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Drought to Flood to Drought: A Review of Definitions of Precipitation Whiplash Events, What Causes Them and Their Impacts Over the Continental United States

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ABSTRACT

Precipitation whiplash, the rapid shift from drought to flooding, or vice versa, exacerbates the impact of both extremes compared to if they were to occur separately. The recognition of these types of events is relatively recent, and event precursors, driving meteorology and impacts are poorly understood. In response to this, this review summarises the current state of science of precipitation whiplash events in the United States, analysing event definitions, driving meteorology, impacts and the spatial distribution of the studies. Definitions vary considerably in temporal extent, from the transition between wet and dry conditions happening in less than a week to over a year. The climatological drivers and meteorological conditions creating precipitation whiplash events show significant diversity as well, both due to the varying event definitions and also due to the different geographical settings and range of scales of the studies. A wide range of definitions, drivers and impacts are described here, allowing researchers to better understand the phenomenon that is precipitation whiplash while also creating a foundation for future studies to delve deeper into the topic.

1 | Introduction

Hydrometeorology and Climatology have been a focus area for scientists since the inception of modern meteorology, and arguably long before that society has attempted to better understand how water moves through their regions and systems. Too much water, and we are faced with the risk of flooding, landslides, erosion, infrastructure and crop damage and impaired water quality (Rashid and Wahl 2022; He and Sheffield 2020; Diffenbaugh et al. 2015; Touma et al. 2022; Loecke et al. 2017). Too little water, and we are unable to meet water resource needs, which leads to disruption to agriculture, health and the economy (Basara et al. 2013; Steiner and Anderson 2015). Variability in the temporal and spatial scales of geophysical variables is naturally occurring and continuous (Hurst 1951; Blöschl and Sivapalan 1995; Ghil 2002). Some of this variability and their extremes have been associated with the phase of various large-scale ocean-atmospheric anomalies (teleconnections), such as El Niño-Southern Oscillation (ENSO). Which teleconnection, and to what extent they influence geophysical variables varies. For example, the consideration of teleconnection patterns has proven useful for streamflow forecasting (Engström and Uvo 2016; Hamlet and Lettenmaier 1999; Ng et al. 2017; Villarini et al. 2013). Flash drought occurrence in the United States has also been linked to the phases of various teleconnection patterns (Lesinger and Tian 2022; Christian et al. 2024), indicating that the influence of these large-scale anomalies can lead to both long-lasting as well as brief hydroclimatic extremes. As such, the phenomenon of a rapid change in hydroclimatic conditions is not new

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TABLE 1 | Results from the literature search, including search terms used, databases, number of papers returned and retained based on an initial screening. Words in quotations refer to exact phrasing used. Phrases ending with * indicate that the search engine can treat each word as separate. Words separated by commas or semicolons are simple lists of keywords.

Search term/keyword (s)	Database	Number of papers returned	Number of papers retained
Precipitation whiplash*; USA; rainfall; United States*	Google Scholar	56	15
'Drought and pluvial'; United States*; variability; compound; rainfall	Google Scholar	227	22
'Precipitation whiplash'; transportation; agriculture; society; water resources*, infrastructure	Google Scholar	19	6
Precipitation whiplash USA*	Web of Science	9	8
Compound rainfall* United States*	Web of Science	796	1
Precipitation whiplash hwater resources*	Web of Science	6	4
Flood, drought, variability, precipitation, volatility	Web of Science	7	0
Total		1120	56

per se; rather have these types of phenomena have received more attention in recent decades, possibly due to the exponential growth in high resolution data availability, but also due to a growing interest in extremes as these events are becoming more common and severe due to climate change (IPCC 2021).

Droughts and floods are 'two sides of the same coin' but are typically evaluated separately in terms of their physical mechanisms, causes, trends and impacts. However, temporal sequencing of these events can result in compounding impacts that differ or may even exceed what either event might have done independently. For example, soil hardened by a drought absorbs less precipitation and can in some cases increase the risk for (flash) flooding following heavy rain events (Descroix et al. 2009; Barendrecht et al. 2024; Parry et al. 2016).

There are several names given to these consecutive or short-term 'flips' between hydrometeorological extremes of dry and wet, which here is simply referred to as 'whiplash' events, nomenclature first used in the peer-reviewed literature by Swain et al. (2018). Other examples include 'Precipitation reversal' as the wording used by Goodrich and Ellis (2008), while Rashid and Wahl (2022) uses the term 'consecutive dry and wet extreme', and Qing et al. (2023) calls it 'drought and pluvial transition'. Over the past decade, interest in whiplash has increased as we have observed changes in hydroclimatic extremes, and as we anticipate an increase in the variability of extreme events in a warming climate (e.g., Swain et al. 2018; He and Sheffield 2020; Rashid and Wahl 2022; Raymond et al. 2022). High-impact events linked to whiplash have also occurred in recent years, such as system failures—including the 2017 Oroville Dam failure in California (Vahedifard et al. 2017), the Southern Great Plains drought to pluvial spring of 2015 which led to extensive flooding (Wugofski 2019), increases in wildfire activity (Touma et al. 2022), degradation of water quality (Loecke et al. 2017) and more challenging conditions for water resource managers who may need to switch quickly between contradictory management decisions, such as between flood control and long-term water storage needs.

This review of the current body of knowledge on precipitation whiplash focuses on studies for the continental United States (CONUS), including how researchers have chosen to define the event and under what context(s); its meteorological drivers, ranging from local to planetary scales; the role of anthropogenic climate change on whiplash trends; and its impacts to sectors such as water resources, infrastructure, agriculture and society. Additionally, the current state of understanding of this topic is discussed, and areas for further study are suggested. We hope that this article will be a resource for researchers and professionals who have a vested interest in understanding precipitation whiplash. This paper is organised as follows: First, the methodology used for identifying and reviewing the literature is described. Next, the findings are presented, grouped into definition of events, the driving meteorology and the impacts of the events. Lastly, the discussion summarises the findings and suggests future directions of study.

2 | Methods

This paper takes a systematic review approach (Berrang-Ford et al. 2015) and aims to be an assessment and summary of the current state of knowledge in the field of precipitation whiplash events in the United States, recognising both drought-pluvial and pluvial-drought. To accomplish this, a number of key terms were defined (Table 1) that then were used to search for relevant literature. Although meteorological whiplash events are not new as a weather phenomenon, their first description and definition in the scientific literature was relatively recent, with (Swain et al. 2018) being arguably the first to use the term whiplash explicitly. Due to the relative novelty of the concept of meteorological whiplash events, no time limitations were given on the publication dates, and the term 'whiplash' was not included in all searches, to avoid excluding relevant papers which might use different terminology.

The search was limited to government reports, peer-reviewed journal articles and student theses and dissertations written in

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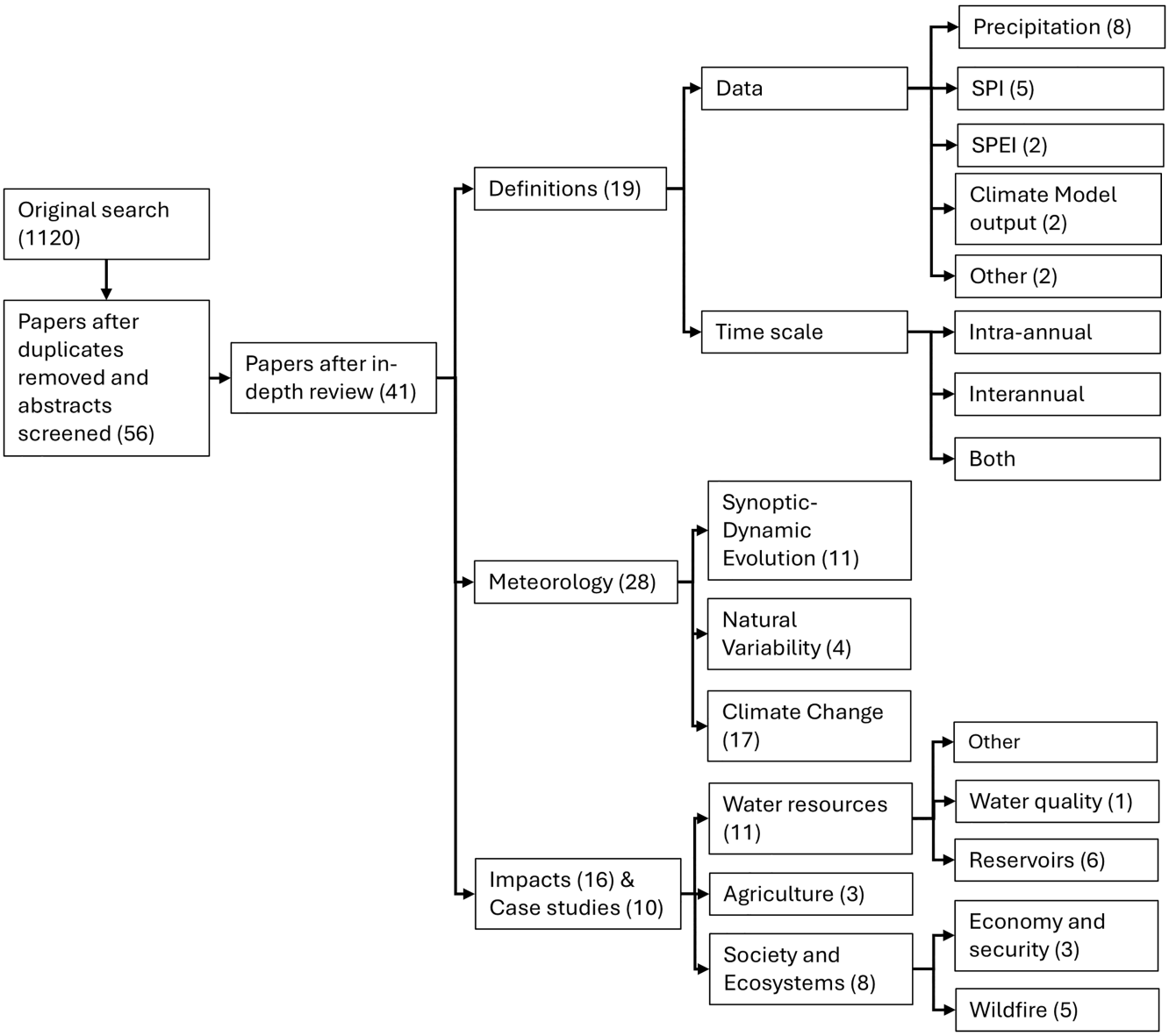


FIGURE 1 | Flow chart of methods and number of papers in each category. The total number of papers does not add up, as some papers tackle multiple themes (e.g., both a definition and a meteorology section), which leads to duplicate counts. [Colour figure can be viewed at wileyonlinelibrary.com]

English. Two different databases were used in the search for publications: Google Scholar and Web of Science. The keywords were first determined and used in Google Scholar. Next, they were used in Web of Science, but as this yielded an extreme number of publications, few of which were relevant, the number of keywords used in each search in Web of Science was reduced (see Table 1).

Next, the articles retained from the searches were compiled into one list, and duplicates and unrelated titles were removed, resulting in 56 articles being kept for further in-depth review. In this review process, the number of articles was further reduced to 41, and the remaining articles were categorised depending on their content into one or multiple of the following categories: Driving Meteorology, Definition of Event and Impact of Event (Figure 1).

Figure 2 reflects the relative novelty of the concept of meteorological whiplash events, as the first study published on the phenomenon that was identified in this search is from the year 2007 (van der Schrier and Barkmeijer 2007). The number of publications on the topic was sporadic until 2017, after which the interest and recognition of the topic have increased.

This review considers scientific literature on meteorological whiplash events impacting the United States. This search resulted primarily in regional and continental studies, but global studies are also included if they report findings for the United States. The map in Figure 3 shows the study areas of the papers included in this review. Some articles used general names for geographical regions, such as 'the Midwest' (Chen and Ford 2023; Ford et al. 2021) or 'Southern Great Plains' (Puxley et al. 2024; Wugofski 2019; Steiner and Anderson 2015), the extent of which is somewhat subjective.

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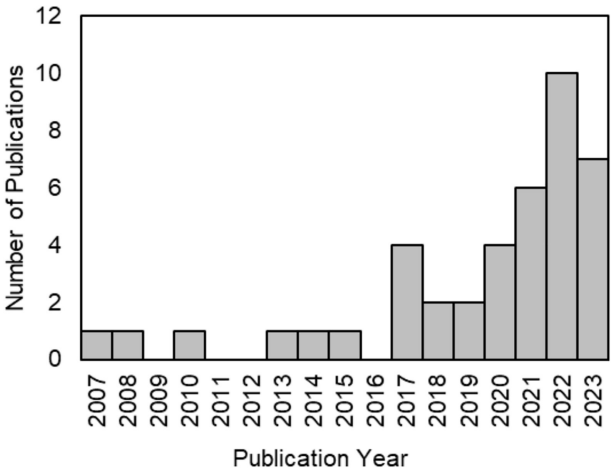


FIGURE 2 | Number of publications per year. The first paper on the topic was published in 2007, but the term 'whiplash' was not used until 2018.

In these cases, only the states that are either specifically mentioned in the article's text, or whose borders are fully within the maps presented in the article are included.

As can be seen in the maps in Figure 3, certain regions of the U.S. have been subject to more whiplash studies than others. Oklahoma and California have been included in the most studies, four each, while the majority of the states on the east coast, a cluster of states in north-central United States, Hawaii, and Alaska have not been part of any regional studies. All of the U.S. was considered in two studies, the North American continent in four studies, and 12 studies were global and included results for the United States.

3 | U.S. Precipitation Whiplash Definitions

After initial review, 19 articles were classified as containing a whiplash event definition. A more thorough analysis of these 19 papers resulted in the exclusion of four which were deemed off topic or duplicates. The definition of a whiplash event was evaluated based on (1) what type of data were used to identify the extremes, including the thresholds for a drought and pluvial respectively and (2) the timescale(s) considered for the shift from drought to pluvial (or vice versa).

3.1 | Data Used to Identify Whiplash Events

Different types of precipitation data dominate the whiplash analyses reviewed here. Eight studies use precipitation data which is either accumulated for a time period of interest (e.g., monthly, seasonal, or annual) or converted into a running

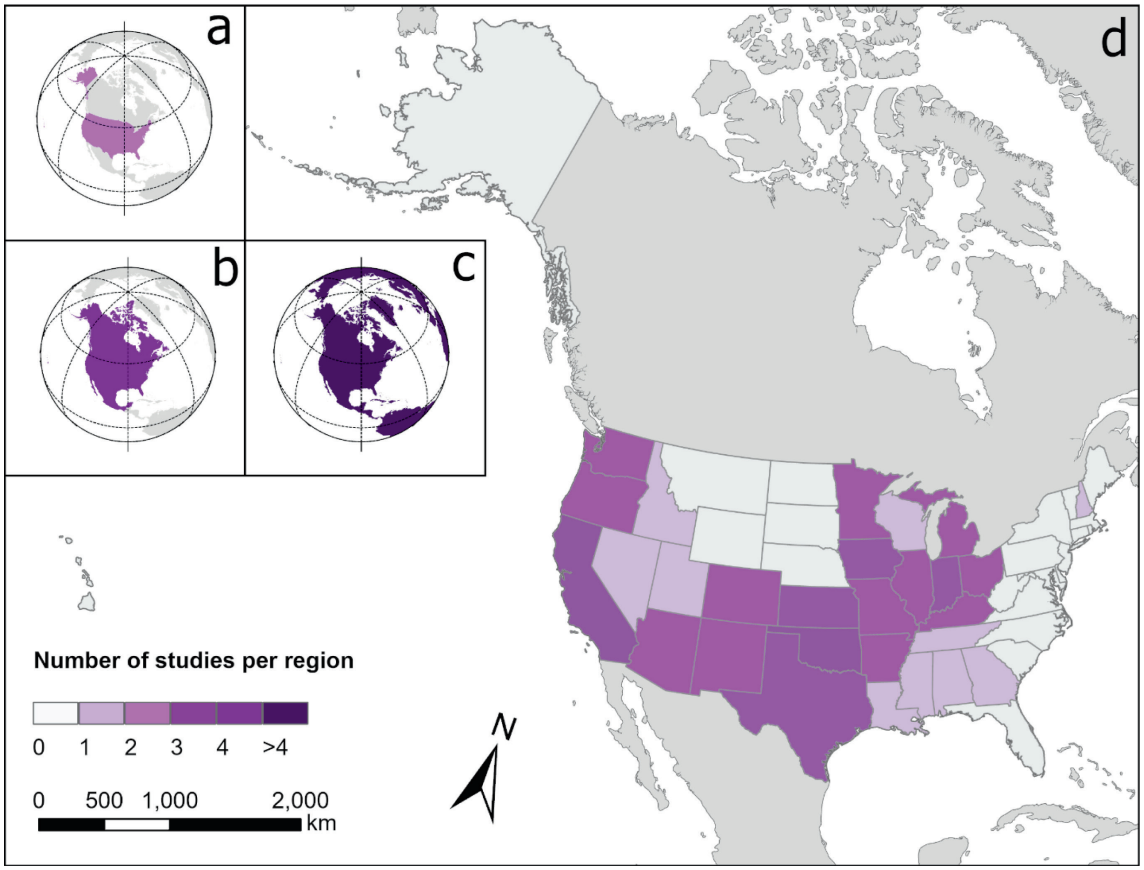


FIGURE 3 | Maps indicating the number of studies focused on (a) the United States, (b) North America, (c) an international scale, but reporting results for the United States and (d) the number of times different states within the country have been part of a regional study.

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mean or anomalies over various timescales (Aylward and Oliveira 2020; Loecke et al. 2017; McKinnon and Deser 2021; Puxley et al. 2024; Raymond et al. 2022; Swain et al. 2018; Tan et al. 2023).

Precipitation-derived products are also re-occurring among the studies, the most prevalent being drought metrics. One example is the Standardised Precipitation Index (SPI), which is an index of the probability of the observed precipitation that can be calculated on different time scales (McKee et al. 1993). This review demonstrates that SPI is one of the most used data sources for identifying whiplash events (Cheng and Liu 2022; Chen and Ford 2023; Ford et al. 2021; Francis et al. 2022; He and Sheffield 2020) but the SPI values considered a drought vs. a pluvial vary significantly. Loecke et al. (2017) and Swain et al. (2018) use an SPI value of − (+) 1.6 to define drought (wet) conditions, guided by the U.S. Drought Monitor's threshold for extreme drought. A few studies use the less conservative SPI value of (±) 1, which roughly corresponds to the 16th and 84th percentiles of the precipitation distribution (Aylward and Oliveira 2020; Tan et al. 2023). Three studies used soil moisture data in conjunction with SPI to more accurately reflect ground conditions (Aylward and Oliveira 2020; He and Sheffield 2020; Qing et al. 2023). Another dataset that has proven useful in whiplash research is the Standardised Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al. 2010) which, in addition to precipitation, includes temperature data and can capture droughts that are intensifying because of the compound impact of precipitation deficit and high temperatures. The studies that used the SPEI index required it to reach ±1 to represent a pluvial (drought) (Rezvani et al. 2023; Rashid and Wahl 2022).

A suite of projected future precipitation data products from various climate models was also used in the studies that considered how extreme hydrologic swings, such as whiplash events, might be impacted by climate change (Chen and Ford 2023; Loecke et al. 2017). In these cases, whiplash information was typically derived based on cumulative precipitation thresholds.

3.2 | Timescale of the Whiplash Event

The time scales set consider both the length of sustained drought/pluvial conditions, and in most cases also the time window for the 'flip' between wet and dry conditions. A few studies also limit the timing of the extremes to certain seasons and months of the year, typically linked to the regional water year (Loecke et al. 2017; Aylward and Oliveira 2020; Swain et al. 2018), while the majority of the articles take an unconditional approach, including droughts and pluvials occurring any time of the year.

Nine studies considered intra-annual fluctuations, four interannual variations and an additional two papers considered both the intra- and inter annual time scales. On the intra-annual scale, the shortest time frame was defined by Francis et al. (2022), who defined a weather whiplash event as 'a long-lived (four or more consecutive days), continental-scale pattern in the upper-level circulation that shifts markedly and rapidly (over 1–2 days) to another substantially different (but not necessarily long-lived) pattern, bringing an abrupt end to persistent weather conditions' (Francis et al. 2022, 3), meaning that the whole whiplash event could last less than 1 week. The same paper is also one of the few that mentions the spatial scale of the event, although it is not clearly defined. The paper recognises that the circulation shifts can lead to hydrologic whiplash, but does not include a definition of the hydrologic extremes per se. The second shortest time scale for a whiplash event was defined by Qing et al. (2023), who set the minimum duration of a drought event to 15 days, followed by a minimum of 5 days of the other extreme. The same study is also the only one in this review which uses different datasets for their definition of dry (soil moisture) and wet conditions (precipitation). Considering this very short time frame, and that soil moisture, which often is used as an indicator of agricultural drought (Liu et al. 2016; Sánchez et al. 2018), is used, rendering this definition to only capture truly extreme whiplash events.

Several studies considered multiple time scales when trying to identify whiplash events in a precipitation time series. For example, 1, 3 and 6-month SPI averages were used by Chen and Ford (2023) and Ford et al. (2021). Table 2 is a summary of the definitions of the hydrological extremes, datasets used and details regarding the temporal length of the transition.

4 | Meteorological and Climatological Drivers

Our literature sample included 28 papers that included a focus on meteorology (synoptic-dynamic evolution), climate variability and/or climate change. In most cases, more than one of these topics was considered in each article. Nearly 60% of papers involved analysis of the effects of climate change on whiplash; around 40% focused on synoptic-dynamic evolution, often in conjunction with the above. Only four papers analysed the role of natural variability (e.g., teleconnections).

4.1 | Meteorological Evolution

The meteorological 'ingredients' for whiplash events (or consecutive dry-pluvial transitions) have not been examined extensively, instead, much of our understanding derives from studies that explore drought or pluvial independently. For example, in the southeastern U.S., drought onset and persistence are linked to warm season reversal in moisture convergence, resulting in zonal moisture divergence and only very weak meridional convergence, which is attributed to a strengthening or westward and northward displacement of the North American Subtropical High (NASH) into the interior CONUS. Conversely, pluvial periods are notable for sustained and unusually strong meridional moisture convergence (Kam et al. 2014), meaning that moisture is persistently being sourced from the tropical Caribbean. During the cool season, a typical pattern of drought is a west U.S. ridge and east U.S. trough anomaly, which produces dry continental northwesterly flow over the domain, also noted by Dong et al. 2011 for the drought period of a drought-pluvial transition in the U.S. Southern Great Plains (SGP).

Over the Great Plains, pluvial events are linked to a higher frequency of synoptic wave (low pressure) activity, which, like the southeast, aids in transporting rich moisture northward and can aid in enhancing precipitation efficiency (Wugofski 2019;

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TABLE 2 | Summary of definitions used in the reviewed papers. Only papers that include specifics regarding the length and magnitude of the hydroclimatological extremes were included. For more details regarding the definitions, the readers are directed to the full text of each paper.

Author(s)	Year	Definition of pluvial/drought	Dataset	Transition	Intra-annual	Interannual	Transition type
Aylward et al.	(2020)	One winter's rainfall is followed by a winter with at least one standard deviation lower rainfall (unidirectional)	Seasonal Precipitation	Season to season		Y	Pluvial-Drought
Chen and Ford	(2023)	SPI ± 1.6	Daily precipitation	Transition occurs within the 30/90/180 day moving window	Y		Both
Cheng and Liu	(2022)	Annual mean precipitation at 20/80th percentile	Daily precipitation	Year to year		Y	Both
Cheng and Liu	(2022)	SPI ± 0.5 and 0.7	Monthly precipitation	Monthly	Y		Both
Ford et al.	(2021)	SPI of ± 1.6	Daily precipitation	Transition occurs within the 30/90/180 day moving window.	Y		Both
He and Sheffield	(2020)	Meteorological: SPI1 of ± 1 Agricultural: Monthly avg. soil moisture in 84/16th percentile	Monthly Precipitation and Soil moisture	3 months	Y		Both
Loecke et al.	(2017)	Pos/negative Weather Whiplash index[a]	Daily precipitation	Index value for Jan-Jun vs. index value for Jul-Dec	Y		Drought-Pluvial
McKinnon et al.	(2021)	80/20th percentile of DJF precipitation	Daily precipitation	Year-to-year		Y	Both
Puxley	(2024)	75/25th percentile of total precipitation, ALSO: min 10 days in one extreme before the flip	Daily precipitation	Calendar months and 30 day moving window (2 approaches)	Y		Both
Qing et al.	(2023)	Drought: Soil moisture below 15th percentile for min 15 days, Pluvial: SPI above 85th percentile	Drought: Daily soil moisture Pluvial: Daily Precipitation	Flip between the extremes within 5 days	Y		Drought-Pluvial
Rashid and Wahl	(2022)	SPEI of ± 1 for at least 6 months	Monthly Precipitation	Monthly[b]	Y	Y	Both
Raymond et al.	(2022)	90/10th percentile of total precipitation	Daily precipitation	Followed by a year of the other extreme		Y	Both

(Continues)

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TABLE 2 | (Continued)

Author(s)	Year	Definition of pluvial/drought	Dataset	Transition	Intra-annual	Interannual	Transition type
Rezvani et al.	(2023)	SPI/SPEI of ± 1	Daily precipitation	Extreme lasting min 1 month, followed by the other extreme within 6 months	Y		Both
Swain et al.	(2018)	Year to year: 20th and 80th percentile Month to month: 1 st.dev. difference in monthly precipitation	Monthly precipitation	Year to year (rainy season) and also month to month	Y	Y	Both
Tan et al.	(2023)	90th/10th percentile of 30 day rolling sum standardised precipitation anomalies	Daily precipitation	Within 30 days	Y		Both

[a]Calculated as the total precipitation from January to June of each year, minus the total precipitation from July to December of the previous year, divided by the total precipitation over the entire period. (Loecke et al. 2017).
[b]It's unclear how long the transition period can be.

Dong et al. 2011). Drought in the plains is linked to the northward displacement of the subtropical jet and a weakening or eastward movement of the NASH, which weakens northward moisture transport via the low-level Jet (LLJ) (Basara et al. 2013). Additionally, the high-low dipole anomaly between the western and northern/eastern U.S. (respectively) is effective at suppressing the LLJ (Dong et al. 2011) Therefore, between these two regions, the movement and intensity of the NASH during the warm season are potential factors in how much or how often whiplash events occur. The Southern Plains is also influenced by continental high pressure, where pluvial conditions in the Plains states can be aided by anomalous ridging over the Midwest, which promotes southerly flow from the Gulf of Mexico (Dong et al. 2011).

Elsewhere in CONUS, pluvial-drought transitions can also be linked to whether the climatological storm tracks are active or suppressed, such as for the western CONUS, which is influenced by the strength and position of the north Pacific (Aleutian) low (Swain et al. 2018). Along the Atlantic and Gulf of Mexico coastlines, some whiplash events may be contributed to by tropical storms or disturbances in otherwise dry synoptic regimes (Song 2022). Precipitation reversals may also be linked to active Rossby wave trains and specifically Rossby wave breaking, which create anomalous wind flow in the lower troposphere that can result in blocking and near-stationary flow, allowing the atmosphere to maintain a particular state (e.g., unusually dry, warm, or cool and wet) over days to weeks (e.g., de Vries et al. 2024).

In terms of the overall probability, or risk, of occurrence, the Central U.S. is presently one of the continental U.S. 'hotspots' f activity (Rashid and Wahl 2022), extending through the Plains states into interior Canada (Wheaton et al. 2023). In parts of this region, it is estimated as a 25% chance that a drought year is followed by a pluvial year (He and Sheffield 2020; Christian et al. 2015). The odds of an event occurring in the warm (generally defined as April–September) and cool (October–March) seasons depend on that region's precipitation climatology. Whiplash at shorter time scales (e.g., 1–6 months) tends to be linked to the seasonality of precipitation, where events can be associated with the delayed onset of traditionally wet periods, or early cessation, or an intensification of climatological transitions (Mullens 2023).

Scaling down to the land-surface level, a few studies have explored potential relationships between drought, pluvial, their transition and land-atmosphere interactions (Basara et al. 2013; Qing et al. 2023). These processes, and the strength of the coupling, appear to change depending on whether the antecedent conditions are dry or wet, with dry condition favouring a negative soil moisture—moisture convergence feedback. In this case, a dry surface and subsurface increases surface heating, vertical ascent through the formation of a thermal low, and subsequent low-level convergence. Thus, the dry condition results in local flow that favours moisture import and can lead to a transition from dry to wet conditions. On the other hand, a dry surface can exacerbate drought through lowering albedo, increasing sensible heat fluxes and reducing evapotranspiration. Which of these processes 'wins' likely relates to specific in situ condition, proximity to remote water sources and ability for air to rise. In

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antecedent wet conditions, one proposed pathway for whiplash is through a negative soil moisture-latent heat feedback, where removal of soil moisture through latent heat flux contributes to atmospheric moisture and thus precipitation. Despite the potential for local to regional influences of land surface, most cases of whiplash are primarily controlled by the large-scale environment (Qing et al. 2023).

This section identifies that there is a significant body of work studying drought and pluvial conditions and their evolutions; however, the synoptic-dynamic evolutions of reversals in drought and pluvial (whiplash) were not a primary focus of any of the studies summarised here, indicating the topic is widely open for further study.

4.2 | Relationships With Natural Variability

Given that whiplash is the product of synoptic-scale anomalies, it could be expected that its evolution may be related to planetary modes of variability; however, the overall body of knowledge in this aspect for CONUS remains thin. Studies considered in this paper largely derive from the southern tier of the United States and from global studies. In the southern U.S., drought-pluvial transitions have been linked to phase changes of the El Niño Southern Oscillation (ENSO) (Goodrich and Ellis 2008; Rashid and Wahl 2022). For example, in the southwestern U.S., large dry-to-wet reversals between consecutive winter (peak precipitation) seasons were associated with neutral to El Niño conditions, while wet-to-dry was associated with El Niño to La Niña or El Niño to neutral (Goodrich and Ellis 2008). The physical mechanisms for this year-to-year whiplash could be linked to the movement of the Pacific jet streams. During El Niño, a strengthened subtropical jet promotes more frequent cyclonic activity over the U.S. southwest, which is conducive to pluvials, but neutral and, in particular, La Niña, promote a more variable and northerly displaced storm track, which favours drier winters. However, not every transition is associated with a whiplash event. In fact, for their more localised study of large reservoirs in Arizona, Goodrich and Ellis noted that transitions between ENSO phases were not good predictors of precipitation reversals, and that the largest consecutive wet (winter) season whiplash events in their dataset were entirely in a neutral phase. Goodrich and Ellis (2008) suggest a role for other modes of variability as well, including the Atlantic Multidecadal Oscillation (AMO), East Pacific Oscillation and Pacific North American Pattern (PNA), which were all significantly associated with precipitation reversals in their study area. During seven winters with ENSO neutral and positive PNA, large wet-to-dry reversals occurred in every case. The authors note that a positive PNA under El Niño typically increases precipitation, but that the situation is reversed when ENSO is neutral. The varying and compounding relationships between multiple modes of variability indicate the complexity of relationships between natural variability and whiplash, especially at the regional-local scales.

In the Great Plains, there are inconsistent associations between ENSO and drought or pluvial (Basara et al. 2013). More broadly, warmer (cooler) Pacific SSTs are linked to more (less) precipitation. This is linked to a strengthening of the Hadley circulation, and thus enhanced subsidence over the Gulf of Mexico and southern and eastern United States. A warm Atlantic (positive AMO) can also exacerbate drought due to weakening the low-level jet; thus, the inverse of these conditions may associate with pluvials. However, since the AMO is slowly varying, variations in this phase are not responsible for short-term whiplash, but the overarching AMO phase may potentially modulate the influence of other higher-frequency modes of variability. Dong et al. (2011) note the potential role of the West Pacific (WP) teleconnection, which is characterised in its positive phase as higher heights/pressure over the central and western northern Pacific and lower height over the Aleutian and sub-arctic north Pacific and eastern Pacific west of the United States. The positive phase of the WP and the PNA were both significantly correlated to cyclonic activity over the southern United States, associated with a southward displacement of the jet stream, resulting in pluvial conditions; thus, implying that phase changes in these patterns can promote drought-pluvial transitions.

Based on the findings presented here, there is considerably more understanding of the role of natural variability on independent cases of drought and pluvial, but very little on their combination. Therefore, further studies of how precipitation whiplash (reversals) respond to various modes of variability over CONUS are warranted, as elucidating these processes more clearly could potentially provide insights into the predictability of whiplash on seasonal to sub-seasonal timescales.

4.3 | Influence of Climate Change

Given the propensity for the literature sample to contain analysis of climate change on whiplash frequency and/or magnitude (17 papers, roughly 60% of our meteorology and physical process sample), there has been generally more attention paid to understanding whiplash in a changing climate, compared to its causal mechanisms. As is described below, the results of these climate projection studies point toward an increase in whiplash frequency over the 21st century over CONUS; however, studies of past observational or reanalysis-based trends have shown mixed evidence of secular trends to the present day (Rashid and Wahl 2022; He and Sheffield 2020; Stevenson et al. 2022), including no trend (Rashid and Wahl 2022; He and Sheffield 2020), a decrease in the interval between a drought or pluvial condition, an increase in persistence of dry and pluvial periods and a tendency for a larger change in pluvial magnitude as compared with drought (Stevenson et al. 2022).

For the western United States, climate change studies have been in part motivated by the impacts of compounding extremes, such as drought and wildfire followed by pluvial periods being associated with landslides, or antecedent pluvial followed by drying resulting in green up of vegetation that later results in enhancing wildfire risk (Swain et al. 2018; Touma et al. 2022). Consecutive rainy (winter) season projections for the southwest suggest an increase in whiplash, which was attributed to synoptic mechanisms that govern current wet and dry conditions, such as anomalous high- or low-pressure systems and blocking (Swain et al. 2018); however, there is an increase in variability between them. Under higher future moisture availability, pluvial periods are enhanced and dry periods are a result of an increase in the strength or persistence of high pressure, which

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opposes any role of higher climatological moisture. Moreover, alongside an increase in heavy precipitation days, there is evidence of higher wildfire risk, as estimated based on climate model projections of the fire weather index (product of temperature, humidity and wind speeds) and a shortening of the interval between their occurrence (Touma et al. 2022). The trend was attributed to an increase in fall and winter precipitation followed by drying in the subsequent warm season. In contrast, studies that examined possible changes to warm season rainfall from the North American Monsoon showed little evidence of changes in whiplash linked to monsoon variability in a warmer climate (Tan et al. 2023).

More broadly and globally, year-to-year whiplash events (i.e., pluvial year followed by dry, or vice versa) were projected to increase in frequency by 10%–25% (using the RCP4.5 emissions pathway, Raymond et al. 2022). Another study using the large-ensemble Community Earth System climate Model version 1 (CESM-LENS) under an RCP8.5 emissions pathway, and 55 realisations of 22 CMIP6 models under high emissions, corroborates this finding, in this case with month-to-month precipitation whiplash (based on 30-day running accumulations) suggesting global increases in whiplash frequency and the risk of experiencing whiplash (~+55%) by the late 21st century (Tan et al. 2023). Cheng and Liu (2022) use probability analysis to project an increase in land areas with a 50% or greater probability of experiencing a dry-wet transition on interannual timescales, including a hotspot in eastern North America. A smaller model ensemble by (Chen and Ford 2023), also evaluating year-to-year reversals, produced global increases in frequency by 25%–60%. Globally, Chen et al. noted the greatest climate-change contributed increase in whiplash frequency in the transition zones between the subtropics and midlatitudes, and a propensity for changes in the frequency and magnitudes of whiplash events to be governed by the magnitude of the pluvial phase (i.e., wet periods becoming much wetter). Over North America, the relative change in whiplash (at 30-day running accumulation timescales) increases more over the west and north (Tan et al. 2023), backed for the U.S. west and southwest by a few studies including (Swain et al. 2018; Chen and Ford 2023). However, (Tan et al. 2023) find most of the continent has more than 90% of ensemble members agreeing with the sign of the change. Duration between drought and pluvial peaks in this study shows a decline that largely fails to be statistically significant, but intensity shows a robust uptick for almost all of North America.

The apparent evidence from these studies points to a relatively consistent picture of future increases in whiplash, even when the authors have utilised different study domains, definitions, data and tools. However, most studies explore trends rather than physical processes conducive to whiplash, and their representation in climate models. There is also a large gap in regional analyses outside of the western United States which could be addressed with further research.

5 | Impacts and Case Studies

Our literature sample included approximately 16 papers where effort was made to discuss specific and expected impacts of whiplash events. Figure 4 shows a word map (panel a) constructed from the introduction and motivation sections of these articles, and panel b shows quantitative summary information on the breakdown of topic areas and the proportion of these impact articles that considered three prominent focus areas qualitatively (general description, no specific analysis – Qual) and quantitatively (focus of paper, effort to make connection between whiplash and impact – Quant). The three key topics discussed below were prominently listed among the impacts of concern, as shown in Figure 4a. However, Figure 4b indicates the number of specific quantitative analyses on relationships between whiplash and impacts was very small.

5.1 | Water Resources

Whiplash events are linked to a mixture of impacts to water quality, water quantity and management. Most studies sampled in this review paper, however, only provide a general description of potential impact as part of a motivation statement, rather than a quantitative or detailed analysis of cause and effect. Stated impacts include an increase in interannual volatility being linked to complicating water management strategies (Raymond et al. 2022; He and Sheffield 2020; Ford et al. 2021; Rashid and Wahl 2022; Dąbrowska et al. 2023) presumably because of less predictability in precipitation and faster transitions between dry and pluvial conditions creating opposing management decisions at relatively short notice. For example, during drought, water resource managers will act to conserve water resources, such as increased water storage in dams and reservoirs. In a pluvial, however, water must often be released to avoid dam failure (He and Sheffield 2020).

Goodrich and Ellis (2008) explore hydrologic response of large (case example: Salt Watershed) and small (case example: Verde watershed) reservoirs that supply water to Phoenix, Arizona. In their analysis, which spans from mid-20th century through to a record-breaking pluvial winter 2004/5, they identify that larger reservoirs are impacted primarily by dry to wet transition between successive winters (peak synoptic-scale precipitation season for the southwest), and small reservoirs impacted by wet to dry transitions. They contend that overall, risks are enhanced for municipalities that rely on smaller reservoirs due to water volumes being more influenced by seasonal and annual variability of water input. In terms of the potential for water infrastructure damage, Rashid and Wahl (2022) and He and Sheffield (2020), following (Vahedifard et al. 2017) cite the failure of the Oroville dam in California in February 2017. The meteorological conditions prior to this event were a persistent multi-year drought until 2016, followed by an exceptional pluvial during the winter of 2016/17 contributed by frequent high-impact atmospheric rivers. While the role these conditions played in the Dam failure was not explored, the coincidence of these conditions to the event suggests a relationship exists.

He and Sheffield (2020) note further examples of significant drought-pluvial transition events that resulted in coincident damage and disruption, including a fast transition to pluvial during fall 2015 over South Carolina, where drought was ameliorated by a deep moisture plume contributed by Hurricane Joaquin, and maintained over the region by a stationary front. Likewise, the Southern Plains extensive drought of 2011–15 was

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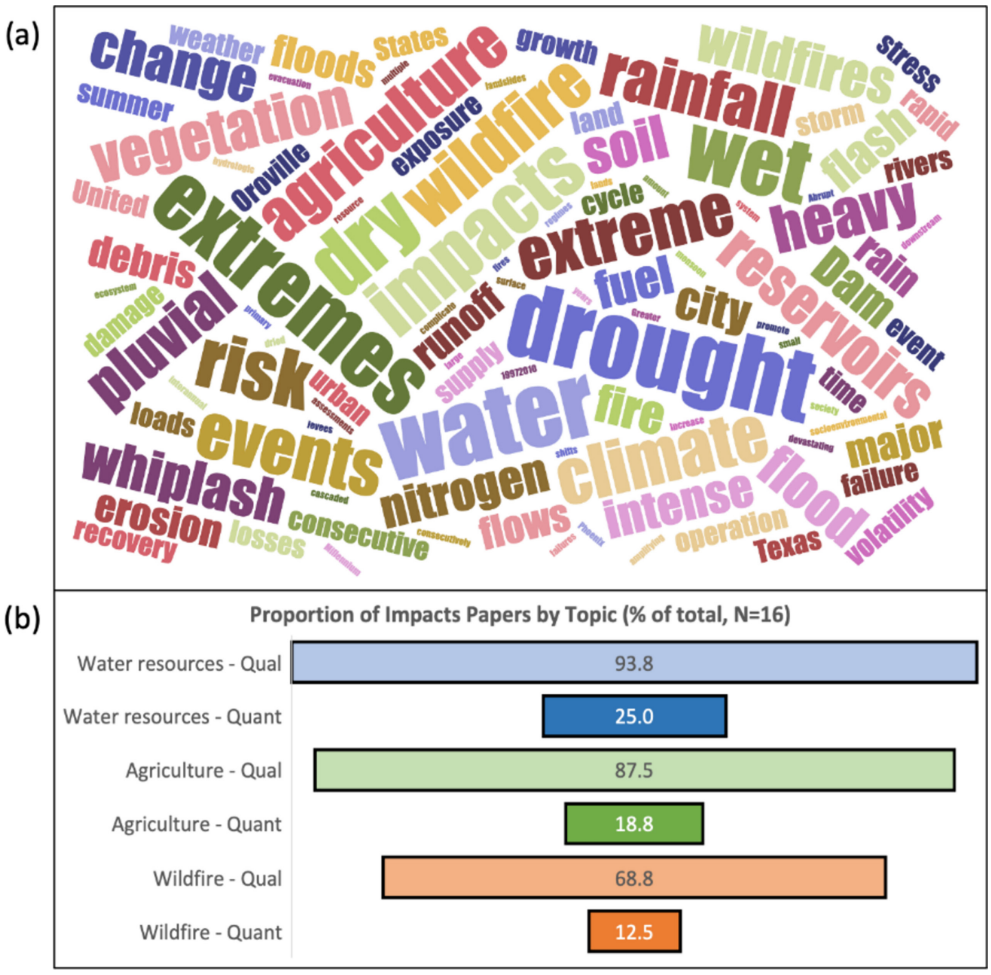


FIGURE 4 | (a) Word-cloud highlighting frequently used language within introduction and motivation sections of articles where impacts were specifically mentioned. The size of the word reflects the normal logarithm of the frequency of use, truncated to the top 200 words. Panel (b) shows the percentage of impact papers which included qualitative (Qual) or quantitative (Quant) information on three primary topics. The word-cloud generator used for this analysis was courtesy of Jason Davis, https://www.jasondavies.com/wordcloud/.

suddenly terminated in Spring of 2015 by a 3-month pluvial, described by Wugofski (2019). This event produced extensive flooding, road closures and scouring, infrastructure damage and property damage to the region. He and Sheffield contend that the precursor changes in vegetation and landscape owing to the drought may have exacerbated impacts from the subsequent pluvial. Issues of vegetation change during drought are noted in western U.S. studies on drought and include vegetation loss from wildfire and an increase in soil density and surface impermeability (Touma et al. 2022; Tan et al. 2023). A subsequent pluvial is therefore more likely to result in initially substantial runoff, flooding and landslides or erosion before the water can percolate into the deeper subsurface.

Water quality issues associated with whiplash were explicitly examined by Loecke et al. (2017) for the 2012–2013 Midwestern U.S. drought-pluvial transition. They note that the drought likely increased nitrogen loading in soils, which was then mobilised during the spring pluvial. This excess nitrogen then ran off into rivers and streams, estimated as 34% above the typical flow mean-weighted mean in concentration. The authors conclude that precipitation whiplash has a discernible negative impact on water quality to the extent that EPA drinking water standards may not be met under similar or worse conditions in the future.

Notably, while there are substantial negative effects of whiplash on water resources and management, the above-documented examples of seasonal and interannual whiplash, particularly pluvial following drought, have been beneficial to the replenishment of reservoirs when it was sorely needed (Puxley et al. 2024; Christian et al. 2015; Rezvani et al. 2023; Wheaton et al. 2023). This comes with adverse impacts associated with excess water, but it can be a boon for water storage and provide relief from drought management. Over the longer term, however, the complexity of managing higher variability is apparent in scenario planning and prediction for water management. For example, (Albano et al. 2021) in structured interviews and scenario-based exercises for western water professionals noted that respondents found the high variability scenario to particularly highlight adverse effects to certain river basins, such as the Truckee River that helps to supply Reno–Sparks, NV, municipal water. In this scenario, respondents noted that reduced upstream reservoir capture during repeated wet years can result in lessened reserves during subsequent droughts.

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5.2 | Agriculture

Agricultural productivity has historically relied on a relatively stable and predictable climate, and crop or economic loss is tied to both drought and extreme pluvial. In the former case, drought results in poor crop and livestock outcomes due to a lack of water resources, especially when coupled with extreme heat (e.g., Steiner and Anderson 2015). Pluvial conditions flood fields, increase erosion, promote disease and produce low yields and economic damage to farmholders. Productive regions of the United States are also those vulnerable to weather whiplash, including the Great Plains, Midwest and Southwest (California).

While whiplash is not explicitly examined, (Steiner and Anderson 2015) note that high variability is already endemic to the U.S. Southern Plains and cites both increased frequency and intensity of drought as well as exceptional rainfall and flash flooding as primary concerns in the region. Ford et al. (2021) evaluate whiplash trends in the U.S. Midwest, motivated by the agriculture-based economy of the region. The 2011–2013 precipitation reversal (drought to pluvial) was linked to nutrient runoff from agricultural fields, as investigated by Loecke et al. (2017). Events that occur during sensitive portions of the growing season – particularly wet to dry events before or during the season, are linked to poor crop outcomes (Dixon and Segerson 1999; Basara et al. 2013; Liu and Basso 2020). Authors of these regional studies note the concern over potential increases in future whiplash as a mechanism for increasing exposure to adverse agricultural impacts. Ford et al. (2021) make a connection between whiplash and 'flash drought', defined as a rapid, typically sub-monthly, onset of drought (Otkin et al. 2015; Christian et al. 2015). Trends in flash drought and whiplash in the Midwest, characterised by 90- to 180-day transitions between pluvial and drought, both follow similar patterns (Basara et al. 2013), manifested as a decrease in transition time between dry and wet states, and an increase in flash drought frequency. While each of these studies provide valuable qualitative information on impact, none of the papers in our sample focused directly on quantifying or measuring specific impacts from whiplash on agriculture, leaving this topic very open and necessary as an avenue of future work.

5.3 | Society and Ecosystems

The primary cited impacts of whiplash on society and ecology include damage from erosion, landslides and flooding and wildfires, with these impacts often compounding and accentuating damage. For example, landslides in the U.S. west have been strongly linked to antecedent wildfire activity, which strips the land of trees and bushes that stabilise the slope soils. Therefore, drought and wildfire activity followed by pluvial conditions are concerns for exacerbation of landslide risk (Touma et al. 2022; Raymond et al. 2022; Tan et al. 2023; Puxley et al. 2024). Another stated causal mechanism for wildfire increases is when pluvial conditions during the growing or 'greening' seasons (e.g., warm season) are followed by a rapid onset or severe drought. This provides enhanced available fuel for fire activity under the dry regime when vegetation is both plentiful and becoming increasingly desiccated through evapotranspiration (Goodrich and Ellis 2008; Puxley et al. 2024; Tan et al. 2023).

Touma et al. 2022 specifically explore relationships between whiplash and wildfire frequency. They note that previous highly damaging debris flows have occurred under the above circumstances, such as the December 2017 Thomas fire in California being succeeded by an intense rainfall event in a similar area a month later, resulting in debris flows in Montecito, 23 fatalities, and over $200 million in property damage. They calculate a forest fire weather risk index (FWI), based on a Canadian index of the same name (Van Wagner 1987) to quantify the frequency of extreme fire weather days (top 0.1% of the FWI) and evaluate its temporal and spatial links with extreme precipitation (top 0.1% of daily precipitation by magnitude) through defining various temporal periods of high precipitation followed by wildfire (3-months to 1-year—or 'compound length') under a changing climate using CESM1-LE. In all study regions (western U.S.) and projections, there were indications, many significant, of relationships between the variables, which varied geospatially and in timing (e.g., time of year the precipitation increases are most significant to wildfire activity), depending on the compound length.

Aylward and Oliveira (2020) explore wildfire links to economic damages in the western United States (12th Economic District). They use a wildfire hazard potential index (or 'WHP', Dillon et al. 2015), categorising it as 'elevated' or 'mild' and projecting its magnitude to 2040 by building a regression-based model that relates the WHP to precipitation, variability (whiplash) and temperature. Their result produces a statistically significant relationship between whiplash frequency and higher WHP values. Moreover, using county-level economic data, they project an almost doubling of economic output exposure to high wildfire risk by 2040 ($2.1 trillion–$4.0 trillion), however they note considerable uncertainty in these values owing to both climatic and economic projections. Outside of the western United States, there is little direct analysis of the wildfire and whiplash connection in the literature sample. Puxley et al. (2024) conjects that the pluvial summer–fall 2017 and subsequent dry winter in the Southern High Plains may have exacerbated wildfire coverage but did not provide a quantitative analysis. None of the studies provided information that directly explores ecosystem impacts in the U.S. east.

Wildfire was the most frequently explored topic outside of agriculture and water resources. However, a review article by Dąbrowska et al. (2023) explores how drought and pluvials can impact urban environments globally. Their work did not explicitly evaluate whiplash but did note how whiplash can threaten efforts to increase and maintain green space through drought leading to plant stress, and subsequent heavy rain to enhanced erosion, loss of foliage and introduction of pollutants. Given the need to mitigate greenhouse gas emissions, which in the urban environment can include the addition of green space, an increase in whiplash threatens to undermine the health of these spaces. This work also notes how increased variability decreases lead time for city officials to manage and prepare for hazards. Simpson et al. (2023) explore adaptation under climate change

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and for compound events globally but note that a minority of papers they reviewed (23%) evaluate temporally compounding events quantitatively. The most common vulnerabilities expressed in this review included low income, food insecurity and limited access to institutional and financial resources. Responses to compound events are typically reactive, but over time have become more proactive, particularly if a region suffers a notable impact from an adverse event, implying that lessons are being learned that can be employed to mitigate future hazard.

6 | Discussion and Conclusion

This paper describes the current state of the science of precipitation whiplash based on studies in the United States. In addition to quantitative analysis of existing studies, the definitions, driving meteorology and impacts of events are analysed and presented. The study at hand is limited by the language (English) of the articles reviewed, as well as the study area (United States). There are many papers on precipitation whiplash focusing on other regions, particularly in Asia. However, the review conducted here presents a plethora of phenomenon definitions as well as a whole suite of different meteorological and climatological drivers. Our key messages include:

Firstly, there is a diversity of methods used to define precipitation whiplash, with the most common variables being precipitation data or anomalies at specific thresholds that reflect dry and pluvial conditions, or use of drought indices such as SPI and SPEI. Temporal variability in definition is particularly striking, and some of these shifts, labelled as 'whiplash' would simply be referred to as year-to-year variability by other researchers in the field, but the authors recognise that the selection of the temporal period is related to the research questions being addressed. Most commonly, whiplash is expressed as changes between dry and pluvial periods (and vice versa) over 1 month, 3–6 months (seasonal), consecutive peak wet seasons, or inter-annually.

Secondly, the primary purpose of the studies evaluated here was to examine trends in whiplash, meteorological drivers, climate projections and relationships to surface impacts. Notable gaps exist, particularly in ascertaining the precise causal mechanisms of whiplash, and possible relationships to planetary variability. Most studies that provide regional to national-scale meteorological analysis suggest a 'tug of war' between synoptic-dynamic regimes that favour dry or pluvial conditions. For example, in the Southern United States, the magnitude and extent of the North American Subtropical High (NASH), frequency of synoptic waves and associated moisture and air mass transport, and location and intensity of storm track activity are all implicated in precipitation reversals, but that specific cause-effect evolutions are not clear from the literature we examined Natural modes of variability that have been examined include ENSO, PNA, AMO and the West Pacific teleconnection, however the relative dearth of work and the lack of detailed qualitative or model-based analysis means that relationships to whiplash remain preliminary. The role of climate change on present and future trends has been investigated more than either of the other subcategories and shows more general agreement regarding the direction of trends, with some regional differences that relate to specifics of the study or definitions of whiplash. While there are more mixed results regarding historical trends, most climate-projection based studies suggest an increase in the frequency of whiplash, an increase in the intensity—particularly of the pluvial component, and a decrease in the 'break' periods between whiplash activity. These results therefore point to a more variable and extreme hydroclimate for much of the United States under global warming.

Finally, studies that provided information on the impacts of whiplash were explored, identifying three key focus areas related to water resources, agriculture and society and ecosystems, the latter of which was dominated by discussion of wildfire. Most studies only consider these topics qualitatively, meaning that only general inferences between cause (whiplash) and effect (impact) are obtained. Several studies do however attempt to provide quantitative impacts analysis, primarily through regional case studies. These examples point to whiplash increasing compound wildfire and erosion/debris flow risks in the western U.S. and reducing water quality by increasing nitrogen loading of soils and then into streams through runoff. Water management may also become more complex under whiplash, particularly in the management of collected water (e.g., dams and reservoirs) that calls for prioritising storage during drought, but release during pluvial or sudden extreme precipitation.

The outcomes of this review point to a wealth of potential for new research and applications within this topic area. It also highlights complexities that remain to be untangled. Suddenly onsetting drought and floods ('flash drought' and 'flash flooding') have been the topic of numerous studies. Due to their rapid development and sudden impact, a significant body of literature has been dedicated to accurately forecasting and predicting these events. Whiplash events, which may contain a flash flood and/or drought but also consider the pre-existing condition (a drought or flood) are more complex and less understood. The compound impacts caused by the consecutive hazards have to date largely been ignored, and instead, the drought and flood have been analysed separately. The authors suggest that future studies of the prediction and impacts of pluvial extremes also consider pre-existing conditions, as the 'starting' environmental conditions will impact the nature of the event, and this approach will allow for our understanding of whiplash events to be further expanded. More generally, compound extremes have become a recent focus in research as researchers and practitioners realise that true understanding of impacts comes from exploring the complex whole of the system.

Additionally, to improve our situational awareness, forecasting and representation of whiplash in numerical models and climate prediction, the drivers of whiplash at its various scales and regions must be examined using synoptic-dynamic perspectives, machine learning techniques, statistical analysis, and model evaluation. This would also require some consistency in the definition of whiplash, and ideally the development of a classification scheme recognising the various scales of the phenomenon. So far to our knowledge, no study has explored multiple sets of criteria for whiplash both using varying data, definitions and temporal intervals. Such an ensemble approach could provide more confidence regarding the nature of historical and projected trends. Developing such datasets that track whiplash over time and domain could be of considerable use to the wider research

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community and stakeholders. Such studies also need not be restricted to the data-rich west. The advent of remote-sensing and sophisticated reanalysis products, in tandem with in situ systems, provides opportunities for global monitoring and analysis.

Author Contributions

Esther Mullens: conceptualization, investigation, writing – original draft, methodology, visualization, writing – review and editing, formal analysis, project administration. **Johanna Engström:** conceptualization, investigation, writing – original draft, methodology, visualization, writing – review and editing, formal analysis, project administration.

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Permission to reproduce material from other sources: Panel (a) of Figure four was generated using a free online word cloud generator created by Jason Davis (https://www.jasondavies.com/wordcloud/). The website states that the generated word clouds may be used for any purpose.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Albano, C. M., M. I. McCarthy, M. D. Dettinger, and S. McAfee. 2021. "Techniques for Constructing Climate Scenarios for Stree-Test Applications." *Climatic Change* 164, no. 33. https://doi.org/10.1007/s10584-021-02985-6.

Aylward, J., and L. E. Oliveira. 2020. "Rising Wildfire Risk for the 12th District Economy." *FRBSF Economic Letter* 2020, no. 19: 1–5. https://ideas.repec.org/a/fip/fedfel/88376.html.

Barendrecht, M. H., A. Matanó, H. Mendoza, et al. 2024. "Exploring Drought-To-Flood Interactions and Dynamics: A Global Case Review." *WIREs Water* 11, no. 4: e1726. https://doi.org/10.1002/wat2.1726.

Basara, J., J. Maybourn, C. Peirano, et al. 2013. "Drought and Associated Impacts in the Great Plains of the United States—A Review." *International Journal of Geosciences* 4, no. 6: 72–81. https://doi.org/10.4236/ijg.2013.46A2009.

Berrang-Ford, L., T. Pearce, and J. D. Ford. 2015. "Systematic Review Approaches for Climate Change Adaptation Research." *Regional Environmental Change* 15: 755–769. https://doi.org/10.1007/s10113-014-0708-7.

Blöschl, G., and M. Sivapalan. 1995. "Scale Issues in Hydrological Modelling: A Review." *Hydrological Processes* 9, no. 3–4: 251–290.

Chen, L., and T. W. Ford. 2023. "Future Changes in the Transitions of Monthly-To-Seasonal Precipitation Extremes Over the Midwest in Coupled Model Intercomparison Project Phase 6 Models." *International Journal of Climatology* 43, no. 1: 255–274. https://doi.org/10.1002/joc.7756.

Cheng, L., and Z. Liu. 2022. "Detectable Increase in Global Land Areas Susceptible to Precipitation Reversals Under the RCP8. 5 Scenario." *Earth's Future* 10, no. 12: e2022EF002948.

Christian, J., K. Christian, and J. B. Basara. 2015. "Drought and Pluvial Dipole Events Within the Great Plains of the United States." *Journal of Applied Meteorology and Climatology* 54: 1886–1898. https://doi.org/10.1175/JAMC-D-15-0002.1.

Christian, J. I., M. Hobbins, A. Hoell, et al. 2024. "Flash Drought: A State of the Science Review." *Wiley Interdisciplinary Reviews: Water* 11, no. 3: e1714.

Dąbrowska, D., A. E. Menéndez Orellana, W. Kilian, et al. 2023. "Between Flood and Drought: How Cities Are Facing Water Surplus and Scarcity." *Journal of Environmental Management* 345: 118557. https://doi.org/10.1016/j.jenvman.2023.118557.

de Vries, A. J., M. Armon, K. Klingmüller, R. Portmann, M. Röthlisberger, and D. I. V. Domeisen. 2024. "Breaking Rossby Waves Drive Extreme Precipitation in the World's Arid Regions." *Communications Earth & Environment* 5: 493. https://doi.org/10.1038/s43247-024-01633-y.

Descroix, L., G. Mahe, T. Lebel, et al. 2009. "Spatio-Temporal Variability of Hydrological Regimes Around the Boundaries Between Sahelian and Sudanian Areas of West Africa: A Synthesis." *Journal of Hydrology* 375, no. 1–2: 90–102.

Diffenbaugh, N. S., D. L. Swain, and D. Touma. 2015. "Anthropogenic Warming Has Increased Drought Risk in California." *Proceedings of the National Academy of Sciences* 11213: 3931–3936. https://doi.org/10.1073/pnas.1422385112.

Dillon, G. K., J. Menakis, and F. Fay. 2015. "Wildland Fire Potential: A Tool for Assessing Wildfire Risk and Fuels Management Needs." In *Proceedings of the Large Wildland Fires Conference*, edited by E. Robert, M. W. Jolly, R. Parsons, and K. L. Riley, 60–76. U.S. Department of Agriculture. https://www.fs.usda.gov/treesearch/pubs/49429.

Dixon, B. L., and K. Segerson. 1999. "Impacts of Increased Climate Variability on the Profitability of Midwest Agriculture." *Journal of Agricultural and Applied Economics* 31: 537–549. https://doi.org/10.1017/S1074070800008828.

Dong, X., B. Xi, A. Kennedy, et al. 2011. "Investigation of the 2006 Drought and 2007 Flood Extremes at the Southern Great Plains Through and Integrative Analysis of Observations." *Journal of Geophysical Research* 116, no. D3: D03204. https://doi.org/10.1029/2010JD014776.

Engström, J., and C. B. Uvo. 2016. "Effect of Northern Hemisphere Teleconnections on the Hydropower Production in Southern Sweden." *Journal of Water Resources Planning and Management* 142, no. 2: 05015008.

Ford, T. W., L. Chen, and J. T. Schoof. 2021. "Variability and Transitions in Precipitation Extremes in the Midwest United States." *Journal of Hydrometeorology* 22, no. 3: 533–545. https://doi.org/10.1175/JHM-D-20-0216.1.

Francis, J. A., N. Skific, S. J. Vavrus, and J. Cohen. 2022. "Measuring 'Weather Whiplash' Events in North America: A New Large-Scale Regime Approach." *Journal of Geophysical Research: Atmospheres* 127, no. 17: e2022JD036717.

Ghil, M. 2002. "Natural Climate Variability." In *Encyclopedia of Global Environmental Change*, edited by M. MacCracken and J. Perry, vol. 1, 544–549. Wiley & Sons.

Goodrich, G. B., and A. W. Ellis. 2008. "Climatic Controls and Hydrologic Impacts of a Recent Extreme Seasonal Precipitation Reversal in Arizona." *Journal of Applied Meteorology and Climatology* 47, no. 2: 498–508. https://doi.org/10.1175/2007JAMC1627.1.

Hamlet, A. F., and D. P. Lettenmaier. 1999. "Columbia River Streamflow Forecasting Based on ENSO and PDO Climate Signals." *Journal of Water Resources Planning and Management* 125, no. 6: 333–341.

He, X., and J. Sheffield. 2020. "Lagged Compound Occurrence of Droughts and Pluvials Globally Over the Past Seven Decades." *Geophysical Research Letters* 47, no. 14: e2020GL087924.

Hurst, H. E. 1951. "Long-Term Storage Capacity of Reservoirs." *Transactions of the American Society of Civil Engineers* 116, no. 1: 770–799.

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IPCC. 2021. "Climate Change 2021: The Physical Science Basis." In *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by V. Masson-Delmotte, P. Zhai, A. Pirani, et al. Cambridge University Press. https://doi.org/10.1017/9781009157896.

Kam, J., J. Sheffield, X. Yuan, and E. F. Wood. 2014. "The Influence of Atlantic Tropical Cyclones on Drought Over the Eastern United States (1980–2007)." *Journal of Climate* 26, no. 10: 3067–3086. https://doi.org/10.1175/JCLI-D-12-00244.1.

Lesinger, K., and D. Tian. 2022. "Trends, Variability, and Drivers of Flash Droughts in the Contiguous United States." *Water Resources Research* 58, no. 9: e2022WR032186.

Liu, L., and B. Basso. 2020. "Impacts of Climate Variability and Adaptation Strategies on Crop Yields and Soil Organic Carbon in the US Midwest." *PLoS One* 15: e0225433. https://doi.org/10.1371/journal.pone.0225433.

Liu, X., X. Zhu, Y. Pan, S. Li, Y. Liu, and Y. Ma. 2016. "Agricultural Drought Monitoring: Progress, Challenges, and Prospects." *Journal of Geographical Sciences* 26: 750–767. https://doi.org/10.1007/s11442-016-1297-9.

Loecke, T. D., A. J. Burgin, D. A. Riveros-Iregui, et al. 2017. "Weather Whiplash in Agricultural Regions Drives Deterioration of Water Quality." *Biogeochemistry* 133, no. 1: 7–15. https://doi.org/10.1007/s10533-017-0315-z.

McKee, T. B., N. J. Doesken, and J. Kleist. 1993. "The Relationship of Drought Frequency and Duration to Time Scales." *Proceedings of the 8th Conference on Applied Climatology* 17, no. 22: 179–183.

McKinnon, K. A., and C. Deser. 2021. "The Inherent Uncertainty of Precipitation Variability, Trends, and Extremes due to Internal Variability, With Implications for Western U.S. Water Resources." *Journal of Climate* 34: 9605–9622. https://doi.org/10.1175/JCLI-D-21-0251.1.

Mullens, E. D. 2023. "A Synoptic Climatology of Precipitation 'Whiplash' in the United States 1891-2015." Poster, 36th Conference on Climate Variability/37th Conference on Hydrology. AMS Annual Meeting, Denver CO. https://ams.confex.com/ams/103ANNUAL/meetingapp.cgi/Paper/420249.

Ng, J. Y., S. W. Turner, and S. Galelli. 2017. "Influence of El Niño Southern Oscillation on Global Hydropower Production." *Environmental Research Letters* 12, no. 3: 034010.

Otkin, J. A., M. C. Anderson, C. Hain, and M. Svoboda. 2015. "Using Temporal Changes in Drought Indices to Generate Probabilistic Drought Intensification Forecasts." *Journal of Hydrometeorology* 16: 88–105. https://doi.org/10.1175/JHM-D-14-0064.1.

Parry, S., C. Prudhomme, R. L. Wilby, and P. J. Wood. 2016. "Drought Termination: Concept and Characterisation." *Progress in Physical Geography* 40, no. 6: 743–767. https://doi.org/10.1177/0309133316652801.

Puxley, B., E. R. Martin, J. B. Basara, and J. I. Christian. 2024. "The Wildfire Impacts of the 2017-18 Whiplash Event Across the Southern Great Plains." *Environmental Research Letters* 19: 074029. https://doi.org/10.1088/1748-9326/ad54da.

Qing, Y., S. Wang, Z.-L. Yang, and P. Gentine. 2023. "Soil Moisture–Atmosphere Feedbacks Have Triggered the Shifts From Drought to Pluvial Conditions Since 1980." *Communications Earth & Environment* 4: 254. https://doi.org/10.1038/s43247-023-00922-2.

Rashid, M. M., and T. Wahl. 2022. "Hydrologic Risk From Consecutive Dry and Wet Regimes at the Global Scale." *Environmental Research Communications* 4: 071001. https://doi.org/10.1088/2515-7620/ac77de.

Raymond, C., L. Suarez-Gutierrez, K. Kornhuber, M. Pascolini-Campbell, J. Sillmann, and D. E. Waliser. 2022. "Increasing Spatio-Temporal Proximity of Heat and Precipitation Extremes in a Warming World Quantified by a Large Model Ensemble." *Environmental Research Letters* 17: 035005. https://doi.org/10.1088/1748-9326/ac5712.

Rezvani, R., W. Na, and M. R. Najafi. 2023. "Lagged Compound Dry and Wet Spells in Northwest North America Under 1.5°C–4°C Global Warming Levels." *Atmospheric Research* 290: 106799. https://doi.org/10.1016/j.atmosres.2023.106799.

Sánchez, N., Á. González-Zamora, J. Martínez-Fernández, M. Piles, and M. Pablos. 2018. "Integrated Remote Sensing Approach to Global Agricultural Drought Monitoring." *Agricultural and Forest Meteorology* 259: 141–153.

Simpson, N. P., P. A. Williams, K. J. Mach, et al. 2023. "Adaptation to Compound Climate Risks: A Systematic Global Stocktake." *IScience* 26, no. 2: 105926. https://doi.org/10.1016/j.isci.2023.105926.

Song, J. Y. 2022. "Unraveling Compound Extremes: Tropical Storms, Heatwave, Drought, and Wildfire." Thesis. University of Alabama. https://ir.ua.edu/items/e7bff4c8-5068-471c-88ea-79953dc3a365.

Steiner, J. L., and T. Anderson. 2015. "Southern Plains Assessment of Vulnerability and Preliminary Adaptation and Mitigation Strategies for Farmers, Ranchers and Forest Landowners." https://ideas.repec.org/p/ags/usdami/337562.html.

Stevenson, S., S. Coats, D. Touma, and B. Otto-Bliesner. 2022. "Twenty-First Century Hydroclimate: A Continually Changing Baseline, With More Frequent Extremes." *PNAS* 19, no. 12: e2108124119. https://doi.org/10.1073/pnas.210812411.

Swain, D. L., B. Langenbrunner, J. D. Neelin, and A. Hall. 2018. "Increasing Precipitation Volatility in Twenty-First-Century California." *Nature Climate Change* 8, no. 5: 427–433. https://doi.org/10.1038/s41558-018-0140-y.

Tan, X., X. Wu, Z. Huang, et al. 2023. "Increasing Global Precipitation Whiplash due to Anthropogenic Greenhouse Gas Emissions." *Nature Communications* 14: 2796. https://doi.org/10.1038/s41467-023-38510-9.

Touma, D., S. Stevenson, D. Swain, D. Singh, D. Kalashnikov, and X. Huang. 2022. "Climate Change Increases Risk of Extreme Rainfall Following Wildfire in the Western United States." *Science Advances* 8: eabm0320. https://doi.org/10.1126/sciadv.abm0320.

Vahedifard, F., A. AghaKouchak, E. Ragno, S. Shahrokhabadi, and I. Mallakpour. 2017. "Lessons From the Oroville Dam." *Science* 355, no. 6330: 1139–1140. https://doi.org/10.1126/science.aan0171.

van der Schrier, G., and J. Barkmeijer. 2007. "North American 1818–1824 Drought and 1825–1840 Pluvial and Their Possible Relation to the Atmospheric Circulation." *Journal of Geophysical Research: Atmospheres* 112, no. D13: 2007JD008429. https://doi.org/10.1029/2007JD008429.

Van Wagner, C. E. 1987. "Development and Structure of the Canadian Forest Fire Weather Index System." Canadian Forestry Service, Headquarters, Ottawa. Forestry Technical Report 35. 35 p.

Vicente-Serrano, S. M., S. Beguería, and J. I. López-Moreno. 2010. "A Multi-Scalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index—SPEI." *Journal of Climate* 23: 1696–1718.

Villarini, G., J. A. Smith, R. Vitolo, and D. B. Stephenson. 2013. "On the Temporal Clustering of US Floods and Its Relationship to Climate Teleconnection Patterns." *International Journal of Climatology* 33, no. 3: 629–640.

Wheaton, E., B. Bonsal, and D. Sauchyn. 2023. "Compound Extremes of Droughts and Pluvials: A Review and Exploration of Spatio-Temporal Characteristics and Associated Risks in the Canadian Prairies." *Water* 15, no. 19: 3509. https://doi.org/10.3390/w15193509.

Wugofski, S. 2019. "Synoptic and Mesoscale Analysis of the 2015 Southern Great Plains Flash Pluvial." Thesis (University of Oklahoma). https://hdl.handle.net/11244/321053.

10970088, 2025, 8, Downloaded from https://rmets.onlinelibrary.wiley.com/doi/10.1002/joc.8850 by Test, Wiley Online Library on [16/10/2025]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License