JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION

Vol. 58, No. 6 AMERICAN WATER RESOURCES ASSOCIATION December 2022

The Press and Pulse of Climate Change: Extreme Events in the Colorado River Basin

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Research Impact Statement: Increasing risk associated with extreme weather events in the Colorado River Basin is a critical concern to stakeholders and water managers in a changing climate.

ABSTRACT: Extremes in temperature and precipitation are associated with damaging floods, prolonged drought, destructive wildfires, agricultural challenges, compromised human health, vulnerable infrastructure, and threatened ecosystems and species. Often, the steady and progressive trends (or *presses*) of rising global temperature are the central focus in how climate impacts are described. However, observations of extreme weather events (or *pulses*) increasingly show that the intensity, duration and/or frequency of acute events are also changing, resulting in greater impacts on communities and the environment. Describing how the influence of extreme events may shape water management in the Colorado River Basin in clear terms is critical to sound future planning and efforts to manage risk. Three scenario planning workshops in 2019 and 2020 were held as part of a Colorado River Conversations series, identifying potential impacts from multiple intersecting extreme events. Water managers identified climate-related events of concern in the Colorado River Basin that necessitate greater attention and adaptive responses. To support efforts to include consideration of climate-change-driven extremes in water management and planning, we explore the current state of knowledge at the confluence of long-term climate shifts and extreme weather in the Colorado River Basin related to the events of concern that were identified by scenario planning participants.

(KEYWORDS: climate variability/change; water resource planning; watershed management; drought; weather and climate extremes; Colorado River Basin.)

INTRODUCTION

Current climate patterns and annual weather cycles are changing through both pressing (gradual) and pulsing (abrupt, exceeding expected threshold) changes over time. Climate-change-driven trends in global energy dynamics and associated surface temperature changes (along with more complex changes in precipitation patterns) are altering the baseline of extreme events (NASEM 2016; Kossin et al. 2017; IPCC 2021). Increasingly, some extreme weather events, or pulses, that are statistically unlikely and occur in the “tails” of a region’s historical records (see Figure 1) are becoming more frequent and/or intense in the context of the longer-term press of climate change (IPCC 2012; IPCC 2021). For example, global observations indicate that the duration and severity of intense precipitation events are increasing and these changes have been attributed to human-influenced global warming (Min

Paper No. JAWR-21-0049-P of the *Journal of the American Water Resources Association* (JAWR). Received March 20, 2021; accepted May 16, 2022. **Discussions are open until six months from issue publication**.

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Citation: McCoy, A.L., K.L. Jacobs, J.A. Vano, J. KeatonWilson, S. Martin, A.G. Pendergrass, and R. Cifelli. 2022. “The Press and Pulse of Climate Change: Extreme Events in the Colorado River Basin.” *JAWRA Journal of the American Water Resources Association* 58 (6): 1076–1097. https://doi.org/10.1111/1752-1688.13021.

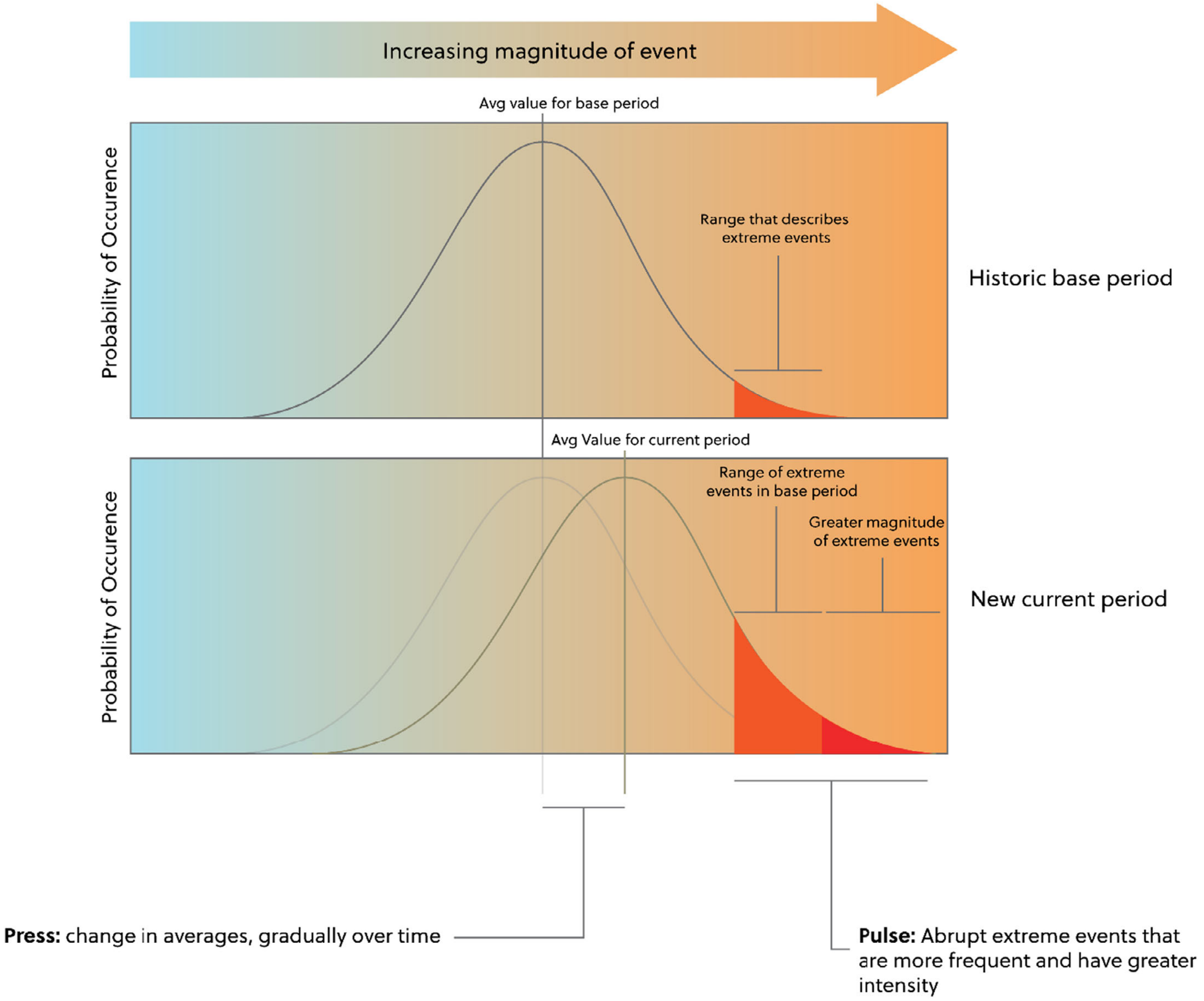

FIGURE 1. As global and Colorado River Basin temperatures rise, a progressive rise in temperature increases the probability of extremely hot weather events that put additional pressure on water supplies and push water management institutions to address supply and demand imbalances. Of note, in addition to the distribution shifting, it may change shape as well (e.g., the tail on the right side could become larger). Figure adapted from IPCC (2012).

et al. 2011). These extremes, in addition to others such as hot extremes, heatwaves, and droughts, are expected to occur more frequently in the future in many regions (IPCC 2021).

Extremes, by definition, are outside the norm — they are in the tails of statistical distributions. Their origins and impacts may not be well understood because they have occurred infrequently in the past. The 2021 Intergovernmental Panel on Climate Change Working Group I report (IPCC 2021) documented increased confidence in attributing extreme weather events to climate change, reinforcing prior assessments such as the National Academies of Sciences, Engineering, and Medicine report (NASEM 2016) that focused on the state of knowledge of the attribution of extreme events in the context of climate change at the global scale (Figure 2). However, there is much more to learn. Notably, while there is considerable information and research on the expected future trends in anthropogenic climate change (such as in average global temperature), fewer studies describe *expected future trends in extreme events*, and even fewer focus on specific regions or basins. This paper provides an overview of the current state of knowledge and research on trends in several categories of climate-related extremes in the Colorado River Basin, as well as offering examples of extreme events that have occurred within the past four years.

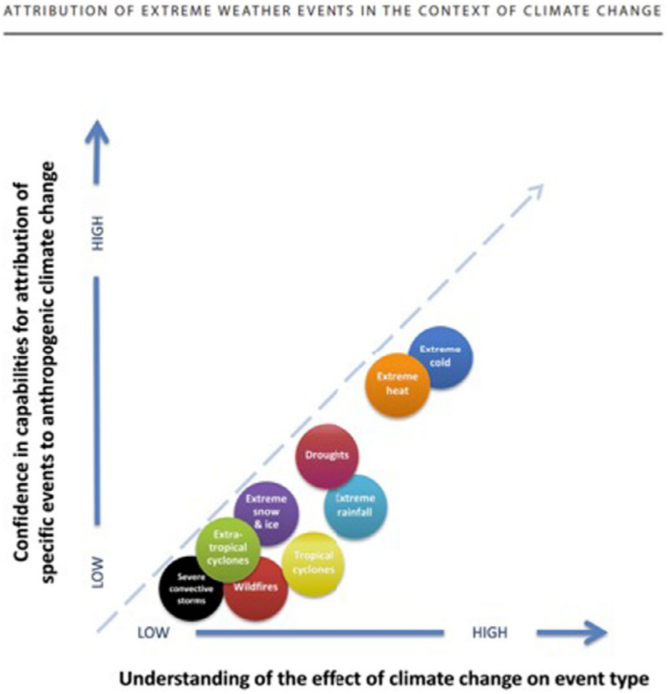

FIGURE 2. Attribution of Extreme Weather Events in the Context of Climate Change (taken directly from NASEM 2016). This figure illustrates the expert panel's evaluation of the state of attribution science for each of these extreme event types. The vertical axis is the range of confidence linked to anthropogenic climate change, while the horizontal axis represents how well the mechanisms of impacts are understood. Extreme heat and cold are highest in both categories because temperature is directly driven by climate change-driven shifts in the energy balance in the atmosphere. This contrasts with wildfire impacts, which are the product of many factors, including soil moisture, fuel loading, wind, temperature, humidity, historical fires, vegetation health, and fire suppression. It is important to note that the science of attribution is evolving quickly, and this figure was created to illustrate the panelists' own views on the state of attribution science as of 2016. For more information regarding this figure, see box 4.1, page 124 of NASEM (2016).

PLANNING AMID EXTREMES

Uncertainties around the future impacts of extreme weather events were identified and prioritized by water professionals in a Scenario Planning series within the Colorado River Conversations Project (https://ccass.arizona.edu/colorado-river-conversations-project). Workshop participants included representatives from all seven Colorado River Basin states, Mexico, Tribes, academics, scientists, water managers, agricultural interests, and nongovernmental Organizations (NGOs) (Jacobs et al. 2020; Gerlak et al. 2021). The Project included three scenario planning workshops that examined the types and impacts of potential intersecting and/or overlapping extreme events in the Basin and developed a series of near-term actions that could help increase resilience in the built and natural environment (Jacobs et al. 2020). The near-term, no-regrets actions identified ranged from collaborative projects to research partnerships to develop more tangible, accessible, and broadly applicable information on extreme weather events.

The Colorado River Conversations Project scenario planning workshops built a series of scenarios based on "nightmare" future conditions that represented the compounding effects of climate-change-driven extreme events with unrelated social and economic challenges (Jacobs et al. 2020; Gerlak et al. 2021). In these conversations, participants identified a range of regionally relevant climate-related and extreme weather events and trends of concern, which included: (1) intensifying heat waves, (2) diminished snowpack, (3) long-duration drying (sustained declines in runoff efficiency), (4) extensive wildfires, (5) short-duration intense wet and dry system shocks, (6) amplified wet and dry swings (climate whiplash), and (7) declines in monsoons. These categories illustrate a broad range of concerns, which are realized through both climate-change-driven presses and pulses and then affected by other factors such as economic downturns, and social and political upheaval. The mechanisms behind each category of these seven concerns are not equally well understood and thus not all well represented in climate and hydrology models. As a result, knowledge about the links to climate change and likelihood of impacts in each category varies (NASEM 2016). To provide context and a basis for further exploration, we describe each type of climate-related event below, including the evidence current research provides about expected future trends in these events (Table 1). These seven concerns were prioritized by workshop participants and are numbered here to help guide readers, but these are not necessarily discrete categories and can be intertwined — for example they may be manifestations of the same mechanisms at different timescales. Through exploring the scientific basis for what is known about trends in extremes, how it is known, and the nature of the uncertainties, we directly respond to Colorado River Basin stakeholders' requests.

The ways in which water managers might respond to these climate-related events differ depending on several factors, including: the anticipated rate of change in a region; the perceived risk to infrastructure and communities; resource availability; and the extent of planning and preparation that would be required to prepare for a broad range of possible future scenarios. Prior to the Colorado River Conversations Project, scenario planning had already emerged as a useful tool for water resources planning in the context of uncertainty and to support ongoing and future decision-making processes (Woodhouse

TABLE 1. Events of Concern and their linkages to climate change in the Colorado River Basin

Events of concern noted by water managers	Climate-change trend defined	Impact of change	Linkage to climate change drivers	Relevant research[1]	A recent example (details in text)
1. Intensifying heat waves	Hotter periods that last longer	• Air quality declines • Water quality declines • Increased fire danger • Ecosystem mortality events • Health and safety impacts, especially for outdoor workers and vulnerable populations	Greenhouse gases trap more heat, lead to warmer temperatures	*US*: Meehl et al. (2009); Cutting et al. (2011); Wuebbles et al. (2017); Fahey et al. (2017); Vose et al. (2017) *Global*: Guo et al. (2018); IPCC (2021)	In the summer of 2020 and 2021, the Colorado River Basin experienced heat wave conditions that exceeded multiple records for a consecutive number of days, with temperatures surpassing historical conditions
2. Diminished snowpack	Less precipitation falls as snow vs. rain, snowmelt occurs earlier	• Reduced streamflow • Earlier peak flows • Water shortages • Recreation limited	More precipitation falls as rain than as snow, warmer temperatures cause early snowmelt	*Basin specific*: Reynolds et al. (2020) *Western US*: Barnett et al. (2005); McCabe et al. (2007); Barnhart et al. (2016); Harpold and Molotch (2015); Li et al. (2017); Harpold and Kohler (2017); Painter et al. (2018); Yan et al. (2018); Musselman et al. (2017, 2018, 2021); Davenport et al. (2020)	Snowpack monitoring stations throughout the West reveal that snowmelt is already occurring earlier in the year
3. Long duration drying (Sustained declines in runoff efficiency)	Streamflow declines even when the same amount of water falls as precipitation	•Reduced streamflow • Water shortages • Agriculture declines	Warmer, thirstier atmosphere leads to more	*US*: Berghuijs et al. (2014) evaporation/transpiration/sublimation of water, drier soils, and less water reaching streams before returning to atmosphere	*Basin specific*: Vano et al. (2012), 2014); Woodhouse et al. (2016, 2021); McCabe et al. (2017); Udall and Overpeck (2017); Hoerling et al. (2019) *Western US*: Das et al. (2011); Gonzalez et al. (2018) *US*: McCabe and Wolock (2016)

(continued)

TABLE 1. (continued)

Events of concern noted by water managers	Climate-change trend defined	Impact of change	Linkage to climate change drivers	Relevant research[1]	A recent example (details in text)
The Upper Colorado River Basin in 2020 and 2021 had unexpectedly low run-off volumes					
4. Extensive wildfires	More areas burned	• Public safety threatened • Air quality declines • Water quality declines • Increased erosion	Increased temperatures, increased drying and reductions in snowpack while lengthening the fire season	*Western US*: Abatzoglou and Kolden (2011); Jenkins et al. (2014); Abatzoglou and Williams (2016); Holden et al. (2018); Kean et al. (2019); Zhang et al. (2020); Brey et al. (2021) *US*: Wehner et al. (2017)	In 2020, Colorado experienced the three largest wildfires in recorded history
5. Short-duration intense wet and dry system shocks	Precipitation intensity increases; each storm brings more water	• Flooding • Increased erosion • Dam safety concerns + Increased groundwater recharge in some locations + Drought relief	A warmer atmosphere holds more water, so when it rains or snows there a greater chance that more precipitation will fall in any given event; additionally, storms are now developing in warmer and more humid environments, ocean surface temperatures drive a worldwide increase in size and number of storms	*Basin specific*: Gutmann et al. (2016); Shamir et al. (2019); Corringham et al. (2019) *Western US*: Zhu and Newell (1994); Corbosiero et al. (2009); Dettinger (2013); Rutz et al. (2015); Alexander et al. (2015); Swales et al. (2016); Demaria et al. (2019); Gershunov et al. (2019); Davenport et al. (2020); Payne et al. (2020); Rhoades et al. (2020) *US*: Easterling et al. (2017); Kossin et al. (2017) *Global*: Trenberth (2011); Pendergrass and Hartmann (2014); Swann et al. (2016); Fischer and Knutti (2016); Simpson et al. (2016); Kossin et al. (2017); Pendergrass et al. (2017); Sippel et al. (2019); Heinze-Deml et al. (2020)	In 2013, the “Front Range Flood” in Colorado resulted from record rainfall and urban runoff volumes
	Rapid onset dry year (flash drought)	• Water shortages • Agricultural losses • Recreation limited • Increased fire danger	Large-scale atmospheric circulation changes increase temperatures, modify precipitation, reduce cloud cover, and increase wind speeds	*Great Plains and Eastern US*: Hoell et al. (2020); Ford and Labosier (2017) *US*: Otkin et al. (2018); Christian et al. (2019); Pendergrass et al. (2020) *Global*: Hoffmann et al. (2021)	Recent example not within the Colorado River Basin
			A combination of more moisture and		July 2021 was the wettest month on

(continued)

TABLE 1. (continued)

Events of concern noted by water managers	Climate-change trend defined	Impact of change	Linkage to climate change drivers	Relevant research[1]	A recent example (details in text)
6. Amplified wet and dry swings (climate whiplash)	Multi-year dry spells broken by a couple of very wet years	• Dam safety concerns • Increased erosion • Management challenge (expecting drought and receiving too much rain instead)	weakening of overall atmospheric circulation, results in a drought-pluvial see-saw	*California / Western US*: Swain et al. (2018); Wahl et al. (2020); Dettinger (2013) *Global*: He and Sheffield (2020); Pendergrass et al. (2017); Pendergrass and Gerber (2016); Konapala et al. (2016); Schwarzwald et al. (2021)	record in Tucson, which came after the “nonsoon” of 2020
7. Dramatic decline in monsoons	Timing of monsoon is later or no monsoon occurs Average rainfall from monsoons lessens Change in frequency and intensity of extreme rainfall events	• Water shortages • Agriculture loses • Less relief from summer heat	Warmer temperatures change atmospheric circulation patterns in ways that inhibit convection and cloud formation	*Southwest US*: Cook and Seager (2013); Pascale et al. (2017); Luong et al. (2017); Demaria et al. (2019); Carroll et al. (2020) *Global*: Emori and Brown (2005); Wang et al. (2021)	In 2020, Arizona’s monsoon was characterized as a “nonsoon” for delivering near record low precipitation

[1] Relevant research articles are cited in Events of Concern 1–7 sections of paper. Research provides evidence as to how these are linked to climate drivers, which is likely to change with time as conditions and understanding evolve. To allow this table to expand and change as more is known, a form of it is posted under the *Projected future climate* section of the Colorado River Science Wiki: http://coloradoriverscience.org.

et al. 2021). Beyond the Colorado River Basin, the Water Utility Climate Alliance and the Water Research Foundation have supported work on assessing risks posed to water utilities from extreme events (Wasley and Jacobs 2020). These groups have invested in this research to help resource managers, planners, elected officials, and others more effectively anticipate risks associated with extreme events and how they may evolve in a changing climate.

COLORADO RIVER BASIN CONTEXT

Current water management frameworks, policies, infrastructure, and socioeconomic systems in the Colorado River Basin were built on assumptions that the range of variability in future climate conditions would be comparable to the historical variability. The headwaters of the Colorado River are located along the spine of the Rocky Mountains, which constitute about 15% of the land area in the Basin but contribute roughly 85% of the annual runoff from high mountain forests, peaks, and meadows. An annual average of 170 million acre-feet (maf) of precipitation has historically fallen over the Colorado River Basin (Lukas and Payton 2020). Mid-latitude winter and spring storms from October–May are a critical driver of annual precipitation and snowpack in the Basin's headwaters (Lukas and Payton 2020). The melting of this snowpack in the late spring produces the bulk of annual streamflows and supports higher reservoir levels throughout the Basin. There is considerable decadal and multi-decadal variability both in the paleo and modern records (Woodhouse et al. 2021). Recent warming climate trends have been linked to decreases in spring snowpack and shifts to earlier runoff timing (Udall and Overpeck 2017; Xiao et al. 2018; Woodhouse et al. 2021).

The Colorado River Compact (1922) and the 1944 United States (U.S.)/Mexico Treaty allocated river flows among seven states (Wyoming, Colorado, Utah, New Mexico, Nevada, Arizona, and California) and the Republic of Mexico based on assumptions that the Basin yielded about 17 maf (or 10% of total precipitation) in natural streamflow available for use and legal allocation. The initial calculations ignored the range of natural variability already known at the time (Kuhn and Fleck 2019), and left no buffer for the dramatic changes that are now occurring.

Paleoclimate records show that historical megadroughts persisted for decades (Meko et al. 2007); the largest of these events would result in major disruptions to water supply in the Basin even in the absence of climate change. Current projections show that a warming climate will likely drive human and natural systems past critical threshold points where water supply systems and ecosystems no longer function as they did before (Udall and Overpeck 2017; Milly and Dunne 2020; Woodhouse et al. 2021). Establishing a legal allocation system that utilized the entire available flows, left little flexibility in management protocols and policies that could absorb the kind of changes that human-caused climate changes are bringing (Kuhn and Fleck 2019). Thirty years of temperature-induced reductions in streamflow have measurably reduced flows into reservoirs such as Lake Powell, alongside a precipitation deficit since 2000. This lack of water has resulted in conditions in 2021 which triggered a series of legally negotiated management responses and emergency releases from Upper Basin storage (upstream of Lees Ferry, Arizona) to maintain hydropower at Lake Powell as outlined by the 116th Congress (2019). These actions underscore the reality that current and future conditions are diverging significantly from the expectations of water managers based on historical conditions, due to both the press of persistent changes and pulse of greater intensity, duration and/or frequency of extreme weather events.

THE *PRESS* OF CLIMATE CHANGE IN THE COLORADO RIVER BASIN

The press of persistent shifts associated with climate change is increasingly well-documented in the Colorado River Basin. Conditions in the 21st Century relative to the 20th Century are overall warmer (Woodhouse et al. 2016, 2021; Cook et al. 2018; Williams et al. 2020), and drier, in the Lower and Upper Basins (NOAA 2022). These changes are reflected through diminished streamflows (Hamlet et al. 2005; McCabe et al. 2017; Xiao et al. 2018), reduced snowpack and increased winter melt (Mote et al. 2018; Musselman et al. 2021), and declines in aquifer recharge (Castle et al. 2014; Thomas et al. 2016; Niraula et al. 2017; Condon et al. 2020).

Over the period of record, both the Upper and Lower Basins have experienced large positive increases in average temperatures (Kuhn and Fleck 2019). An analysis of average annual temperatures from 1895 through 2020 for the Southwest (Arizona, New Mexico, Utah, and Colorado) illustrates over a 2°F increase in 30-year-average-annual temperature over time (Figure 3) (NOAA 2021d). Going forward, global climate models project warming to continue in the Colorado River Basin because of increases in concentrations of greenhouse gases in the atmosphere. Basin temperatures are projected to rise by 1.3°C–3.6°C (2.5–6.5°F) by mid-century relative to the late 20th-Century average, so

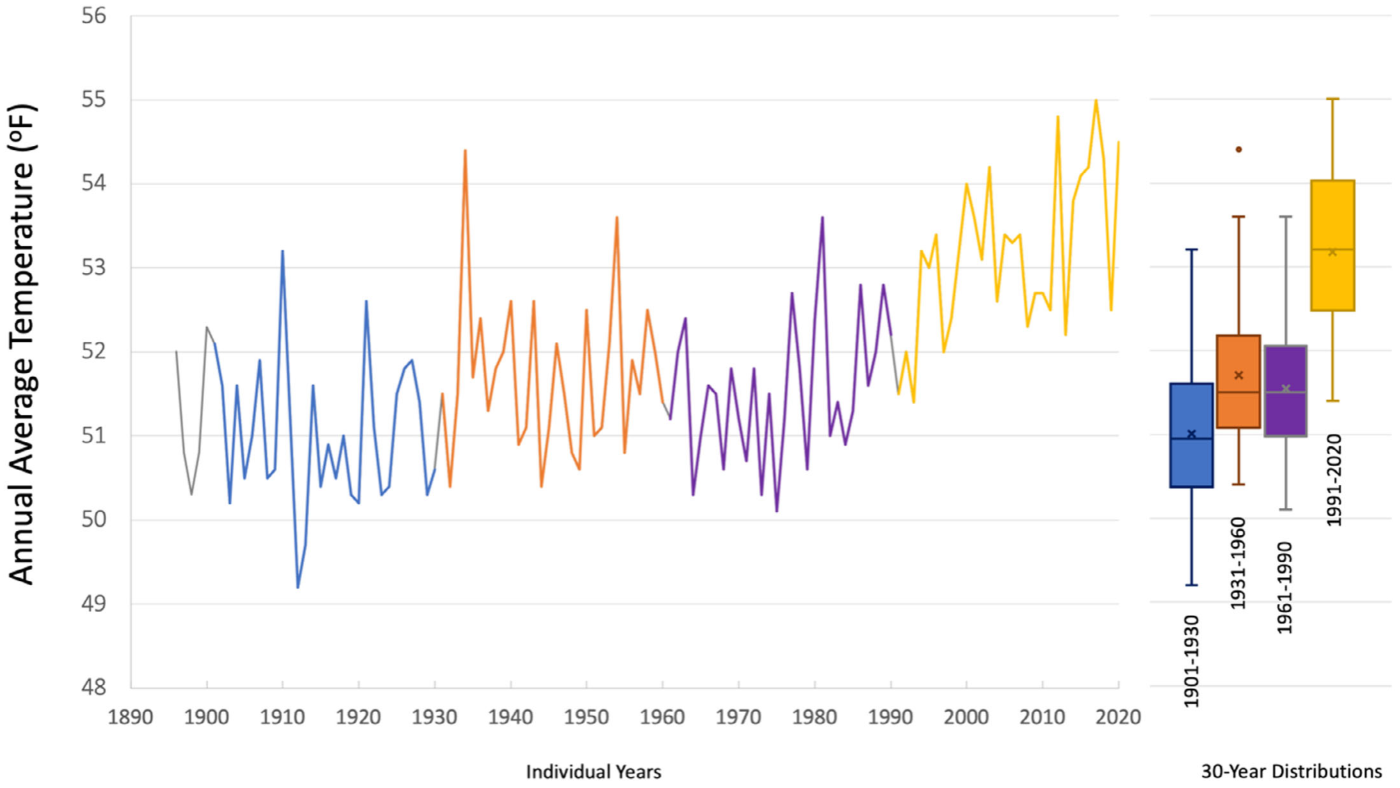

FIGURE 3. Average annual temperatures from 1895 through 2020 for the Southwest Climate Region (Arizona, New Mexico, Utah, and Colorado). The box-and-whisker plots on the right show 30-year distributions. Annual temperatures are greater than 54°F in only one year (1934) prior to 2000 and in seven years (2003, 2012, 2015, 2016, 2017, 2018, 2021) after 2000. Data are from the NOAA National Centers for Environmental Information, Climate at a Glance Regional Time Series dataset (NOAA 2021c).

future periods will be hotter than those in the past (Lukas and Payton 2020). While various techniques (e.g., statistical and dynamical downscaling, incorporating information from paleoclimate evaluations) have been used to estimate future streamflow (see Vano et al. 2014; chapter 11 of Lukas and Payton 2020 for an overview of different methodological and modeled differences), in general these studies collectively indicate even lower streamflows should be expected in future decades. At the same time, multiple studies have demonstrated that the effect of temperature has already become a significant driver of drought conditions in the Colorado River (Udall and Overpeck 2017; Milly and Dunne 2020; Woodhouse et al. 2021).

Streamflows have been reconstructed using tree-ring studies, for example, Woodhouse et al. 2006, over multiple centuries, revealing high decadal and long-term variability. However, even in this historical context, runoff in the last two decades has been remarkably low. Between 2000 and 2021, Reclamation's natural flow data show the water year average natural flow at Lees Ferry is 19% lower than in 1906–1999 (Bureau of Reclamation 2021a). Recent studies demonstrate how climate change is contributing to these streamflow declines through decreased snow accumulation, greater sublimation of snow, higher evapotranspiration rates, and lower soil moisture. In 2017, Udall and Overpeck (2017) found at least one-sixth to one-half of streamflow declines were due to warmer temperatures. Xiao et al. (2018) showed that slightly over half of the decreasing streamflow trends from 1906 to 2014 were linked to warmer temperatures.

Long-term changes in average precipitation and related groundwater recharge impacts are hard to detect in the Colorado River Basin, and even more difficult to model looking forward. There is evidence that winter precipitation in the southwestern U.S. is overall trending downwards (Walsh et al. 2014), though some models suggest that annual precipitation amounts could remain steady or increase in the Upper Basin (not necessarily in patterns translating to greater streamflow, soil moisture, and water availability) (Udall and Overpeck 2017). Recent modeling suggests that over the next 80 years, groundwater infiltration and aquifer recharge will be consistently lower than the previous 65 years (1951–2015), which would significantly impact Lower Basin water supplies (Tillman et al. 2020). In fact, one recent study suggests that groundwater base flow in the Upper Basin may decrease approximately 29% by the 2050s (Miller et al. 2021), which is consistent with other studies that show a tight coupling between base flow and surface water flows (Lukas and Harding 2020). Hoerling et al. (2019) used an event attribution framework to assess the observed flow decline over the last century and found that half of the 20% reduction in flow are a result of long-term climate change, with changes in both precipitation and temperature contributing.

WHERE *PRESS* MEETS PULSE AND SUBSEQUENT IMPACTS

The press and pulse of climate-related events can be interrelated and compounding. If variability remains the same and averages increase (e.g., temperatures), the number of times a value will exceed historical definitions of extremes (e.g., hot temperatures) will increase, so long as these values are additive. This appears to be the case with many extremes. In general, observations of extreme weather events (or *pulses*) show that the intensity, duration and/or frequency of acute events are increasing globally (IPCC 2021). In the Colorado River Basin, climate-change-related extreme events also appear to be on the rise (Box 1) and reflect the list of extreme events of concern developed in the Colorado River Conversations Project (Table 1).

BOX 1. RECENT EXTREME CLIMATE-RELATED EVENTS IN THE COLORADO RIVER BASIN

The past four water years (2018–2021) have seen rapidly changing water supply conditions in the Colorado River Basin. These changes reflect many of the climate-change-related events that were of concern to the Colorado River Conversations Project participants. These events include low run-off volumes in the Upper Colorado River Basin in 2020 and 2021 that were likely an outcome of the lowest recorded soil moisture values in Utah and western Colorado since 1948 (Western Water Assessment 2021). By early 2020, widespread drought conditions emerged across the Colorado River Basin and over the 20-month period from January 2020 through August 2021, the southwestern U.S. experienced the lowest total precipitation and the third-highest daily average temperatures since 1895, as well as the three largest wildfires in recorded Colorado history in 2020 (Carodine 2020). Wet and dry records have also been set. In 2020, Arizona's monsoon was characterized as a "nonsoon" for delivering near record low precipitation (ADWR 2020), while July 2021 was the wettest month on record in Tucson (ADWR 2021). Anticipating which extreme events may increase in frequency and intensity over time in the changing climate of the Colorado River Basin is difficult, yet important for sound planning and proactive risk management.

As recent years have illustrated, weather extremes are creating considerable concern for the Basin's water resources and the people and ecosystems that rely on them. Such events, either individually or in combination, can have a devastating impact on water supplies, delivery and storage infrastructure, watershed health and function, and allocation protocols under scarcity (Jacobs et al. 2020). Exploring how well extreme events in a changing climate are understood and monitored could support more proactive water management and planning. Anticipating future changes in extreme events provides a substantially different research challenge than understanding long-term climate trends (Knutson et al. 2017).

Another way the press and pulse of climate-related events are interrelated is in how antecedent conditions, which build over time (e.g., press), can affect the severity of an extreme event impact. For example, a short-term, intense drought on the Colorado River that is drier than the driest year in the instrumental record but lasts one year and starts when the reservoirs are full is a different experience than if the same event occurred after two decades of declining reservoirs. In contrast to the Colorado, which has multiple years of potential storage capacity in its reservoirs, cities in California that are largely dependent on smaller surface water reservoirs are less buffered from short-term drying conditions. Because of limited storage, these cities have been in a near-crisis mode during recent years of historically low snowpack.

Geophysical, ecological, and social factors influence the relationship between extremes in climate and level of impact, and extreme events are experienced differently depending on the level to which a community, watershed or utility is prepared for such events. As an illustration of the utility of adaptive measures in reducing impacts, the severe drought in California during the 2012–2016 period killed millions of trees, and affected ecosystems, power production, drinking water, and agriculture — causing billions of dollars in economic losses (Lund et al. 2018). Yet, despite the magnitude of these impacts, they would have been even worse without the preparation that did occur, as is evident by comparing the urban impacts from California's 1988–1992 drought to the 2012–2016 event. In the interim, investments in conservation and alternative water supplies were made, and in 2012–2016 state-mandated urban conservation measures (Lund et al. 2018), reduced the overall impacts to the economy. Each community has its own level of preparedness based on an array of physical factors including antecedent conditions, but also based on the degree to which extreme events have been anticipated and adaptive measures are in place.

The concept of thresholds is also important in understanding the impacts associated with pulse events. For example, when floods result in reservoirs having to exceed their maximum expected releases, the risk to life and property vastly increases. The “Front Range Flood” in Colorado in 2013 is an example where thresholds in expected rainfall and urban runoff were exceeded and led to damage in multiple communities (Batka 2014) after massive rainstorms (over 20 inches in parts of Boulder County).

EXTREME EVENTS OF CONCERN IN A CHANGING CLIMATE

We structure our discussion of what is known and how it is known for each of the seven climate-change-related extreme events of concern (Table 1) identified during the scenario planning workshops through addressing the following questions:

1. What are the underlying physical mechanisms of this climate-change-related extreme event of concern?
2. What impacts could be brought on by this change?
3. How is the research community studying this change and what can be said about the extent in which this change is linked to climate change drivers, both now and in the future?

Event of Concern 1: Intensifying Heat Waves

With overall increases in global temperatures, heat waves in the future will be hotter and record high temperatures are expected to progressively increase. Heat waves are a period of unusually hot weather that persists over two or more days with temperatures well above the range of historical averages for that time period for a defined region (Robinson 2001). The Colorado River Basin experienced heat wave conditions in the summer of 2020 and 2021 that exceeded multiple records for the consecutive number of days with temperatures surpassing historical conditions (NOAA 2020, 2021a).

Physical Mechanisms. Heat waves are generally associated with high-pressure systems that trap and force air downward. If the high-pressure system remains stationary for extended periods, rain is unlikely and near-ground temperatures increase (Cutting et al. 2011). With increases in global temperatures, heat waves will be hotter, and record high temperatures progressively increase. In the U.S., the observed record high temperatures each year now outnumber the record lows by 2:1 (Meehl et al. 2009).

Impacts. There is growing evidence that heat waves result in major, and sometimes deadly, health impacts for people, especially children and older adults, those with pre-existing conditions, and those without access to air conditioning. Heat waves can affect the structural integrity and/or functionality of some built infrastructure. Personnel who work outdoors are more impacted than others; heatstroke is a serious concern (WUCA et al. 2020). For many heat waves, there are also important feedbacks that amplify drought and heat, set the stage for wildfires (Trenberth 2011), and cause major plant and animal mortality events in ecosystems (Guo et al. 2018). From a water management perspective in the Colorado River Basin, heat waves drive up water demands for power production for air conditioning and for agricultural and urban irrigation.

Linkages to Climate Change. There is high confidence that global average temperatures will continue to increase as a direct consequence of human-caused changes to the atmosphere (Wuebbles et al. 2017). In addition, models project somewhat larger increases in extreme hot temperatures than in average temperatures (Fahey et al. 2017; Vose et al. 2017). While it is plausible that atmospheric circulation configurations will change patterns of heat waves and persistence of extremely hot conditions (IPCC 2021), circulation changes in climate models are not consistent. More specifically, in the Colorado River Basin, extreme heat events are likely to increase in frequency, magnitude, and intensity, but the range and peaks are uncertain, especially as circulation changes may enhance heat waves beyond what thermodynamics alone would suggest.

Event of Concern 2: Diminished Snowpack

In the Rocky Mountains, and Colorado River Basin specifically, over 70% of the water that feeds rivers and supplies water downstream is derived from snowmelt (Li et al. 2017). Snowpack provides important seasonal storage of water supplies by capturing cold-season precipitation and releasing it gradually throughout the warm season. The amount of water held in snow and timing and speed of melting is critical in determining overall water availability, and these characteristics of the snowpack are vulnerable in a changing climate (Musselman et al. 2021). Changes in snowpack in the Colorado River Basin have been affecting river runoff, with downstream impacts on the region's ecosystems, agriculture and urban centers, groundwater replenishment and reservoir storage (Barnett et al. 2005). Shifting the balance between rain and snow can also affect the likelihood and severity of floods, with impacts varying considerably depending on location (Harpold and Kohler 2017; Musselman et al. 2018; Yan et al. 2018).

Physical Mechanisms. Several mechanisms can alter the spatial extent and depth of the snowpack: the amount of precipitation in the cool season and the temperature when precipitation occurs (whether rain or snow). Temperatures once snow is on the ground also determine when and how fast the snowpack melts (Musselman et al. 2017) and whether it sublimates. Sublimation, or direct evaporation of snow (solid phase of water) to water vapor has been shown to reduce snowpack more quickly under warmer air temperatures (Harpold and Kohler 2017; Lukas and Harding 2020). In general, warmer temperatures result in more precipitation falling as rain vs. snow and snowpack melting earlier in the year. This leads to earlier peaks in river hydrographs, and lower runoff during the summer. Additionally, when warmer temperatures result in rain falling at higher elevations in the watershed (which previously would have been snowfall), there is a larger area contributing liquid water. This mechanism can result in flooding, which has been studied in greater depth in the Pacific Northwest (Tohver et al. 2014). Other environmental conditions such as dust-on-snow, rain-on-snow, anomalously warm temperatures, and increased wind can also drive a rapid decrease in snowpack which can result in both snow droughts and increasing floods (McCabe et al. 2007; Musselman et al. 2018; Painter et al. 2018; Reynolds et al. 2020).

Impacts. Reduced snowpack in spring can impact both human-built and natural systems, and has been tied to water scarcity, groundwater overdraft, tree mortality, insect outbreaks, and increased wildfire risk (Berghuijs et al. 2014; Diffenbaugh et al. 2015; Harpold and Molotch 2015; Barnhart et al. 2016; Harpold and Kohler 2017). Additionally, if precipitation falls as rain instead of snow, near-term inflow to reservoirs increases and water may need to be released early in the season to comply with flood management practices and reservoir operation rule curves.

Linkages to Climate Change. Climate change has already diminished, and will continue to diminish, the amount of water that is held in snowpack. Future climate change projections, as evaluated by Li et al. (2017), show the amount of runoff that comes from snowmelt (as opposed to rain) will decline by about one-third in the western U.S. by 2100. Snowpack monitoring stations throughout the West reveal that snowmelt is already occurring earlier in the year (Musselman et al. 2018, 2021; Lukas and Harding 2020), a trend that will be exacerbated by increasing temperatures in the future.

How changes in snowpack will affect flood peaks is less clear as those peaks are influenced by many factors in addition to precipitation and seasonality, including antecedent conditions and whether the watershed has a snowpack-dominated source region. Though much of the western U.S. is shifting toward rain-dominated flooding, especially near the coast, there has been little evidence correlating this trend with increased flood magnitude (Davenport et al. 2020).

Event of Concern 3: Long-Duration Drying (Sustained Declines in Runoff Efficiency)

Runoff efficiency is broadly expressed by how much of the water that falls in a watershed makes its way into the river, calculated as the ratio of streamflow to the precipitation over the watershed (McCabe and Wolock 2016). While precipitation is an important driver of interannual streamflow variability in most basins, including the Colorado River Basin (Woodhouse et al. 2016; McCabe et al. 2017), changes in precipitation do not directly translate into identical changes in streamflow, for example, a 10% change in precipitation is associated with a 20%–30% change in streamflow in the Upper Colorado River Basin because of the large role of evapotranspiration in the water cycle (Das et al. 2011; Vano et al. 2014; Hoerling et al. 2019). Runoff efficiency is a framework to examine how streamflow is being altered by temperature and related factors, separate from precipitation.

Physical Mechanisms. In the Colorado River Basin, upwards of 80% of water that falls as precipitation returns to the atmosphere through evapotranspiration (transpired by plants or evaporated from soil and water). As a result, a small change in evapotranspiration rates, which is driven by higher temperatures, can lead to significant reductions in streamflow and reduced soil moisture (Western Water Assessment 2021). This appears to be a major source of change in runoff in the Colorado River Basin, although other related factors such as soil moisture, snow sublimation, seasonality of precipitation, changes in vegetation, and land-use patterns are also important. For example, the speed of snowmelt might change how much water is infiltrated and evaporated (Vano et al. 2012; Barnhart et al. 2016).

Impacts. Runoff efficiency appears to be declining overall, with especially low runoff efficiency occurring in recent years, resulting in escalating concern about the reliability of Colorado River supplies. These changes can be thought of as a steady press on the system, although when reservoirs are low, this continual decline in runoff accumulates over a season or over years in large reservoirs, resulting in impacts that can cross management thresholds and lead to more acute impacts. Decreased runoff efficiency makes it harder for reservoirs to refill and could, when not compensated by precipitation, require mandatory cutbacks of Colorado River deliveries, with national and international ramifications (Udall and Overpeck 2017). For instance, in August 2021, the Bureau of Reclamation announced the first-ever shortage on the Lower Colorado River (Bureau of Reclamation 2021c) due to the combination of lower precipitation and runoff efficiencies. The intersection of rising water demands with water delivery curtailments presents water managers with difficult tradeoff decisions.

Linkages to Climate Change. There is more confidence associated with rising temperatures and the implications for runoff efficiency and resulting river flows than there is with the changes in the precipitation component of reduced runoff. Increased temperatures will reduce the volume of available moisture in both soils and in river flows (Gonzalez et al. 2018) and these changes are clearly linked to climate change. Over the years, studies have estimated what the range of reductions per degree of change in temperature might be using various models and methods (see overview in (Vano et al. 2012; Lukas and Harding 2020). Recently, Udall and Overpeck (2017) estimated how temperature increases alone can reduce the flows of the Colorado River, projecting reductions of up to 20% by midcentury. Woodhouse et al. (2021) assessed historical droughts in the context of a range of projected warming, and found, in alignment with earlier studies, that temperatures reduce runoff efficiency generally, and that these reductions become larger as temperature increases (specifically, they found average decreases in water year flow averaged 6% for the +1°C scenario and up to 31% for the +4°C scenario).

Event of Concern 4: Extensive Wildfire

Nearly all ecosystems in the Colorado River Basin have co-evolved with periodic, if not frequent, wildfire, and some major forest types are dependent on wildfire for perpetuation. However, society and infrastructure are poorly adapted to wildfire with dramatic consequences for human health, water supply, ecosystem health, and property. This is a growing challenge as wildfires are getting larger and more severe. Although there is some debate about whether the number of fires has been increasing in recent decades, there is no debate about the fact that the incidence of large fires has been increasing (Wehner et al. 2017).

Physical Mechanisms. Several complex climate-related mechanisms are responsible for the increased frequency and intensity of wildfires across different ecosystems in the Colorado River Basin. Direct drivers include increased temperatures, which increase drying and reduce snowpack, while lengthening the fire season and changes in precipitation and wind (Holden et al. 2018; Brey et al. 2021). Additional mechanisms at play are related to fuel load and conditions, historical prevalence of fire in the landscape, species composition and density, harvesting legacies, and fire exclusion. In grasslands, the spread of invasive grasses, driven by changes in the freeze-free season, frequency of wet winters, and the earlier onset of the fire season, are likely factors in generating a feedback loop of invasive species and increased wildfires (Abatzoglou and Kolden 2011). In western forests, long-standing ecological interactions between trees and eruptive bark beetles are being modified by climate change, and models suggest a high likelihood of continued high tree mortality and associated wildfire risk (Jenkins et al. 2014). On a broad scale, recent work connects increases in wildfires (area burned) to changes in Hadley circulation (large global-scale tropical atmospheric circulation) due to greenhouse-gas warming, which results in increased drying (Zhang et al. 2020). Physical and ecological factors that can indirectly alter wildfire risk vary across different regions of the Colorado River Basin, but increased temperatures are a direct driver that points towards increased risk over time.

Range of Impacts. Wildfires may permanently alter the landscape when ecosystems cannot fully recover. They can also have synergistic impacts with other categories of events (e.g., long-duration drying, precipitation intensity that leads to flooding). An examination of floods in 2012 and 2013 following a wildfire in Colorado illustrates how fires, and subsequent increases in the rate of runoff due to loss of vegetation, can greatly increase peak flows. One flood was among the largest rainfall-runoff floods per unit area recorded in the U.S. (Brogan et al. 2017). Furthermore, these events can trigger debris flows that move sediment, boulders, and other debris at incredible speeds, causing substantial destruction, including rapid sedimentation of reservoirs (Kean et al. 2019). Sedimentation in reservoirs following major wildfires has been a problem for water utilities in most western states. Severe air quality problems (with major impacts on people with asthma or other forms of lung disease) are associated with major fires both locally and across the globe (Reisen et al. 2015).

Linkages to Climate Change. The 2017 4th National Climate Assessment (Volume 1) indicates with high confidence that the incidence of large forest fires in the western U.S. and Alaska has increased since the early 1980s and is projected, with medium confidence, "to further increase in those regions as the climate changes, with profound change to regional ecosystems" (Wehner et al. 2017). Because of the many factors associated with wildfire frequency and intensity described above, it is difficult to project climate-change-related wildfire changes, yet estimates show that about half of the increase in western U.S. burned area from 1984 to 2013 is due to climate change (Abatzoglou and Williams 2016; NASEM 2016).

Event of Concern 5: Short-Duration Intense Wet and Dry System Shocks

During the scenario planning workshops, participants raised the concern that there would be an increase in the number of short-duration, intense system shocks in the Colorado River Basin. These were defined as either extremely wet years (e.g., brought on by intense precipitation events, longer-duration events, or higher frequency of storms) or, alternatively, a devastating dry year.

Physical Mechanisms. Several related mechanisms can lead to wetter or drier system shocks. All precipitation events, including those associated with winter and springtime mid-latitude cyclones as well as those associated with the summer monsoon and remnants from tropical cyclones, are now developing in warmer and more humid environments. Consequently, storms produce more heavy precipitation, even as total annual precipitation may decrease (Trenberth 2011). The same warming that makes precipitation more intense may also lead to more drying. We highlight two mechanisms for enhancing short-duration intense system shocks:

Precipitation Intensity Increases. Heavy precipitation intensity is likely to scale with the increase in moisture in the atmosphere because warmer air can hold more water, (typically this relationship, known as the Clausius-Clapeyron or C-C relationship, is about a 7% increase per 1°C (1.8°F) increase in temperature (Callen 1985; Pendergrass and Hartmann 2014; Fischer and Knutti 2016). Because oceans serve as the primary water vapor source for most extreme precipitation events, increases in ocean surface temperatures also drive this near-global increase (Jewett and Romanou 2017).

One example of climate-related swings in precipitation is the North American Monsoon, which provides a large portion of annual precipitation to the southern part of the Colorado River Basin during the warm season. There is evidence that the intensity of sub-daily monsoon precipitation has increased in the Southwest U.S. while at the same time monsoon events may become less frequent due to synoptic pattern changes (Demaria et al. 2019). This dichotomy is discussed more fully in *Event of Concern 7: Dramatic Decline in Monsoons* below.

For hurricanes and tropical storms — the remnants of which have caused significant flooding in the Colorado River Basin in recent decades — rainfall is projected to increase (Kossin et al. 2017). These storms only occasionally directly impact the Colorado River Basin itself (particularly Arizona, in contrast to coastal cities, for example), but moisture from these storms does travel inland and can bring heavy rains and cause significant flooding, as experienced in southern Arizona in 1983 and 1993 (Corbosiero et al. 2009).

Another example is strong West Coast storms, which carry more water as global temperature increases. In the Colorado River Basin, plumes of low-level moisture originate in the tropical Pacific and make landfall on the West Coast (Zhu and Newell 1994). These events are one of the primary sources of extreme wintertime precipitation in both the Lower and Upper Colorado River Basins. Atmospheric Rivers (ARs) or "pineapple express" type storms originate over subtropical waters. With time, as the ocean warms and moisture increases, ARs may increase in intensity, bringing more precipitation to California and the interior of western North America (Rutz et al. 2015; Swales et al. 2016). AR tracks may also shift latitude, due to the changes in large-scale atmospheric circulation including the jet stream (Simpson et al. 2016). Research into ARs shows that they are dependent on both weather and climate-scale processes, that increased atmospheric moisture may amplify precipitation, and that the pathway of the jetstream and location of landfall play an important and complex role in how and where storms travel (Alexander et al. 2015; Swales et al. 2016; Payne et al. 2020; Rhoades et al. 2020). Projections of the future role of AR storms in the Colorado River Basin and western U.S. are complex and remain uncertain (Kossin et al. 2017).

Rapid Onset Drying (Flash Droughts). Defined as a drought that has a sudden onset and rapid intensification, flash droughts unfold over less than a month and vary considerably in their geographic extent, from a few kilometers to an entire region (Otkin et al. 2018; Christian et al. 2019). They typically coincide with large-scale atmospheric circulation which leads to precipitation deficit, high temperatures, clear skies, and/or wind speeds that lead to rapid drying (Ford and Labosier 2017; Pendergrass et al. 2020). Flash droughts can produce acute impacts, and they have been a recent research focus. In the Colorado River Basin, the primary mechanism that would be expected to drive flash drought is precipitation deficit, since the Basin is mostly arid (with evapotranspiration in a moisture-limited state). This differs from regions of the eastern U.S., where flash droughts gained a lot of recent attention, in that the typical high soil moisture state in that region (where evapotranspiration is energy-limited instead of moisture-limited) can set the stage for rapid increases in evapotranspiration when the regime changes from energy- to moisture-limited. Recent research emphasizes that precipitation deficits are key drivers of flash drought in many regions, though (Hoffmann et al. 2021), and this would be expected to apply to the Colorado River Basin as well, but the magnitude of its impact is not yet clear. Another topic of recent research is a phenomenon related to, but distinct from, flash drought, which can also result in rapid on-set drying, is rapid-intensification snow drought — where snowpack rapidly declines due to dust-on-snow, rain-on-snow, or warm temperatures (Pendergrass et al. 2020).

Impacts. In general, the mechanisms that underlie these short-duration intense system shocks suggest that as warming increases, short-duration intense wet system shocks will also increase along with possible impacts. Less is understood about flash droughts. Both are described below.

Precipitation Intensity Increases. Increasing precipitation intensity has implications for overbank flows in rivers and for dam safety, as dams are generally designed based on historical hydrology, not necessarily considering projections of future hydrologic conditions. Flooding can lead to a broad array of risks, including direct risks to human life, destruction of residential, commercial, and industrial properties, loss of agricultural lands and associated activities, and interruption of communications, energy, transportation, and water treatment systems.

Extreme precipitation events generated by ARs have had dramatic economic impacts on western states, including those in the Colorado River Basin. Research on insured flood losses estimated areas in the Lower Basin where losses due to ARs were between 26% and 84% from 1978 to 2017 (Corringham et al. 2019). Though AR losses in the Colorado River Basin were smaller compared to coastal areas (where proportions are upwards of 99%), contributions were still significant (Corringham et al. 2019). The likelihood that ARs and associated storms will become more intense (wetter, longer, and wider) (Gershunov et al. 2019) paints a worrying picture of increasingly magnified impacts.

Higher precipitation intensity can also be beneficial. For example, in the Southwest, where groundwater recharge is dependent on large runoff events, the rate, and volume of natural recharge and potential stormwater capture and recharge could increase (Thomas et al. 2016). ARs on the west coast have also been shown to be drought busters in California, Oregon, and Washington (Dettinger 2013) and a recent study shows that about a third of the annual peak snow water in the Upper Colorado River basin comes from ARs (Xiao and Lettenmaier 2021).

Rapid Onset Drying (Flash Droughts). Flash droughts can drawdown water supplies, erasing gains from higher precipitation, or put additional pressure on critically low water supplies. Other impacts might include disruptions to recreation and increased wildfire risk (as occurred in the 2017 Northern Great Plains flash drought (Hoell et al. 2020).

Linkages to Climate Change. Precipitation Intensity Increases. Well-understood mechanisms such as the relationship between ability of the air to hold moisture with increasing temperature underpin much of what we understand about the atmosphere and increase confidence that changes in the frequency and intensity of heavy precipitation will likely occur in the future. The Fourth National Climate Assessment indicates medium confidence in increasing frequency and severity of landfalling ARs, though there is less confidence ("low") in increasing winter storm frequency and intensity (partially because of the spatial heterogeneity in patterns) (Kossin et al. 2017).

It is less straightforward to assess where these changes will have the most impact, how big that impact will be, and at what point in the future thresholds of concern will be breached. To get at these questions, changes can be evaluated using multiple approaches including both statistical and dynamical downscaled global and regional climate models (Gutmann et al. 2016; Shamir et al. 2019), attribution studies, and new machine learning techniques (Sippel et al. 2019; Heinze-Deml et al. 2020). However, as noted above, it is far more difficult to model changes in future extremes/pulses than it is to model and project trends in average temperature or precipitation.

While increased precipitation intensity has translated into flooding historically, trends in the western U.S. are mixed with regard to increasing flooding magnitude, in part because: (1) as described above, there are different scales and types of flooding (Kossin et al. 2017); (2) flooding is the result of a complex mix of processes at multiple scales (Easterling et al. 2017; Davenport et al. 2020), (3) the influence of antecedent conditions as well as altitude, latitude, geologic factors; and (4) the presence of other prior events (such as droughts and wildfires). Because of overall increases in intensity of rainfall, local or "flash" flooding is likely to increase in the future, but broader scale events are influenced by many factors in different parts of the Colorado River Basin, and therefore projections of changes in flooding are more difficult at larger scales (Kossin et al. 2017).

Rapid Onset Drying (Flash Droughts). It remains an open question whether short dry-system shocks will increase. Potential evapotranspiration increases with temperature (and the moisture-holding capacity of air), and precipitation variability is projected to increase with warming (Pendergrass et al. 2017), both of which provide favorable conditions for rapid onset drying. However, how plants respond to increasing carbon dioxide might mitigate this response (Swann et al. 2016) but to what degree, especially in the Colorado River Basin, remains an area of active research.

Event of Concern 6: Amplified Wet and Dry Swings

Concern about more frequent and/or intense wet and dry periods is amplified further if swings between the two types of extremes happen in rapid succession, recently referred to as "climate whiplash" (Swain et al. 2018). At the scenario planning workshops, this concern was described as multiyear dry spells broken by a couple of very wet years, and the prevalent concern was whether, in a warmer climate, these swings would become more frequent or rapid.

Droughts and floods are usually studied independently. However, spurred by recent events like California's floods in 2017 — a winter pluvial (a pluvial typically refers to a period of time marked by an intense increase in rainfall) that was preceded by a 6-year drought — more efforts are underway to systematically evaluate the "drought-pluvial see-saw" (He and Sheffield 2020).

Physical Mechanisms. In a warmer climate, more intense wet extremes (e.g., driven by the C-C relationship, mentioned above) and a higher frequency of dry extremes (e.g., longer dry periods driven by warmer temperatures and increasing evaporative demand) are more likely to occur. From the perspective of atmospheric dynamics, this is a combination of increased moisture and weakening of overall circulation that must accompany a change in increased moisture for the water cycle to continue to satisfy the global energy balance. Consequently, more intense precipitation and weakened circulation suggests an expected increase in the drought-pluvial see-saw. These relationships have only just begun to be explored (Pendergrass and Gerber 2016; Konapala et al. 2016; Pendergrass et al. 2017; Swain et al. 2018; He and Sheffield 2020; Schwarzwald et al,. 2021). To date, this is being studied in a variety of distinct ways, for example: event coincident analysis (He and Sheffield 2020); principal component analysis (Wahl et al. 2020); climate model simulations (Swain et al. 2018); and evaluations of historical measures of drought end (Dettinger 2013).

Impacts. The intensification of wet and dry swings has the potential to upset an already precarious balance between reservoir water storage for droughts and reservoirs as flood control management mechanisms, especially when reservoir storage is limited (Swain et al. 2018; Vano et al. 2019). This impacts water resource management and emergency management, as well as a region's economy and ecosystems (Wahl et al. 2020). There are also compounding effects; for example, dry soils are less porous which can increase flooding when heavy rains return, and droughts followed by floods can enhance sedimentation, and as seen in California, a rapid shift could create a situation where extensive fuel builds up and is quickly dried out and subject to fire (Wahl et al. 2020).

Linkages to Climate Change. Investigations of these swings is an emerging field of study. Worldwide, one study suggests that ~11% of global droughts are followed by extreme rainfall (pluvial) events, although over small regions, and that such swings are occurring more frequently, suggesting greater variability driven by climate change (He and Sheffield 2020). More regionally, using future projections of a large ensemble of the Community Earth System Model, Swain et al. (2018) found a 25% to 100% increase in extreme dry-to-wet precipitation events in California, meaning California's already variable year-to-year climate is likely to become more volatile. In California, rapid shifts between wet and dry conditions have occurred historically, and while it is challenging to project the frequency of future shifts, there is evidence that intensified changes in the hydrologic cycle are likely (Swain et al. 2018; Wahl et al. 2020). To date, we are unaware of studies that evaluate these changes, or their impacts, in the Colorado River Basin specifically.

Event of Concern 7: Decline in Monsoons

The North American Monsoon is a core feature in the seasonal precipitation patterns over the Lower Basin, and the southerly portion of the Upper Basin, with summer precipitation peaking between July and September, and accounting for over 70% of the annual rainfall for portions of the Basin (Cook and Seager 2013). Modeling suggests that strong changes in seasonality (monsoon peaks occurring later in the year), could change the timing of extreme events (Cook and Seager 2013). Additionally, monsoons are predicted to be generally drier (up to 40% in areas of the Colorado River Basin) in July and August (Pascale et al. 2017). The 2020 monsoon season was extremely dry and was labeled a “nonsoon,” with July, August, and September seeing record-driest and record-hottest conditions for large portions of the Basin (CLIMAS 2020; Gardner 2020). Moving to the other end of the spectrum, the 2021 monsoon season was so strong that July was the wettest month on record in Tucson and among the wettest months on record in Phoenix (NOAA 2021b). Recent observational and modeling work suggests that portions of the Basin may experience a smaller number of more extreme monsoon precipitation events (subdaily rainfall intensities), particularly in southwestern and central Arizona (Luong et al. 2017; Demaria et al. 2019).

Physical Mechanisms. Climate modeling points to barriers that inhibit convection and cloud formation, resulting in reductions in early monsoon season precipitation. There is strong evidence that these barriers are generated by reduced evapotranspiration (due to lack of moisture at the land surface) and increased atmospheric stability caused by higher temperatures associated with greenhouse gas emissions (Cook and Seager 2013). Research shows that monsoons are becoming more “thermodynamically dominated,” meaning increased moisture in the atmosphere will create more extreme precipitation events (Pascale et al. 2019), although events may occur less frequently.

Impacts. Changes in monsoon seasonality can have wide-ranging impacts on fire and disturbance regimes (Ray et al. 2007; Arizpe et al. 2020), plant communities (Ray et al. 2007), and ranching and cattle grazing (Ray et al. 2007). The delayed or reduced monsoon precipitation patterns may also magnify the impacts of other events such as droughts or wildfire. Work exploring the contribution of the North American Monsoon to streamflows in a headwater basin, East River, Colorado, showed that monsoon rains contributed significantly (10%) to annual flow, but highlighted that summer rains produce more streamflow when there is more snow accumulation (and higher soil moisture conditions), so this impact may diminish in a warmer future (Carroll et al. 2020).

Linkages to Climate Change. A recent review by Wang et al. (2021) of the impacts of climate change on monsoons highlights the patterns described above from multiple studies (change in seasonality, and higher likelihood of extreme rainfall events) but there is low confidence in the results because of local factors, for example, vegetation dynamics, land cover, soil moisture, and remote biases, connections with sea surface temperatures, in the models. However, Wang et al. 2021 attribute high confidence in an overall future decrease in rainfall from the North American Monsoon. A recent hydroclimate analysis of the Lower Santa Cruz River in Arizona used future projections to evaluate monsoon changes and found that the worst-case scenario considered reflected a more variable future with a greater range in season lengths from year to year with “precipitation events becoming more intermittent, but more extreme” (Bureau of Reclamation 2021b), changes already documented in the historical record (Luong et al. 2017; Demaria et al. 2019).

Additional Climate-Related Events

This paper highlights climate-related extremes identified by water managers and their implications for the Colorado River Basin. While the seven categories of climate-related extremes were identified as especially critical, it is important to recognize that for water managers, these may interact with other disruptive social or economic challenges, as well as other climate-change-driven changes which may impact water management indirectly. For example, while sea level rise impacts do not occur within the hydrologic boundaries of the Basin, responses to coastal disturbances can impact the Basin in multiple ways, particularly through supply chain disruption (Fleming et al. 2018). Disruption of the flow of energy, goods and services along the coasts have ripple effects elsewhere. It is nearly certain that sea level will continue to increase over the coming decades. The 2019 IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, indicates that global mean sea level has been rising since 1900, but that the rate of increase has recently accelerated (IPCC 2019).

CONCLUSIONS

We present an overview of the current state of knowledge and research on trends in seven categories of climate-related extremes that had been prioritized as concerns by Basin stakeholders and water managers. Because extreme weather events across the U.S. are related to billions of dollars in economic costs every year (without accounting for human suffering and environmental impacts), it is imperative that water and resource managers are aware of the latest scientific information related to trends in the intensity, duration, and frequency of these events. The science of event attribution, which connects the causes of extreme events to drivers (including climate change) is maturing and has already led to significant progress in our understanding of what to expect in the future. In the near term, the information contained in this paper is intended to provide an accessible and readable summary of both the pulse of extreme weather events and press of progressive average changes in climate, and a context to support planning for a range of future conditions that include greater and more frequent extreme events. Additionally, while the extremes described in the sections above are individually concerning, it is important to recognize the extremes and their impacts may compound.

The press of increasing temperatures suggests a gradual change, which could be relatively easy to adapt to (e.g., adjusting to diminishing snowpack and declining runoff efficiency overtime). However, these same changes also eventually result in years that, when combined with natural variability, cross important thresholds that can decrease surface reservoir and groundwater levels to the point where there are significant impacts (Castle et al. 2014; Tillman et al. 2020). Meanwhile, the character of natural variability itself is changing.

This paper is intended to provide Basin stakeholders and water managers with an understanding of what to expect in terms of *trends in extreme events* (as opposed to general projections of climate change) in the future, based on best available science today. The discussion of each of the extreme events of concern includes a discussion of both climate mechanisms and expected impacts. We also share this information (e.g., Table 1) as part of the Colorado River Science Wiki (www.coloradoriverscience.org) so it can be updated as the science evolves.

Climate change shifts the odds of extreme events by applying a steady press on the system, but it also is changing some of the mechanisms that drive variability and day-to-day weather patterns. This combination is leading to more extreme conditions (pulses) with the potential for more significant water management impacts. Thinking about future conditions in this way is likely to be most helpful to water managers and planners by providing context for building "what if" scenarios and understandings of where the greatest future climate-related risks may be. We also hope this work elevates the questions the research community could explore to further understand extreme climate-related events most concerning to Colorado River Basin decision makers.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available at https://doi.org/10.5281/zenodo.6413075. These data were derived from the following resources available in the public domain: NOAA National Centers for Environmental Information, Climate at a Glance Regional Time Series.

ACKNOWLEDGMENTS

We thank the Walton Family Foundation for providing support for this effort. We are particularly indebted to Ken Kunkel, Jeff Lukas, Mike Dettinger, Mike Crimmins, and Jason Giovannettone for sharing their insights on these issues and to our reviewers for pointing out important issues to be addressed. J.A.V. time was supported by NOAA Climate Program Office, Sectoral Application Research Program, NA18OAR4310259. A.G.P. was supported by the U.S. Department of Energy, Office of Science, Office of Biological & Environmental Research (BER), Regional and Global Model Analysis (RGMA) component of the Earth and Environmental System Modeling Program under Award Number DE-SC0022070 and National Science Foundation (NSF) IA 1947282 and by the National Center for Atmospheric Research (NCAR), which is a major facility sponsored by the NSF under Cooperative Agreement No. 1852977.

AUTHOR CONTRIBUTIONS

Amy L. McCoy: Conceptualization; formal analysis; methodology; project administration; writing – original draft. Katharine L. Jacobs: Conceptualization; formal analysis; methodology; project administration; writing – original draft. Julie A. Vano: Conceptualization; formal analysis; writing – original draft. J. Keaton Wilson: Data curation; visualization; writing – original draft. Season Martin: Conceptualization; writing – original draft. Robert Cifelli: Writing – original draft; writing – review and editing. Angeline G. Pendergrass: Writing – original draft; writing – review and editing.

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