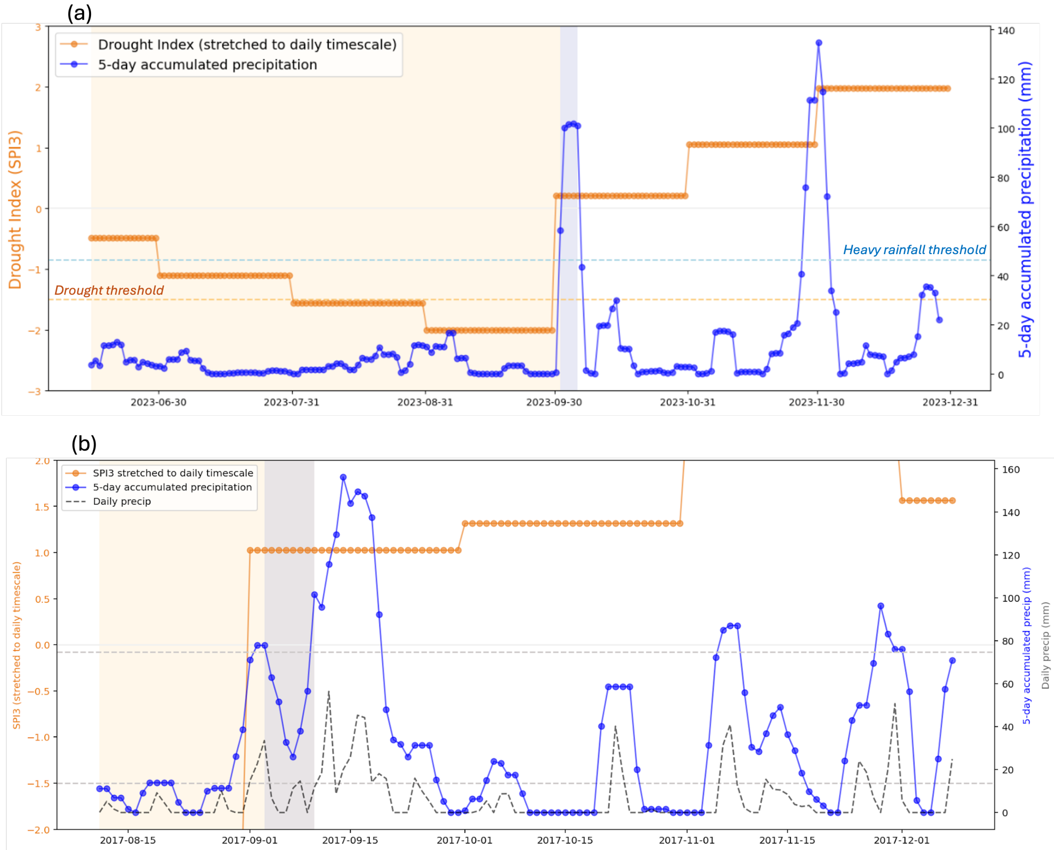

Figure 1. Elicitation of an abrupt drought-to-heavy-precipitation event in (a) Gippsland (Australia) and (b) Zadar (Croatia) using the proposed framework.

3.2 Characteristics of the weather whiplash events in Australia and in Europe

Figure 2 shows the frequency and seasonality of these events over the two study regions. The spatial distribution of these events reveals substantial regional variability. Across both Australia and Europe, mid-latitude regions exhibit relatively higher frequencies and magnitudes of drought-to-heavy-precipitation transitions, indicating those regions have higher hydroclimatic volatility These regions are characterised by strong atmospheric variability and shifting storm tracks that may facilitate abrupt hydroclimatic transitions. The spatial pattern for Australia shows the southern part of Australia as more prone to abrupt (high frequency) flip-flops. These spatial distributions are different from the ones obtained for annual rainfall variability, implying that rainfall variability at shorter timescales is different from that at longer timescales. This underscores the importance of understanding such weather whiplash events. Seasonal patterns differ between the two study regions. The seasonal plot tells use when are they more likely. In Australia, flip-flop events occur most frequently during austral summer and autumn, when convective rainfall systems are most active. In Europe, events occur most commonly during boreal spring, coinciding with transitional atmospheric circulation patterns and increased storm activity.

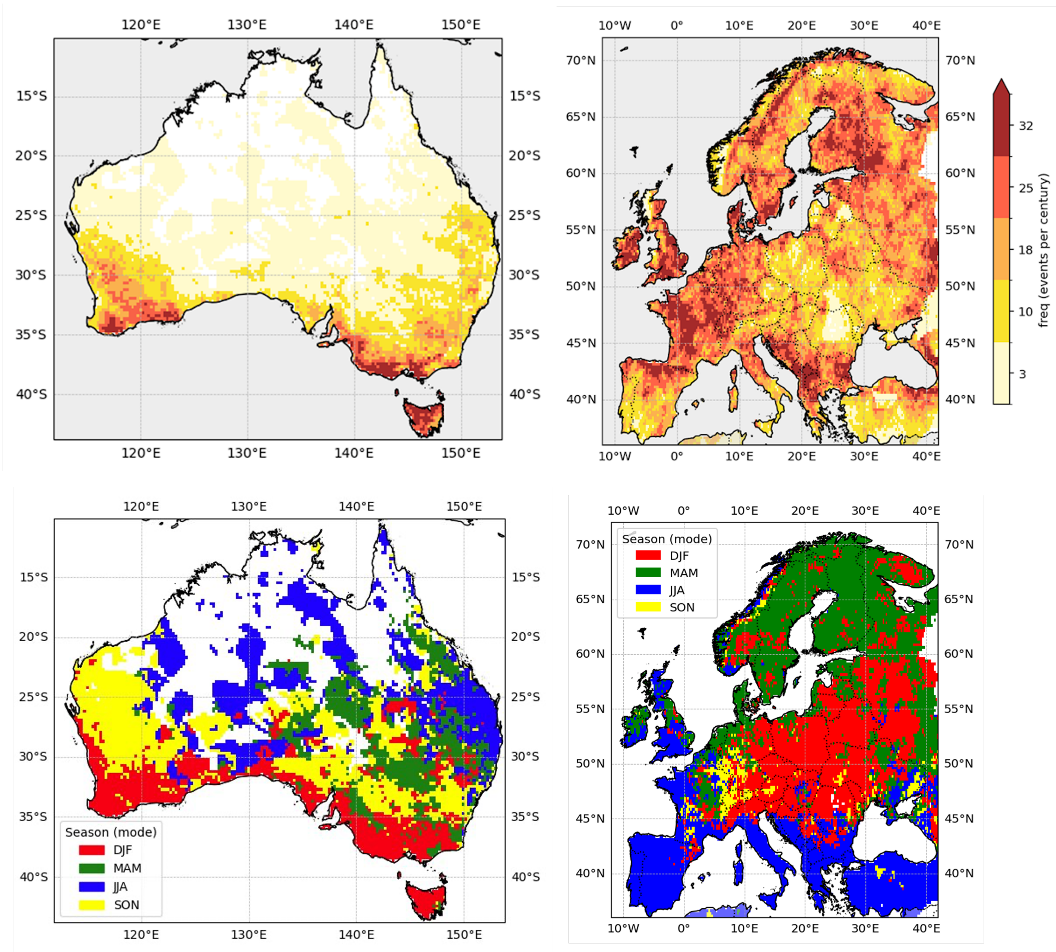

Figure 2. Maps showing the frequency (top row) and the seasonality (bottom row) of the weather whiplash events over Australia and Europe.

Figure 3 shows the average magnitude of these events. In general, events identified in humid or temperate climates tend to exhibit larger precipitation magnitudes compared to those in arid regions. The magnitude tells us how heavy is the rainfall associated with these events. Maximum event magnitudes are associated with convective storm systems or large-scale synoptic disturbances capable of producing prolonged rainfall. Regions of higher frequency are also regions associated with higher magnitude of the rain events.

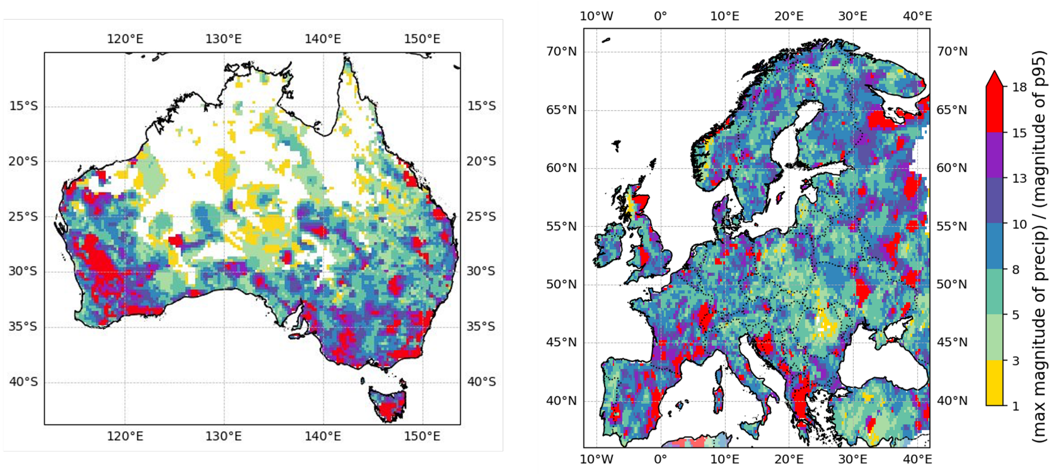

Figure 3. Relative maximum magnitude of the weather whiplash events over the two study regions.

3.3 Role of weather whiplash events in drought recovery

We also evaluated the influence of flip-flop events on drought recovery. Figure 4 shows the comparison of drought recovery when there is a flip-flop event versus when there is no flop-flop event. Results indicate that heavy precipitation following drought conditions often leads to short-term recovery in meteorological drought indices, as reflected by SPI-3 values. Meteorological drought recovery speeds up by nearly 2 months when the flip-flop events occur. However, this recovery does not always translate into sustained improvements in soil moisture conditions, particularly in regions where rainfall intensity leads to rapid runoff rather than infiltration. Consequently, while flip-flop events may terminate meteorological drought conditions, they do not necessarily resolve longer-term hydrological drought.

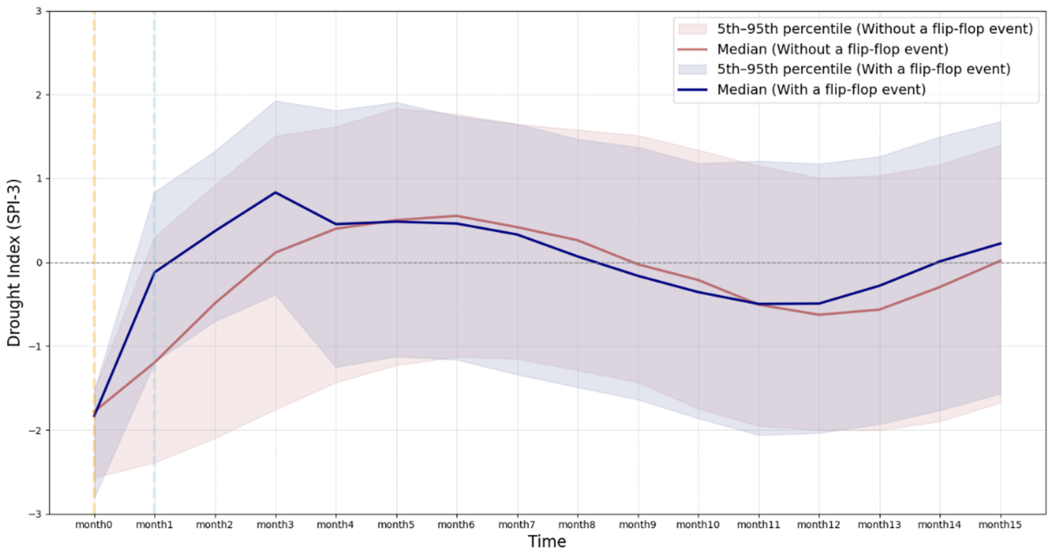

Figure 4. Composite of all trajectories of the drought indicator SPI-3, with the blue (red) range encompassing events when the drought is (is not) followed by a heavy precipitation event.

4 Conclusions

This study developed a precipitation-based framework for identifying abrupt drought-to-heavy-precipitation transitions and applied it to Australia and Europe over the period 1950–2022. Our results highlight the importance of considering rapid transitions between hydroclimatic extremes within climate risk assessments. The findings here show that mid-latitude regions exhibit higher frequencies and magnitudes of these events. Further, seasonal occurrence differs between regions, with peaks in austral summer–autumn in Australia and boreal spring in Europe. Heavy precipitation following drought conditions often contributes to short-term meteorological drought recovery but does not always result in sustained hydrological recovery.

Even for regions where drought-to-heavy-precipitation events are relatively rare, their impacts can be disproportionately large due to the vulnerability created by preceding drought conditions. Drought-stressed ecosystems, agricultural systems, and infrastructure may be less resilient to intense rainfall. These events also challenge traditional risk management approaches that treat droughts and heavy precipitation as separate hazards. Instead, integrated frameworks are needed to capture compound interactions between different extremes. Projected intensification of the hydrological cycle under climate change may further increase the likelihood of abrupt transitions. Climate models suggest that many regions may experience longer dry periods punctuated by more intense rainfall events, potentially increasing the frequency of climate whiplash events. Improved monitoring and early warning systems are therefore critical for managing the risks associated with such rapid hydroclimatic transitions.

Conflict of Interest declaration

The authors declare no conflicts of interest relevant to this study.

Data Availability

The EOBS data used in this study can be found at `https://surfobs.climate.copernicus.eu/dataaccess/access_eobs.ph`. The fifth-generation European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis data, ERA5, can be accessed at `https://cds.climate.copernicus.eu`.

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