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NOAA DROUGHT TASK FORCE REPORT ON THE 2020–2021 SOUTHWESTERN U.S. DROUGHT

ACKNOWLEDGMENTS

NOAA DROUGHT TASK FORCE IV LEADS

Justin S. Mankin*
Assistant Professor, Department of Geography, Dartmouth College

Isla Simpson*
Scientist 2, Climate and Global Dynamics Laboratory, National Center for Atmospheric Research

Andrew Hoell*
Meteorologist, NOAA/Physical Sciences Laboratory

Rong Fu
Professor, Department of Atmospheric & Oceanic Sciences, UCLA

NOAA MAPP

Daniel Barrie
Program Manager, NOAA Climate Program Office

Courtney Byrd
Program Specialist, NOAA Climate Program Office

Wenfei Ni
Program Specialist, NOAA Climate Program Office

NOAA NIDIS

Joel Lisonbee
Regional Drought Information Coordinator, NOAA/NIDIS, CIRES

Amanda Sheffield
Regional Drought Information Coordinator, NOAA/NIDIS, CIRES

Molly Woloszyn
Regional Drought Information Coordinator, NOAA/NIDIS, CIRES

Adam Lang
Communications Coordinator, NOAA/NIDIS, CIRES

KEY CONTRIBUTORS

H. Annamalai
Research Professor of Oceanography, School of Ocean and Earth Science and Technology, University of Hawaii

Arun Kumar
Chief, Development Branch, Climate Prediction Center, NCEP

Richard Seager
Palisades Geophysical Institute/Lamont Research Professor, Lamont Doherty Earth Observatory of Columbia University

Martin Hoerling
Meteorologist, NOAA/Physical Sciences Laboratory

Mingyue Chen
Meteorologist, Climate Prediction Center, NCEP

Cenlin He
Project Scientist, Research Application Lab (RAL), National Center for Atmospheric Research (NCAR)

Paul Dirmeyer
Professor, Department of Atmospheric, Oceanic and Earth Sciences , George Mason University

Jason E. Smerdon
Lamont Research Professor, Lamont Doherty Earth Observatory of Columbia University

Flavio Lehner
Assistant Professor, Department of Earth and Atmospheric Science, Cornell University

Mathew Barlow
Professor, Department of Environmental, Earth, and Atmospheric Sciences, UMASS-Lowell

Christopher B. Skinner
Assistant Professor, Department of Environmental, Earth, and Atmospheric Sciences, UMASS-Lowell

Harmanveer Singh
Research Assistant, Department of Geography, Dartmouth College

Ben Livneh
Assistant Professor, Department of Civil, Environmental, and Architectural Engineering, University of Colorado, Boulder, CIRES

DESIGN AND LAYOUT

Fiona Martin
Visual Science Communicator, Visualizing Science

*These authors contributed equally.

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On the Cover: **Aerial view of Lake Mead and Hoover Dam.**
Credit: weltreisendertj

ABSTRACT

Using the state-of-science and the collective expertise of the NOAA Drought Task Force, this report addresses three questions about the period of below normal rain, snow, runoff, and soil moisture, known as the 2020–21 U.S. Southwest drought: (1) How bad is it? (2) What caused it? And (3) When will it end?

▲ These six southwest U.S. states experienced exceptional drought since January 2020. Credit: NOAA, Fiona Martin

For the six states of the U.S. Southwest (Arizona, California, Colorado, Nevada, New Mexico, and Utah)[i], January 2020 through August 2021 have been exceptional in the instrumental climate record since 1895, with the lowest total precipitation and the third-highest daily average temperatures recorded, which together imposed an unyielding, unprecedented, and costly drought. This exceptional drought punctuates a two-decade period of persistently warm and dry conditions throughout the region. The low precipitation across U.S. states and seasons appears to have been largely due to natural, but unfavorable, variations in the atmosphere and ocean. As such, predicting when total precipitation will return to pre-drought levels is a challenge. While summer 2021 brought welcome monsoon rains to parts of the Southwest, several seasons, or years, of above-average rain and high elevation snow are needed to replenish rivers, soils, and reservoirs across the region. This suggests that for much of the U.S. Southwest, the present drought will last at least into 2022, potentially longer. At the same time, exceptionally warm temperatures from human-caused warming have melted snowpack and drawn water from the land surface more rapidly than in previous years. The warm temperatures that helped to make this drought so intense and widespread will continue (and increase) until stringent climate mitigation is pursued and regional warming trends are reversed. As such, continued warming of the U.S. Southwest due to greenhouse gas emissions will make even randomly occurring seasons of average- to below-average precipitation a potential drought trigger, and intensify droughts beyond what would be expected from rainfall or snowpack deficits alone. Human-caused increases in drought risk will continue to impose enormous costs upon the livelihoods and well-being of the ~60+ million people living in the six states of the U.S. Southwest, as well as the broader communities dependent on the goods and services they produce. ◆

For much of the U.S. Southwest, the present drought will last at least into 2022, potentially longer.

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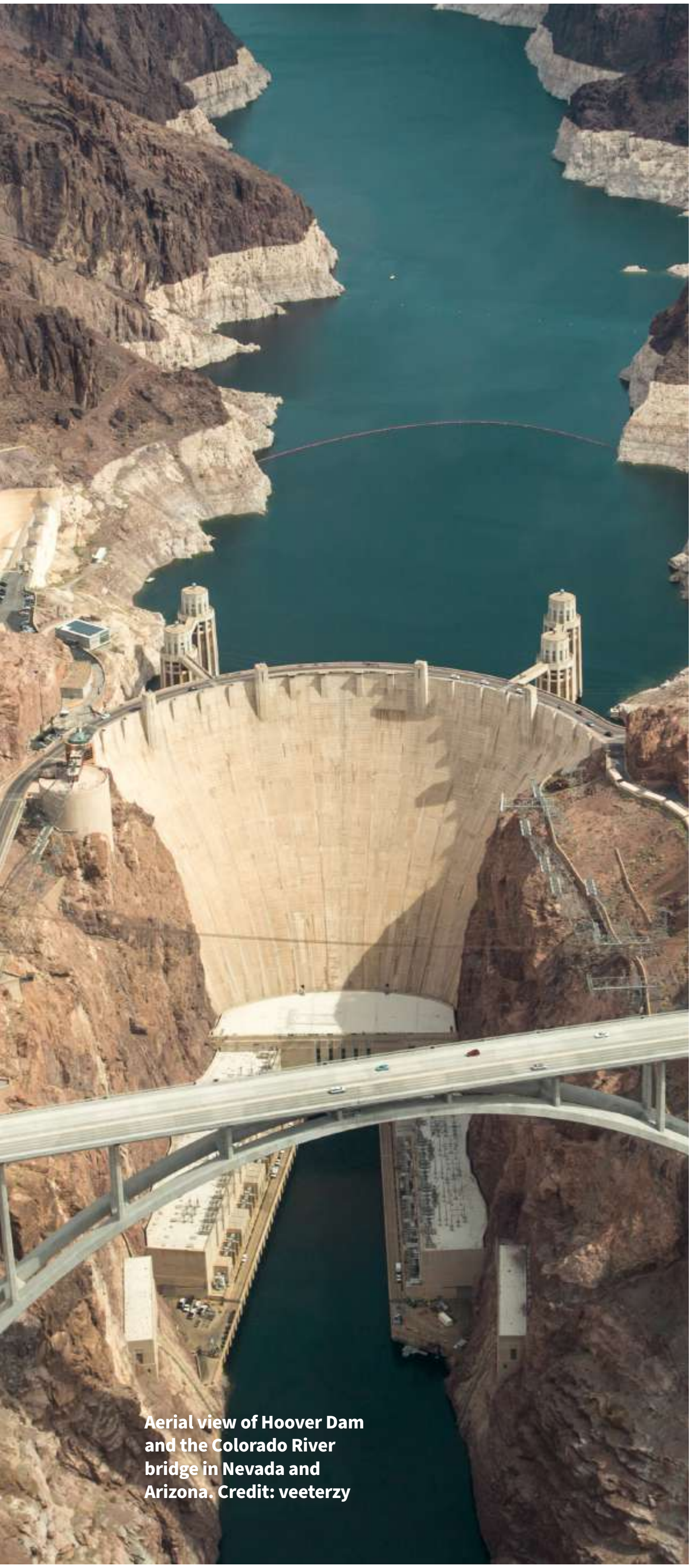
[i] The 2020–21 drought covers much of Western North America, including parts of Canada and Mexico. This report centers on the U.S. Southwest as the 2020–21 drought has been most persistent and severe there.



Aerial view of Hoover Dam and the Colorado River bridge in Nevada and Arizona. Credit: veeterzy

HOW BAD IS IT?

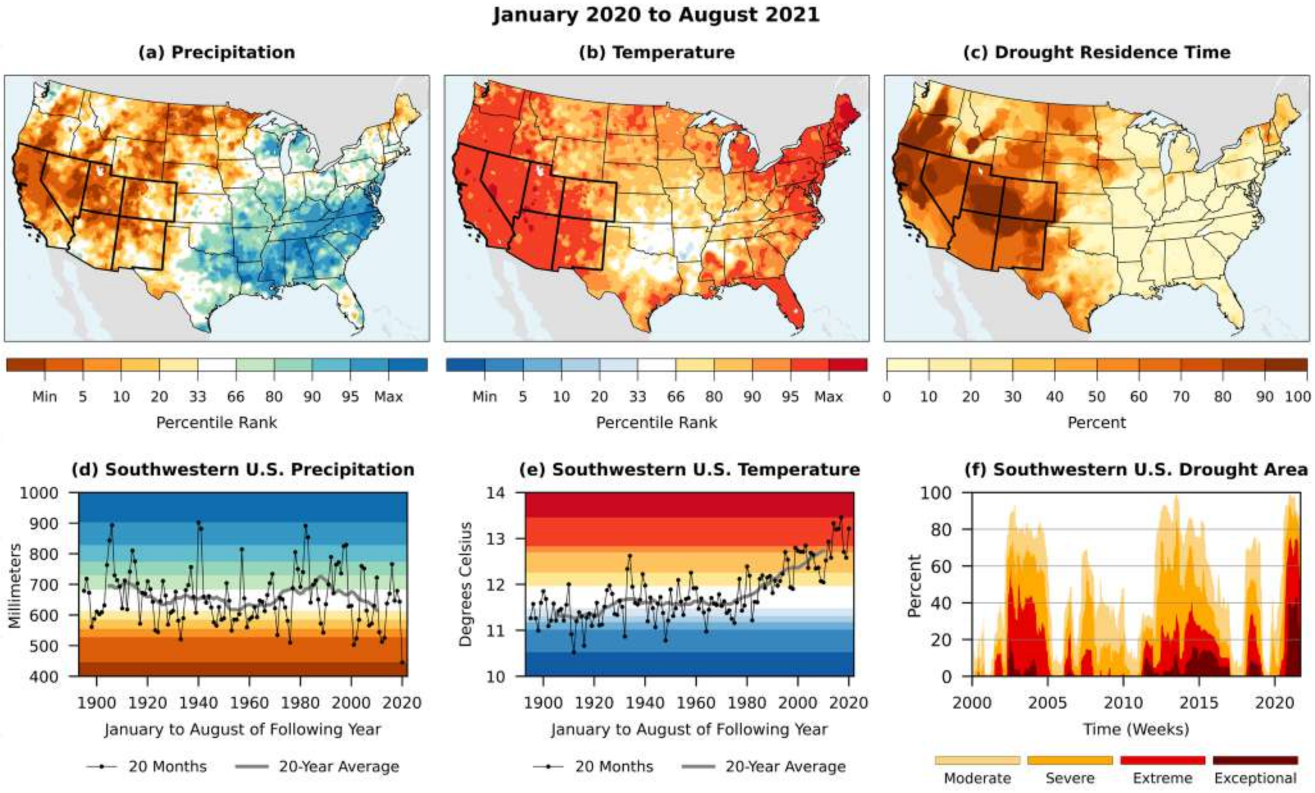
The 2020–21 drought plaguing the U.S. Southwest (*see Box 1*), which emerged first in the Four Corners region in winter 2020, is exceptional in the instrumental and paleoclimate records, imposing massive water shortages and socioeconomic costs, triggering emergency declarations, and has even led to the first ever water delivery shortfall among the states sharing the Colorado River[1], the most important river basin in the region (*Table 1*)[ii].

[ii] A Colorado River water delivery shortfall presents a unprecedented political, social, economic, and legal challenge for the tens of millions of people directly reliant on water from the Colorado River, as they negotiate whose water rights are yielded, which crops are fallowed, which hydropower plants curtail electricity production for which communities, and which basins face mandatory water use restrictions.

BOX 1

What is Drought?

Drought occurs when a water deficit at the land surface ensures that water demands cannot be met. Drought is typically defined based on where water supply and its demand are being considered. For example, most droughts begin due to a period of low precipitation, creating what is known as a *meteorological drought*. At some point, the low precipitation can dry soils, leading to an *agricultural drought*. Finally, if river and stream flow is impacted, the drought can become a *hydrologic drought*. It is important to note three things: first, not all meteorological droughts become agricultural or hydrologic droughts. Second, agricultural or hydrologic droughts can occur without a meteorological drought, such as through poor human management. Finally, the major socioeconomic impacts of droughts tend to be associated with hydrologic and agricultural droughts, as they more directly affect human-managed systems, like hydropower and agriculture. The 2020–21 Southwestern U.S. drought examined here began in the winter of 2019–2020 in the Four Corners region as a meteorological drought and by summer of 2020, became both an agricultural and hydrologic drought.



▲ **Figure 1:** **The January 2020–August 2021 (*a*) precipitation rank and (*b*) temperature rank relative to equivalent January to August 20-month periods since 1895 from NOAA's Monthly U.S. Climate Gridded Dataset (NClimGrid)[3]. The January 2020–August 2021 drought residence time (*c*), calculated as the percent of the January 2020–August 2021 period spent in a drought class of "moderate drought" (i.e., "D1") or more based on the U.S. Drought Monitor (USDM)[4]. For the 20-month period of January to August of the following year, time series of (*d*) total precipitation and (*e*) daily average temperature over California, Nevada, Utah, Colorado, Arizona, and New Mexico. Also shown in (*d*) and (*e*) are the 20-year averages of those time series. Colors in (*d*) and (*e*) represent the percentile ranks from (*a*) and (*b*). (*f*) time series of the total area in drought classes ("moderate", "severe", "extreme", or "exceptional", D1–D4) expressed as a percent of the total six-state area based on the USDM.**

Successive dry and warm winter seasons in 2020 and 2021, along with a dry 2020 summer monsoon, have led precipitation totals over the 20 months between January 2020 and August 2021 to be the lowest on record since at least 1895 over the U.S. Southwest (*Fig. 1a, d*). Daily average temperatures across the six states were the third-highest on record over that same period (*Fig. 1b, e*). Both of these 20-month anomalies have occurred in the context of a longer term (presumed natural) period of declining precipitation (*Fig. 1d*, "20-Year Average") and a (human-caused) warming trend (*Fig. 1e*, "20-Year Average"). Together, the exceptionally low precipitation and warm temperatures[2] reduced mountain snowpack and increased evaporation of soil moisture, leading to persistent and widespread drought over the last 20 months, as classified by the United States Drought Monitor, (USDM, *Fig. 1c, f*). The spatial extent of the 2020–21 Southwestern U.S. drought spans many major Intermountain and West Coast watersheds, including the Upper and Lower Colorado, the Great Basin, the Rio Grande, and California Coastal basins, including the Sacramento and San Joaquin.

Precipitation totals over the 20 months between January 2020 and August 2021 [are] the lowest on record since at least 1895 over the U.S. Southwest.

The environmental, social, political, and economic consequences of this drought have been swift and severe. With massive economic losses from the drought having already occurred due to its associated heat and wildfires in 2020, drought impacts continue to manifest in 2021. The 2020 wildfire season burned over 10 million acres, with exceptionally large areas burned in California, Colorado, and Arizona. In contrast, 2021's wildfire risk has been centered on the West Coast, particularly in California. This is because

Colorado enjoyed late-season snow accumulation and Arizona, which suffered a rapid onset of wildfires this Spring, has welcomed wet monsoon rains.

While neither Colorado's snow nor Arizona's rains have ended the drought in those states, they have diminished wildfire risks greatly. It remains, however, that the nation's wildfire resources were fully committed by mid-July, quite early in the wildfire season, and continue to be. As of early September, more than 43,000 fires have burned over 5 million acres[5], portending a costly and lengthy wildfire season and continued risk to life and property.

Many surface water reservoirs in the U.S. Southwest, which store water and are designed to buffer periods of drought, have been at historic lows.

Many surface water reservoirs in the U.S. Southwest, which store water and are designed to buffer periods of drought, have been at historic lows. Total reservoir storage across all six states were at 57% of average Spring capacity heading into summer 2021 (*Table 1*)[6]. The spatial extent of the drought spans the entirety of the crucial Colorado River basin, which supplies drinking water for 40 million people including 22 federally recognized tribes[7], electricity supply for nearly 800,000 households[8], irrigation for over 5.5 million acres of land, and river flow for seven National Wildlife Refuges, four National Recreation Areas, and eleven National Parks[7]. The reservoirs in the Lower Colorado River below Lees Ferry at the Utah–Arizona border, which provide water and hydropower to Las Vegas, Los Angeles, Phoenix, San Diego, and Tucson, have also been at record lows. Such historically low reservoir levels throughout the Southwest have major implications for electricity blackouts amidst record-setting heatwaves, as hydropower production shortfalls from the drought, coupled with high electricity demand from air conditioning create conditions for both planned and unplanned blackouts.[9] Moreover, as the economy recovers from the COVID-19 pandemic, the low reservoir levels imply disruptions to fishing and recreation (as boat launches close in national parks, for example[10]), potentially slowing recovery for many tourism-based economies. In fact, the immediate

TABLE 1

	Percent of average May 2021 reservoir storage[6]	2020 economic cost of drought (drought and wildfire)[11]	Drought state of emergency declared
Arizona	51%	$5M–100M ($100M–250M)	Yes, since 1999
California	58%	$250M–500M ($10B–20B)	Yes (April 2021)
Colorado	84%	$250M–500M ($1B–2B)	Yes (June 2021)
Nevada	58%	$5M–100M ($100M–250M)	No
New Mexico	42%	$5M–100M ($100M–250M)	Yes (October 2020)
Utah	92%	$5M–100M ($100M–250M)	Yes (March 2021)
TOTAL	57%	$515M–1.3B ($11.4B–23B)	5 of 6 states

▲ Table 1: For each of the six states considered (and for the six-state total), the percent of average Spring reservoir capacity in 2021 (based on average May reservoir levels from the National Water and Climate Center), the cost of the drought and the drought plus wildfire for 2020 (based on the National Centers for Environmental Information) and whether (and when) a state of emergency has been declared by the Governor of each state. In June 2021, the Navajo Nation also reissued a drought emergency declaration[12]. As of the writing of this report, Nevada's Governor has not issued a state of emergency for the drought, but has for the Caldor Fire[13].

▲ **Aerial view of a neighborhood in Phoenix, Arizona. Credit: Jessica Kirsh**

economic losses associated with the drought for 2020 alone are approximately between $515M and $1.3B[11], not including losses from associated wildfires, which raises the costs to be between $11.4B and $23B (*Table 1*). The costs from 2021 have yet to be estimated, but are likely considerable.

With 2021 having emerged as a second consecutive year of hot and dry conditions, many governors took steps to prepare water districts and citizens for the coming water limitations. Arizona reissued its drought state of emergency, which has been in place since 1999[14]. The California Governor has declared three separate states of emergency, the first in April for the Russian River basin, which supplies drinking water to more than 600,000 people in Sonoma and Marin counties[15], the second in June for the Sacramento-San Joaquin, Klamath and Tulare Lake basin[16] in the Central Valley, whose irrigated agriculture supplies a quarter of the nation's food[17], as well as water for more than 7 million people[18]. The third declaration[19] came in July, asking for voluntary water use reductions of 15%. In June, Colorado has declared a state of emergency for 21 western counties due to the drought and the state is in its highest drought mitigation activation level (Phase 3)[20]. Nevada has imposed use restrictions[21], while New Mexico[22] and Utah[23] have both issued drought emergency declarations (*Table 1*). With the Colorado River water-sharing agreement set to expire in 2026, Colorado River–dependent states and tribal governments are already negotiating terms of future use[24]. The threat of water shortage deliveries in 2021 is certain; crucially, the states sharing the Colorado have a Drought Contingency Plan, which is the framework whereby Lower Basin states like Arizona, California, and Nevada make cutbacks, while the Upper Basin retains some flexibility for reservoir operations[25]. ◆

Dying juniper tree in Monument Valley, Arizona. Credit: John D. Smith

WHAT CAUSED IT?

Drought is caused by low precipitation, high temperatures and its associated vapor pressure deficits or VPD (*Box 2*), or a combination of the two[2]. The 2020–21 Southwestern U.S. drought was caused by an unfortunate combination of variations in climate that led to a sequence of low precipitation seasons (most likely natural) beginning in the winter of 2019–20 (*Fig. 2a–d*), and by both natural and human-caused warming (*Fig. 2e–h*). Evidence for both is discussed below.

ON PRECIPITATION

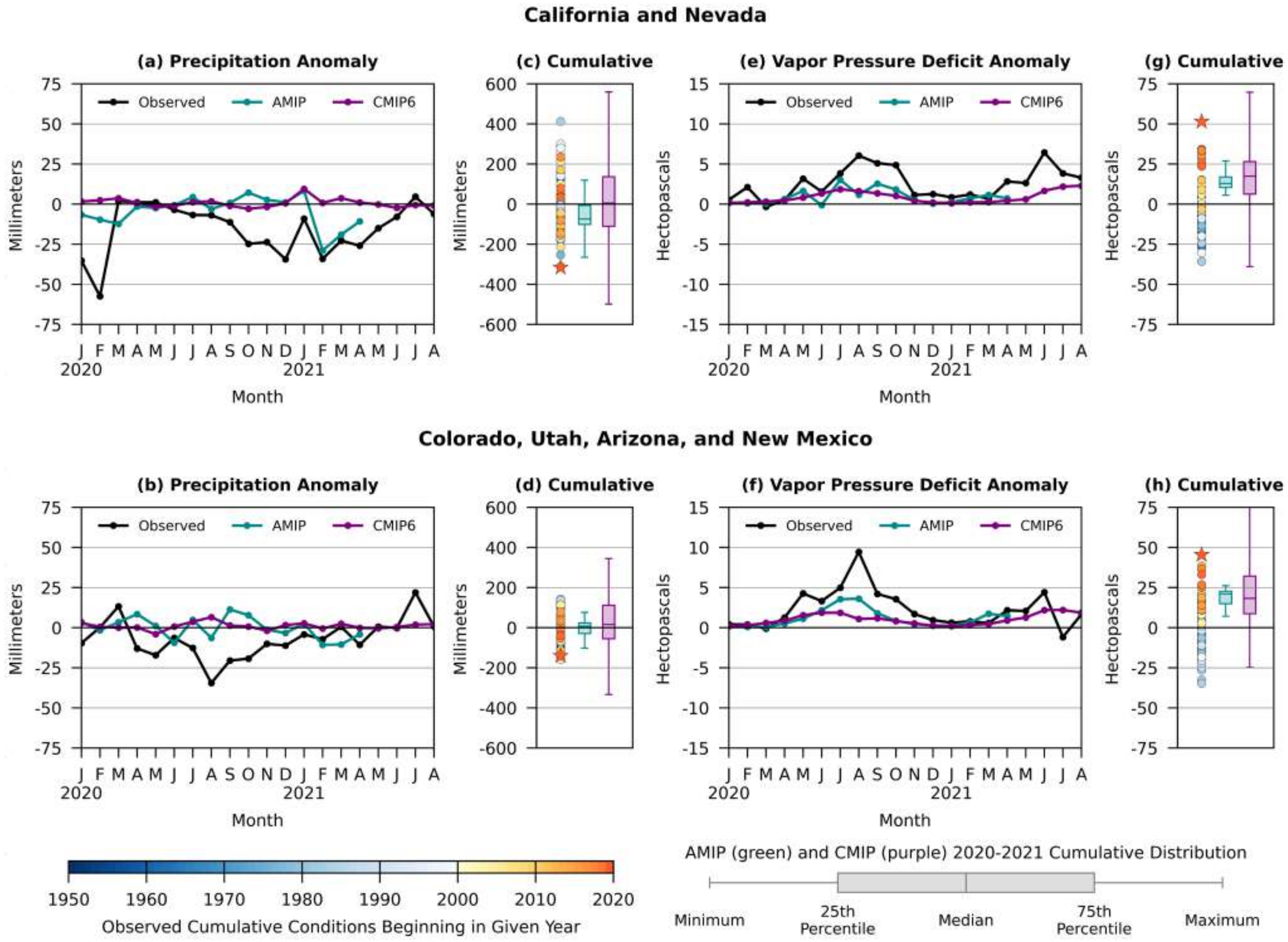
The U.S. Southwest is a large region with diverse precipitation drivers and seasons, from crucial snow accumulation in high elevation regions to summer monsoon rain in the southwest. For simplicity, the region can be characterized as having two principal precipitation seasons: one in winter associated with eastward-moving

BOX 2

What is VPD?

Vapor pressure deficit, or VPD, is a quantity that combines temperature and humidity to indicate the atmospheric demand of moisture from the land surface (e.g., soils, streams, rivers, lakes, etc.). VPD is in units of hectopascals, or hPa, which is a measure of pressure (force per unit area). Here the value represents the difference in pressure exerted by water vapor in the ambient air versus the pressure water vapor *would* exert if the ambient air were saturated (i.e., if relative humidity brought to 100%). In other words, VPD is an indicator of the difference between how much water vapor the atmosphere is capable of holding and how much it actually holds at any given time. As temperature increases, atmospheric demand of water increases exponentially. As such, higher VPD means the atmosphere can extract more water from the surface, drying it out.

Enhanced VPD can be both a driver and a consequence of drought. For example, when precipitation is high and moisture is plentiful, VPD is low (*Fig. 4a*). In contrast, when precipitation is low and the air and soil are dry, VPD can be high. This can increase temperatures, as sunlight goes to heating the air rather than evaporating water. Other factors, such as the rise in temperatures caused by increased greenhouse gas concentrations, can increase VPD regardless of changes in precipitation.



▲ Figure 2: For two subregions, California and Nevada average (*top*) and Colorado, Utah, Arizona, and New Mexico average (*bottom*), the January 2020–August 2021 observed (*black line*) and simulated (AMIP, an atmospheric model, CAM6, forced by observed sea surface temperatures (*teal line*); CMIP6, ocean–atmosphere Earth system models (*purple line*) precipitation (*a,b*) and vapor pressure deficit (*e,f*) anomalies are shown. For each variable and region, the observed monthly anomaly (NCEI NClimGrid for precipitation[3], ERA5[28] for VPD) is shown in black, the ensemble mean of the forecasts represented by the AMIP (CAM6 simulations) shown in teal, and the fully coupled model ensemble mean from CMIP6 shown in purple. Also shown is the total (cumulative) precipitation (*c,d*) and vapor pressure deficit (*g,h*) for each 20-month period of January through August from 1950 onward, colored by year. For all regions, the 20-month period of January 2020–August 2021 stands out as the most extreme (*see stars*). Also shown is the model ensemble distributions for the total precipitation and vapor pressure deficit from the AMIP and CMIP6 simulations for January 2020–August 2021.

low pressure systems from the Pacific Ocean that allow crucial snowpack to accumulate in California, western Nevada, Utah, and Colorado, generally between December and March; and one in summer associated with the North American Monsoon providing rains for Arizona, New Mexico, Colorado, and southern Utah. The initial cause of the drought for the majority of the U.S. Southwest has been successive seasons of very low precipitation, beginning in the winter of 2020 for California and Nevada (*Fig. 2a*) and lasting up to 2021's summer monsoon, which brought much needed rainfall for the states of Colorado, Utah, Arizona, and New Mexico (*Fig. 2b*). The total precipitation between January 2020 and August 2021 was only ~68% of the long-term average across the entire region, with the 20-month precipitation total being the lowest on record (*Fig. 2c,d*). The causes of these successive low precipitation periods vary by season and are known to varying degrees of scientific confidence.

For example, while persistently cool ocean temperatures in the tropical Pacific[26] *likely* contributed to some of the low precipitation in Winter 2021 in California and Nevada (e.g., "AMIP" line in Fig. 2a, see inset *Box 3*), such ocean temperatures do not account for the low precipitation in Summer 2020 in any of the six states considered

(*Fig. 2a, b*). Moreover, the average across model simulations in both the AMIP and CMIP6 experiments (*Fig. 2a and Box 3*) do not reproduce the precipitation deficit over the last 20 months. Together, the model results suggest that random (and likely natural) variations in the atmosphere (i.e., internal atmospheric variability) led to the sequential seasons of low precipitation. This can be seen in four features of Figure 2. Firstly, the AMIP simulations (teal lines in *Figs. 2a and b*) do exhibit lower than average precipitation for some seasons, such as the Winter of 2021, and to a lesser extent, the Winter of 2020, both of which were associated with La Niña events in the tropical Pacific, a known cause of low precipitation in the Southwest. However, the AMIP simulations, despite being given real-world ocean temperatures, do not fully reproduce the low precipitation. This suggests that ocean temperatures were not culpable for all of the precipitation deficit. Secondly, the average across the CMIP6 simulations also does not reproduce the observed sequence of low precipitation seasons (purple lines in *Figs. 2a and b*). This suggests that there is no one external forcing (e.g., greenhouse gases or aerosol forcing) that can account for the precipitation declines that were observed. Thirdly, there is no temporal trend in the observed cumulative precipitation for all 20-month periods since 1895 (colored dots, *Fig. 2c,d*), which along with the model results suggests that there is not a human-caused precipitation trend (*see Box 3*). Lastly, while neither the average across the AMIP or CMIP6 experiments reproduces the precipitation declines over the last 20 months, some individual model simulations for CMIP6, which contains a larger sample of simulated climate than AMIP, do (as seen in the spread in the box plots presented in *Fig. 2c,d)*. This last piece of evidence suggests that while there is no shared response across simulations, 20-month precipitation totals as low as observed can be simulated by the models as a result of natural internal variability. As such, the low 20-month precipitation totals could have occurred by chance. It is important to note that there is the potential for various feedbacks between the land and atmosphere to depress precipitation as well. Low snowpack and soil moisture, for example, can deepen a drought by increasing temperatures and providing less moisture to the atmosphere for future precipitation[27]. However, the role of these kinds of land–atmosphere feedbacks (relative to natural variations) in sequencing the seasons of low precipitation remains an area of active research and is

BOX 3

The models: “CMIP6” & “AMIP”

Climate models are sophisticated computer programs that simulate the physics, chemistry, and biology of the factors most relevant to climate in the Earth System, such as the ocean, atmosphere, land, and ice. These models, which are essentially accounting machines of the budgets of energy, mass, and momentum on our planet are designed and built by national labs in various countries and/or academic institutions, known as “modeling groups.” To compare the answers provided by different models, modeling groups perform highly standardized experiments, known as “Model Intercomparison Projects” or MIPs.

The CMIP6 (*Fig. 2*), or 6th Phase of the “Coupled Model Intercomparison Project,” is the overarching project name for all of the climate model experiments that are endorsed by the World Climate Research Program and have been coordinated across modeling groups. In this report, CMIP6 refers to standard experiments where each model simulates recent climate based on known, external factors, and simulates future climate based on projections of such external factors. These external factors (or forcings) include solar intensity, land use changes, greenhouse gas and aerosol emissions, as well as volcanic eruptions. As such, the CMIP6 experiments give an indication of how much the models agree that those external factors are responsible for the observed climate, such as the observed warming over the recent decades or, in the case of the projections, how changes in these external factors will modify the climate going forward.

The AMIP (*Fig. 2*), or “Atmospheric Model Intercomparison Project,” is one of the principal experiments under the CMIP6. It is an experiment in which the atmosphere and land components of the model freely simulate climate in response to known external forcings and real-world ocean temperatures, rather than ocean temperatures simulated by the model. In that sense, the AMIP simulations give us an indication of how much the models agree that ocean temperatures specifically determined what happened in the atmosphere, like sequential seasons of low precipitation over the U.S. Southwest, for example. In this report, the AMIP results from a model called CESM2-CAM6 are presented.

not something that can be assessed with the results from Figure 2. While human-induced global warming has not been identified as a cause for the low precipitation itself, the question remains an active area of research to identify whether and how the thermodynamic effects of both global- and regional-scale warming to date have shaped the dynamics of seasonal precipitation in the region.

▲ **View of the Colorado River in Marble Canyon, Arizona. Credit: Dominic Gentilcore**

ON TEMPERATURE

While precipitation was exceptionally low in 2020–2021, temperatures over the same period were exceptionally warm. These warm temperatures caused both a shortened snow season and the record-high vapor pressure deficit, or VPD, observed over the 20-month period of January 2020 to August 2021 (*Fig. 2e–h and Box 2*)[3]. While precipitation deficits may have contributed to some of the high temperatures that occurred in Summer 2020 (*Fig. 2e,f*), it is clear that additional increases in VPD from human-caused warming helped ensure that below-normal precipitation, even if only due to unlucky weather, would make drought more likely. Since VPD is shaped by both temperature and humidity (*see Box 2*), the low precipitation totals in July and August of 2020 lowered humidity further, helping to reinforce the already high VPD from warm temperatures (*Fig. 2a, b and Fig. 2e, f*). At the same time, analysis based on weather analogs suggests that randomness in the atmosphere can only account for ~50% of the exceptional summer 2020 VPD. This result implies that human-caused warming played a significant role in the anomalously high VPD over the last 20 months. Reinforcing this finding is the clear temporal trend in observed cumulative VPD (*Fig. 2g,h*, colored dots with values increasing in time) while a similar trend is not found in precipitation (*Fig. 2c,d*). This illustrates that VPD has been increasing with observed warming. As such, the drought was made more impactful by human-caused warming, because the warming helped drive the record high summer 2020 VPD, which deepened and spread the drought across the region.

The drought was made more impactful by human-caused warming...

While both the direct (*low water supply from several seasons of low precipitation*) and intensifying (*high water demand from regional warming, high VPD, and melting snowpack*) causes of the 2020–21 drought are known (*Fig. 2*), the drought research community does not yet know the precise physical mechanisms that led the consecutive precipitation seasons, which initiated the drought, to be so exceptionally low. In particular, it is not clear what mechanisms caused the extremely dry 2020 summer monsoon. Questions remain about the role of potential feedbacks between the land and overlying atmosphere in suppressing 2020's summer rains. Near-record burned areas from wildfire across the West were certainly influenced by drought conditions, but there is also the possibility that newly burned land surfaces influence conditions to exacerbate drought risk in subsequent seasons[29]. Forecast models[30] failed to predict the low precipitation in Summer 2020, though it is unclear whether this prediction failure is due to model deficiencies or instead is attributable to random (and unpredictable) variations in weather and climate. Answering this question likely holds the key for pinpointing the mechanistic causes of this extraordinary drought and better anticipating its future likelihood in a warmer climate. ◆

Willow Lake near Prescott, Arizona, after the much-needed monsoon rains in late summer 2021. Credit: Georgeanne Hanna

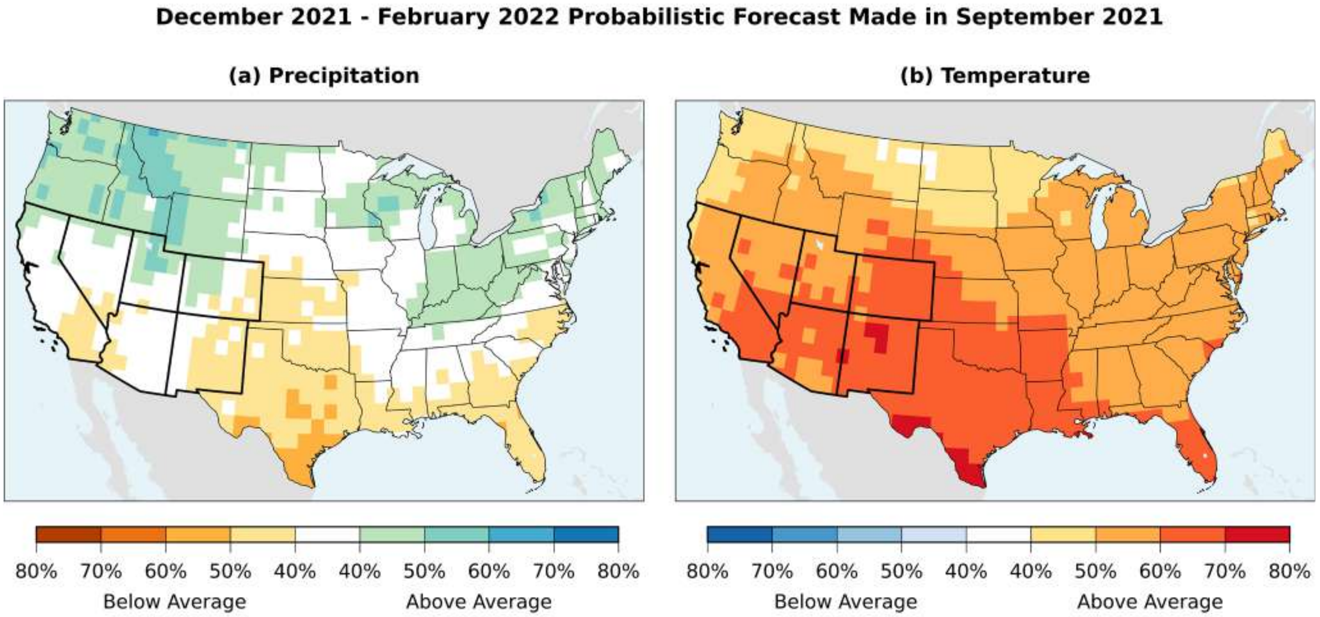
WHEN IS IT GOING TO END?

Drought conditions will improve when water supply from precipitation increases, water demand from high temperatures decreases, or some combination thereof occurs. Because the successive seasons of below-average precipitation appear to have come from natural, but unfavorable, variations in the atmosphere and ocean, precipitation may return to pre-2020 drought levels at some point after Winter 2021-2022, which is already forecast to be drier than average for some parts of the drought-stricken region (*Fig. 3a*).

Crucially, 2020–21's record low precipitation has occurred in the context of increasing (and projected[31]) aridification in the U.S. Southwest, which is largely due to human-caused surface warming (*Fig. 1e and Fig. 4*), and is arguably part of a much longer, and exceptional, multidecadal drought[32]. These factors, coupled with the existing deficits in soil moisture, snowpack, and reservoir water storage, suggest that this drought will likely continue well into 2022 for parts of the U.S. Southwest. Warming reduces snowfall and snow accumulation in mountain regions, which further reduces streamflow and soil moisture in spring and summer when plants and people demand water most. Moreover, if warming alters the dynamics that give rise to precipitation (although models on average do not suggest this, *Fig. 4*), or if precipitation variability continues to be unfavorable in the coming seasons (slightly below average precipitation is forecast for Winter 2021–2022 in the southern portion of the region) (*Fig. 3a*), the drought could last considerably longer.

ON PRECIPITATION

Precipitation is highly variable in the U.S. Southwest due to natural variations in weather and climate, with wet and dry years and wet and dry decades (*Fig. 1d*). There is no evidence based on climate models that greenhouse gas forcing has made either 2020's record low precipitation (*Fig. 4a*), or the precipitation decline over the last several decades, more likely (*Fig. 4b*)[32,33]. The model simulations shown in Figure 4a suggest that a year like 2020 has about a 2% chance of happening and



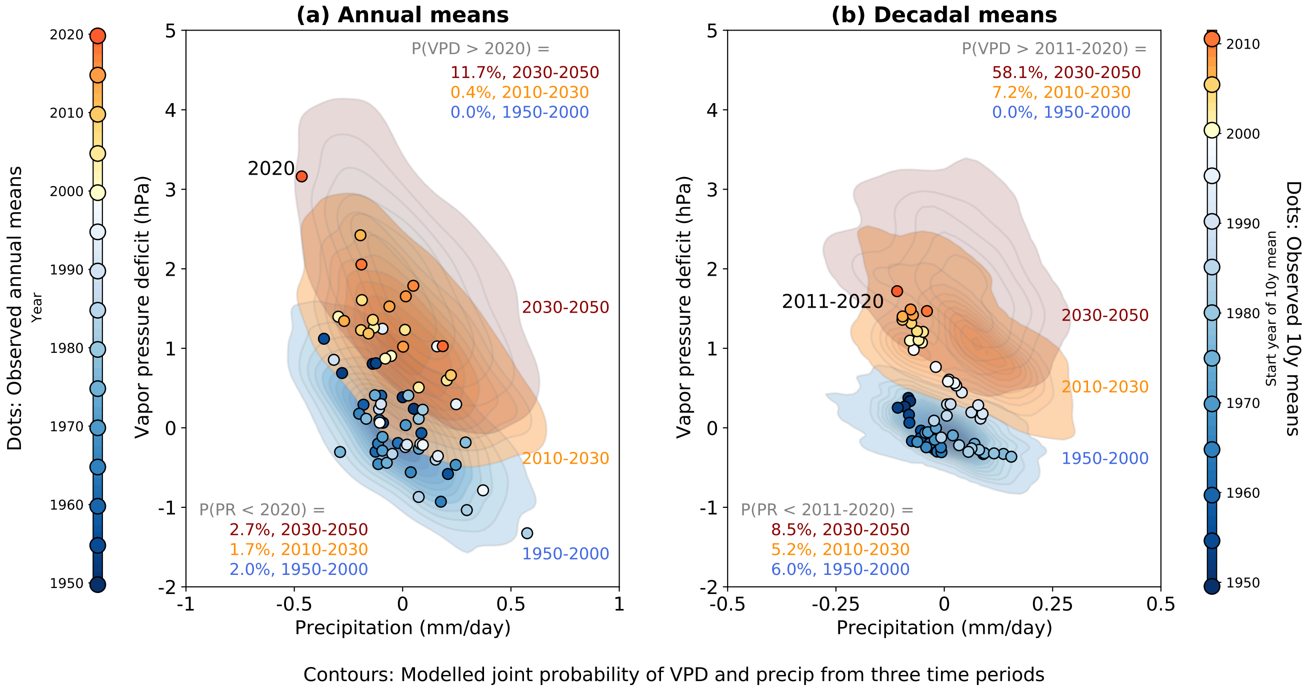
▲ **Figure 3:** **Precipitation (*a*) and temperature (*b*) forecasts for December 2021 through February 2022 from the North American Multi-Model Ensemble (NMME) made in September 2021. Colors show the likelihoods of above- or below-average conditions.**

that human-caused climate change has not substantially altered this probability. Similarly, the simulations indicate that a decade with precipitation as low as 2011–2020 has about a 5–6% chance of occurring and, again, climate change has not substantially altered this probability. Instead, these extreme and unlucky variations in precipitation appear to be driven by random variations in the atmosphere and short- and long-term variations in ocean temperatures. While 2020 and 2011–2020 precipitation deficits have been extreme and rare, both values are statistically consistent with the 120-year observational record. The long-term decline in precipitation between the 1980s and 2010s has been attributed in part to a decades-long shift to cooler ocean temperatures in the eastern Pacific along the North American coast and a warm shift in Atlantic Ocean temperatures over the same period. For that reason, the La Niña event (cold tropical eastern Pacific Ocean temperatures) forecast to form this coming Winter[34] increases the likelihood of below-average precipitation in Winter 2021–2022. The seasonal forecast shown in Figure 3a suggests a small chance of precipitation being below average. This forecast, along with the forecasted warm temperatures (*Fig. 3b*) implies that the drought will continue. At the same time, above-average precipitation could mean drought relief for some regions, such as northern California and parts of Utah and Colorado. For example, a wet spring and early summer in 2021 has brought some drought relief to eastern Colorado. Similarly, Arizona had its rapidly emerging wildfire season dampened by a wet summer monsoon in 2021. It remains, however, that regional precipitation changes for the coming decades are uncertain[35] (see the broadening x-axis extent of the contours in *Fig. 4*). However, there is modest consensus that California winters may be slightly wetter[36], but punctuated by warmer and drier Fall and Springs, along with larger swings between very wet and very dry years[37].

Precipitation is highly variable in the U.S. Southwest due to natural variations in weather and climate, with wet and dry years and wet and dry decades.

ON TEMPERATURE

Regional warming trends driven by global warming will continue to increase the evaporation of water from the land and melt mid- and high-elevation snowpack earlier in the year, or prevent it from accumulating in the first place. In a given year, atmospheric demand for moisture, as measured by VPD, tends to be highest when precipitation is lowest (e.g., *Fig 4a*, teal dots). As such, wet years are both cooler and have higher atmospheric



▲ **Figure 4: Observed and modeled precipitation (*x-axis*) and vapor pressure deficit, VPD (*y-axis*) anomalies relative to the 1950–2000 mean, averaged over the 6 states in the U.S. Southwest. Panel (*a*) shows annual means and (*b*) shows decadal (10-year running) means. Dots show the values from each year or decade from observation-based data color-coded by year. The contours show the joint probability of precipitation and VPD for three different time periods (1950–2000, 2010–2030 and 2030–2050) from the CMIP6 climate model experiments. The contours indicate the relative probability of the models simulating that joint precipitation-VPD value in the time period considered, with darker contours representing higher likelihoods, and the white regions outside of the contours representing a small, but non-zero probability. Observed VPD has increased over time while precipitation has not exhibited a systematic long-term trend; both of these trends align with the model projections. Furthermore the 2030–2050 contours suggest that this trend toward increasing VPD will continue. The probabilities quoted in each panel reflect the model-based probability of a year or decade with as high VPD (*top right*) or low precipitation (*bottom left*) as 2020 or 2011–2020 occurring in the different time periods. Note that the probability of 0.0% refers to a probability of less than 1 in 1980 years (the total number of years of simulation considered for the 1950–2000 period). Observed VPD comes from ERA5[28]; observed precipitation comes from NCEI NClimGrid[3]; model data comes from 33 different Earth System Models that contributed to CMIP6 and were forced with the SSP5-8.5 scenario after 2014, which assumes no climate mitigation.**

water vapor content, which leads to lower values of VPD. At the same time that precipitation influences VPD, so too does temperature. Longer-term trends in VPD due to regional warming can be seen in the temporal increase in VPD (from the teal values common in the 1950s, to orange values common in the 2010s in *Figs. 4a,b*). This rise in VPD is consistent with expectations based on climate models (compare colored dots from observations with contours from models in *Fig. 4*) and from these models such VPD increases can be attributed to rising surface and atmospheric temperatures, which are driven primarily by rising atmospheric greenhouse gas concentrations. Therefore, the increasing atmospheric demand for water from the land (as measured by VPD, *Fig. 4*) will only end if human-caused greenhouse gas emissions are reduced and regional warming trends are reversed. That said, it is notable that even in the presence of the observed warming trend, 2020 as an individual year was extreme (*Fig. 4a*), as low precipitation and high temperatures created conditions for extremely high annual-scale VPD. Moreover, a comparison of the observations with the model projections suggests that both the annual- and decadal-scale VPD values associated with the Southwestern U.S. drought were exceptionally unlikely in a pre-2000 climate (*Fig. 4a,b*, blue contours). For example, not one year or decade of a pre-2000 climate simulated by the models had VPD values as high as those observed in 2020 or 2011–2020 (almost 2,000 years

Longer-term increases in VPD and greater aridification of the U.S. Southwest will not end without curbing greenhouse gas emissions.

of simulated climate contribute to this analysis). The models also indicate that drought intensifying VPD trends will continue with human-caused warming. By 2030 and with no climate mitigation, more than 1 in 10 years will have VPD values as high as 2020 (*Fig. 4a*) and by 2030–2050, a decade with VPD as high as we have seen in the last decade (2011–2020) will be the norm (*Fig. 4b*). The magnitude and intensity of severe droughts in the region are projected to increase with greenhouse gas emissions[38]. As such, longer-term increases in VPD and greater aridification of the U.S. Southwest will not end without curbing greenhouse gas emissions.

Taken together, even if higher annual precipitation totals occur in coming years, it will take several seasons (and potentially years) of above-average precipitation to replenish the reservoirs, rivers, streams, and soil moisture that 60+ million people depend on for their water, livelihoods, food, power, and recreation. This, when coupled with the La Niña forecast for the coming winter, suggests the ongoing Southwestern U.S. drought will very likely last well into 2022, and potentially beyond. In the longer-term, the atmospheric demands on regional land surface moisture will continue to increase due to rapidly increasing VPD from human-caused global warming. Such growing demands mean a more arid U.S. Southwest and greater sensitivity to droughts in the future. While 2020–21 was an exceptional period of low precipitation, the drought that has emerged is a harbinger of a future that the U.S. Southwest must take steps to manage now. ◆

Aerial view of Lake Powell in Arizona. Credit: Tsuchi

OUTSTANDING QUESTIONS TO BE ANSWERED

The National Oceanic and Atmospheric Administration (NOAA) Drought Task Force, under the aegis of NOAA's Modeling Analysis Predictions and Projections (MAPP) program with support from the National Integrated Drought Information System (NIDIS), is well positioned to address the many science questions that remain about the origins of this exceptional drought and what it implies about the future of water availability for the rapidly growing and economically crucial U.S. Southwest.

Members of the Task Force are actively researching these questions, including:

- What accounts for the forecast errors in seasonal precipitation and temperature in Summer 2020 and other seasons?
- Has warming affected the dynamics or circulation that controls regional and seasonal precipitation, such as through land–atmosphere feedbacks?
- What was more important in accounting for the severity of this drought, the exceptionally low precipitation or the exceptionally warm temperatures?
- What impact will the forecast 2021–22 La Niña have on precipitation and temperature and, more generally, how are natural modes of seasonal to decadal climate variability impacting Southwest U.S. climate?
- What effect will precipitation in Winter 2022 have on the water resources in 2022 over the Southwest?
- How will drought monitoring and management change in the presence of Southwestern U.S. aridification?
- How do warming effects on snowpack influence water availability in the Spring and Summer?
- What are the major sources of uncertainty in regional and seasonal precipitation trends in the U.S. Southwest, and how can they be constrained for more certain projections?

▲ Xeriscaping. Credit: Chansom Pantip

What is the Drought Task Force?

The NOAA Drought Task Force aims to advance drought monitoring and prediction for North America. The Task Force is an initiative of NOAA's MAPP program. The Task Force's research results are expected to help advance basic understanding of drought mechanisms, official national drought products, the development of early warning systems by the National Integrated Drought Information System (NIDIS), and experimental drought monitoring and prediction activities and tools for operational and service purposes as part of the National Centers for Environmental Prediction's (NCEP) Climate Test Bed. The Task Force coordinates with other relevant national and international efforts including the emerging National Multi-Model Ensemble (NMME) capabilities and the international effort to develop a Global Drought Information System (GDIS).

What is MAPP?

The Modeling Analysis Predictions and Projections (MAPP) Program's mission is to enhance the Nation's and NOAA's capability to understand, predict, and project variability and changes in Earth's climate system. MAPP's work directly impacts or provides foundational capability for improving understanding and assessing impacts for decision making. It also aims to improve NOAA products used in mitigation and adaptation. By supporting these goals, the MAPP program plays a crucial role in enabling the Nation to meet the societal challenges created by the impacts of climate variability such as year-to-year changes in the occurrence of extremes or droughts and longer term climate changes. *cpo.noaa.gov/MAPP*

REFERENCES

1 US Bureau of Reclamation. Draft Annual Operating Plan for Colorado River Reservoirs 2022. *https://www.usbr.gov/lc/region/g4000/AOP2022/2022AOP_2021-05-27_Consultation-1.pdf* (2021).

2 Hoerling, Martin & et al. Temperature and Drought: A science assessment by a subgroup of the drought task force. *https://cpo.noaa.gov/Portals/0/Docs/MAPP/Reports/2018/TemperatureDrought/Drought_TF_Temp_Drought_Final_Revised.pdf?ver=2018-07-31-104948-243* (2018).

3 Vose, R. S. et al. Improved Historical Temperature and Precipitation Time Series for U.S. Climate Divisions. J. Appl. Meteorol. Climatol. 53, 1232–1251 (2014).

4 National Drought Mitigation Center. United States Drought Monitor (USDM). *https://droughtmonitor.unl.edu/Data.aspx*.

5 National Interagency Fire Center. National Fire News. *https://www.nifc.gov/fire-information/nfn*.

6 United States Department of Agriculture. Natural Resources Conservation Service National Water and Climate Center. Reservoir Storage *https://www.nrcs.usda.gov/wps/portal/wcc/home/waterSupply/reservoirStorage/*.

7 United States Bureau of Reclamation. Colorado River Basin Water Supply and Demand Study, Executive Summary. 34 *https://www.usbr.gov/watersmart/bsp/docs/finalreport/ColoradoRiver/CRBS_Executive_Summary_FINAL.pdf*.

8 Thiel, Aaron. Climate Change Impacts on Hydropower in the Colorado River Basin. *https://uwm.edu/centerforwaterpolicy/wp-content/uploads/sites/170/2013/10/Colorado_Energy_Final.pdf*.

9 Blunt, Katherine & Carlton, Jim. West Risks Blackouts as Drought Reduces Hydroelectric Power. The Wall Street Journal (2021).

10 National Park Service. National Park Service Glen Canyon Changing Lake Levels. *https://www.nps.gov/glca/learn/changing-lake-levels.htm*.

11 NOAA National Centers for Environmental Information (NCEI). U.S. Billion-Dollar Weather and Climate Disasters. *https://www.ncdc.noaa.gov/billions/time-series/UT* (2021).

12 The Navajo Nation. Navajo Nation Commission on Emergency Management reaffirms drought declaration state of emergency to activate additional resources. *https://www.opvp.navajo-nsn.gov/Portals/0/Files/PRESS%20RELEASES/2021/Jun/FOR%20IMMEDIATE%20RELEASE%20-%20Navajo%20Nation%20Commission%20on%20Emergency%20Management%20reaffirms%20drought%20declaration%20state%20of%20emergency%20to%20activate%20additional%20resources_CEM%20210625.pdf* (2021).

13 The State of Nevada. Declaration of Emergency for the Caldor Fire. *https://gov.nv.gov/News/Emergency_Orders/2021/2021-08-30_-_Declaration_of_Emergency_for_the_Caldor_Fire/* (2021).

14 The State of Arizona. Drought Emergency Declaration PCA 99006. *https://new.azwater.gov/drought/resource/drought-declarations-arizona* (1999).

15 The State of California. State of Emergency Proclamation for the Russian River and Klamath Basins. *https://www.gov.ca.gov/wp-content/uploads/2021/04/4.21.21-Drought-Proclamation.pdf* (2021).

16 The State of California. State of Emergency Proclamation for the Klamath River, Sacramento-San Joaquin Delta, and Tulare Lake Watersheds. *https://www.gov.ca.gov/wp-content/uploads/2021/05/5.10.2021-Drought-Proclamation.pdf* (2021).

17 United States Geological Survey. California Water Science Center, California's Central Valley. *https://ca.water.usgs.gov/projects/central-valley/about-central-valley.html*.

18 United States Bureau of Reclamation. Sacramento-San Joaquin Rivers Basin Study. *https://www.usbr.gov/watersmart/bsp/docs/fy2012/FactSheet-Sacramento-SanJoaquinRiversBasinStudy.pdf* (2012).

19 The State of California. State of Emergency Proclamation for Nine Additional Counties. *https://www.gov.ca.gov/wp-content/uploads/2021/07/7.8.21-Conservation-EO-N-10-21.pdf* (2021).

20 The State of Colorado. State of Emergency Proclamation for 21 Counties. *https://dnrweblink.state.co.us/cwcbsearch/0/edoc/214784/Drought%20Emergency%20(4).pdf?searchid=e77952dd-ecaf-4c70-8962-f1ee8ff2fd5a* (2021).

21 Southern Nevada Water Authority. Restricting outdoor water use. *https://www.snwa.com/importance-of-conservation/restricting-outdoor-water-use/index.html#useless*.

22 The State of New Mexico. Drought Declaration Executive Order 2020-084. *https://www.governor.state.nm.us/wp-content/uploads/2020/12/Executive-Order-2020-084.pdf* (2020).

23 The State of Utah. State of Emergency Declaration Executive Order 2021-7. *https://governor.utah.gov/2021/03/17/gov-cox-issues-drought-executive-order/* (2021).

24 Rice, Matt. We Are Rivers: Colorado River Compact Call Part 1—What Could A Call Mean. (2019).

25 United States Bureau of Reclamation. Agreement Concerning Colorado River Drought Contingency Management and Operations. *https://www.usbr.gov/dcp/docs/final/Companion-Agreement-Final.pdf* (2019).

26 McCabe, G. J., Betancourt, J. L. & Hidalgo, H. G. Associations of Decadal to Multidecadal Sea-Surface Temperature Variability with Upper Colorado River Flow1: Associations of Decadal to Multidecadal Sea-Surface Temperature Variability With Upper Colorado River Flow. JAWRA J. Am. Water Resour. Assoc. 43, 183–192 (2007).

27 Tawfik, A. B. & Steiner, A. L. The role of soil ice in land-atmosphere coupling over the United States: A soil moisture–precipitation winter feedback mechanism. J. Geophys. Res. 116, D02113 (2011).

28 Muñoz Sabater, J. ERA5-Land data. Copernic. Clim. Change Serv. C3S Clim. Data Store CDS (2019) doi:10.24381/cds.e2161bac.

29 Fu, R., A. Hoell, J. Mankin, A. Sheffield, and I. Simpson. Tackling challenges of a drier, hotter, more fire-prone future. Eos, Transactions American Geophysical Union (2021).

30 National Weather Service Climate Prediction Center. NMME Forecasts of Monthly Climate Anomalies for May 2020 - November 2020. *https://www.cpc.ncep.noaa.gov/products/NMME/archive/2020040800/seasanom.shtml* (2020).

31 Seager, R. et al. Model Projections of an Imminent Transition to a More Arid Climate in Southwestern North America. Science 316, 1181–1184 (2007).

32 Williams, A. P. et al. Large contribution from anthropogenic warming to an emerging North American megadrought. Science 368, 314–318 (2020).

33 Lehner, F., Deser, C., Simpson, I. R. & Terray, L. Attributing the U.S. Southwest's Recent Shift Into Drier Conditions. Geophys. Res. Lett. 45, 6251–6261 (2018).

34 International Research Institute for Climate & Society. CPC/IRI Official Probabilistic ENSO Forecast. *https://iri.columbia.edu/our-expertise/climate/forecasts/enso/current/?enso_tab=enso-cpc_plume* (2021).

35 Seager, R. et al. Dynamical and Thermodynamical Causes of Large-Scale Changes in the Hydrological Cycle over North America in Response to Global Warming. J. Clim. 27, 7921–7948 (2014).

36 Neelin, J. D., Langenbrunner, B., Meyerson, J. E., Hall, A. & Berg, N. California Winter Precipitation Change under Global Warming in the Coupled Model Intercomparison Project Phase 5 Ensemble. J. Clim. 26, 6238–6256 (2013).

37 Swain, D. L., Langenbrunner, B., Neelin, J. D. & Hall, A. Increasing precipitation volatility in twenty-first-century California. Nat. Clim. Change 8, 427–433 (2018).

38 Cook, B. I. et al. Uncertainties, Limits, and Benefits of Climate Change Mitigation for Soil Moisture Drought in Southwestern North America. Earth's Future 9, e2021EF002014 (2021).

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Have questions about the report? Please contact:
Justin Mankin | *justin.s.mankin@dartmouth.edu*
Andrew Hoell | *andrew.hoell@noaa.gov*
Isla Simpson | *islas@ucar.edu*