Advanced Review

North American megadroughts in the Common Era: reconstructions and simulations

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During the Medieval Climate Anomaly (MCA), Western North America experienced episodes of intense aridity that persisted for multiple decades or longer. These megadroughts are well documented in many proxy records, but the causal mechanisms are poorly understood. General circulation models (GCMs) simulate megadroughts, but do not reproduce the temporal clustering of events during the MCA, suggesting they are not caused by the time history of volcanic or solar forcing. Instead, GCMs generate megadroughts through (1) internal atmospheric variability, (2) sea-surface temperatures, and (3) land surface and dust aerosol feedbacks. While no hypothesis has been definitively rejected, and no GCM has accurately reproduced all features (e.g., timing, duration, and extent) of any specific megadrought, their persistence suggests a role for processes that impart memory to the climate system (land surface and ocean dynamics). Over the 21st century, GCMs project an increase in the risk of megadrought occurrence through greenhouse gas forced reductions in precipitation and increases in evaporative demand. This drying is robust across models and multiple drought indicators, but major uncertainties still need to be resolved. These include the potential moderation of vegetation evaporative losses at higher atmospheric [CO_2], variations in land surface model complexity, and decadal to multidecadal modes of natural climate variability that could delay or advance onset of aridification over the the next several decades. Because future droughts will arise from both natural variability and greenhouse gas forced trends in hydroclimate, improving our understanding of the natural drivers of persistent multidecadal megadroughts should be a major research priority.

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INTRODUCTION

Recurrent droughts are a normal part of climate variability in Western North America, and recent events (e.g., California, the Southwest) have highlighted the vulnerability of people and ecosystems to the capricious nature of water availability in this region.[1–4] Despite these challenges, however, there is robust evidence from the paleoclimate record that Western North America experienced even worse droughts (*megadroughts*) over the last two millennia.[5,6] These events, many lasting multiple decades, had profound impacts on the contemporary indigenous societies,[7–10] vegetation,[11–13] and landscape.[12,14,15]

Megadroughts are not precisely defined in the literature, but typically refer to persistent drought events in the preindustrial period with durations longer than a decade. These droughts stand in sharp contrast to the shorter length of more recent 20th-century events such as the Dust Bowl (1932–1939) and the 1950s drought (1948–1957). Megadroughts are thus primarily differentiated from more recent instrumental-era droughts in terms of their duration and, occasionally, their spatial extent.[6,16] Even before the research community adopted the term, however, such extreme events were being noted in the paleo record. For example, a 1976 reconstruction of Colorado River flow at Lee's Ferry[17] documented periods of low flows between 1868–1892 and 1564–1600 that were longer than any period in the instrumental record.

The first use of the term 'megadrought' in the broader academic literature was likely 1980, in a publication from the University of Hong Kong referencing a drought in Northern China from 1876 to 1879.[18] The term was used in its more modern capacity several years later, describing rare 15-year drought events in Texas in the proceedings from a meeting on livestock and wildlife management.[19] It was also later invoked in a newspaper article[20] describing a study[5] documenting centennial-scale droughts in the Sierra Nevada mountains, before entering the primary research literature in 1998.[6]

The megadrought concept ultimately gained prominence in the 1990s with Stine[5] and Woodhouse and Overpeck.[6] Stine surveyed relict tree stumps in stream beds in the Sierra Nevada mountains, trees that were over a century old at the time of their death and that only could have become established and survived when the stream bed was dry. Stine surmised that California experienced two centennial-scale periods of aridity in California between 800 and 1300 CE. Furthermore, this study speculated that these events may have been a regional expression of global climate shifts during this interval, suggesting this time period be referred to as the Medieval Climate Anomaly (MCA) instead of the Medieval Warm Period to reflect shifts in both temperature and moisture. Complementing the regional focus of Stine[5], Woodhouse and Overpeck[6] conducted the first large-scale analysis of megadroughts across Western North America. Using a multiproxy approach and historical documents, this study placed locally recorded megadrought events over the last two millennia in a broader spatial context, demonstrating for the first time that megadroughts afflicted nearly every area of the West. These foundational studies helped launch an entire body of megadrought research using a diversity of paleoclimate proxies, including tree rings,[16,21,22] lake sediments,[23] and pollen records.[24] With this expanded network of proxy information came the realization that megadroughts were a relatively common feature of early to middle Common Era climate, with documented events in the Southwest,[25] Mexico,[26] the Montane West,[24,27,28] the Great Lakes,[29] the Central Plains,[12,30] the Pacific Northwest,[23,31] and across nearly all of Western North America.[30]

Despite rapid progress developing the paleoclimate record since Stine[5] and Woodhouse and Overpeck[6], little is known about what caused the megadroughts. These events are not evenly distributed in time, clustering during the MCA (approximately 800–1300 CE) and the centuries immediately thereafter (1300–1600 CE). Forcing differences during the MCA (e.g., enhanced solar or diminished volcanic activity) have therefore been posited as a possible driver, most likely by favoring ocean states conducive to drought over North America.[32] Alternatively, the same processes responsible for recent historical droughts may have also played a role during the megadroughts. These include internal atmospheric variability,[33,34] forcing from sea-surface temperatures (SSTs),[33,35–37] and land–atmosphere interactions.[38–40]

Information on these processes during the Medieval-era megadroughts is nevertheless sparse. Reconstructions of important drought drivers over North America, such as SSTs in the tropical Pacific, are often poorly resolved spatially and temporally, making quantitative comparisons with drought reconstructions difficult. In other cases, the different reconstructions (e.g., drought and SSTs) may even share the same underlying proxies,[41] making any analyses of these different datasets circular. Because of these limitations, most investigations into megadrought dynamics have relied on experiments using general circulation models (GCMs). These include analyses of simulations performed as part of other modeling efforts, such as the Paleoclimate Modelling Intercomparison Project Phase III (PMIP3[42]) or the Coupled Modeling Intercomparison Project Phase 5 - (CMIP5[43]), as well as more targeted model experiments designed to address-specific megadrought hypotheses.[44–46]

Here, we review the state of knowledge of North American megadroughts during the Common Era. We begin with a broad overview of evidence for these events in the paleoclimate record, including major uncertainties inherent in interpreting these events from the available proxies. This is followed by discussion of the evidence, primarily model based, for various hypothesized megadrought drivers, including internal atmospheric variability, persistent SST states, and land–atmosphere interactions. We conclude with a discussion of anthropogenic climate change and megadrought risk, including uncertainties that need to be addressed to improve confidence in our understanding of these extreme events in the past and the future.

MEGADROUGHTS IN THE PALEOCLIMATE RECORD

To highlight megadroughts in the paleo record, we will rely primarily on tree-ring-based reconstructions. Tree rings offer several distinct advantages over other proxies for characterizing drought variability in North America over the last 2000 years. They are annually resolved and precisely dated, providing information for every year with zero dating error. The typical lifespan of trees (several hundred to several thousand years) is well suited for the time horizon of the Common Era. Trees are also widely distributed across North America, allowing for the development of proxy networks that enable high resolution spatial reconstructions, a critical quality for interpreting and analyzing the climate dynamics associated with drought events. Finally, tree growth is highly sensitive to moisture availability over much of North America, ensuring high quality and well validated reconstructions.

One of the most comprehensive reconstructions of North American hydroclimate is the North American Drought Atlas (NADA[16,47]), a two millennia long tree-ring-based gridded reconstruction of summer season (June–July–August, JJA) Palmer Drought Severity Index (PDSI). PDSI is a locally normalized index of soil moisture variability, integrating changes in moisture supply (precipitation) and demand (evapotranspiration) over multiple seasons (about 12 months[48]). The NADA has been used widely to analyze drought dynamics over the historical period and the Common Era, including multiple megadrought studies.[47,49,50] For this review, we have updated the most recent version of the NADA,[47] incorporating 91 new chronologies (from 1845 to 1936) from Mexico, the United States, and Canada to provide better spatial coverage over Western North America back to 800 CE. We highlight three main regions of megadrought activity: California–Nevada (32°N–41°N, 126°W–114°W), the Southwest (28°N–38°N, 114°W–103°W), and the Central Plains (33°N–45°N, 103°W–90°W) (Figure 1). In all three regions, there is a long-term trend or shift toward wetter conditions around 1600 CE. During the MCA and post-MCA centuries, all three regions clearly show persistent periods of multidecadal drought.

Over California–Nevada, the megadroughts originally described in Stine[5] appear as two centennial scale events from 862–1074 CE and 1122–1299 CE, separated by a multidecadal pluvial (Figure 1, top panel). These droughts were geographically extensive, affecting the Northwest, Southwest, and the Central Plains, especially during the second Stine Drought (Figure 2). This latter drought occurred during two of the driest centuries in the record (1100–1299 CE), when enhanced aridity covered much of the contiguous United States.[16,51,52] In the new reconstruction, the spatial pattern of the Stine droughts looks somewhat different from previous reconstructions (e.g., Figure 7 in Cook et al.[47]), although this new version still produces some of the most intense drying in California and the Montane West. Some caution is needed, however, in interpreting some of the drought patterns in these maps over areas with poor proxy coverage. For example, prior to 1000 CE, there are no local tree-ring chronologies available for the Central Plains. The rather severe drought in this area, coincident with Stine #1, is therefore inferred from proxies and reconstructed values from nearby regions. This issue is discussed in more detail below.

The updated NADA also shows two megadroughts connected to disruptions of major Pre-Columbian indigenous societies. The first occurred in the Southwest in the late 1200s (Figure 3(a)), and is thought to have contributed to the depopulation of Mesa Verde and the Four Corners region by Ancestral Pueblo societies.[8,53] This drought, and its association with the Ancestral Puebloans, was first described by some of the earliest dendrochronological work in the Southwest.[54,55] The second drought occurred in the 1300s, centered over the Central Plains (Figure 3(b)). This drought immediately preceded, and continued after, the abandonment of the Cahokia settlements in the Mississippi river valley,[9] the largest city in Pre-Columbian North America north of Mexico. Additional evidence, however, suggests that extreme floods may have also played a role in the abandonment of Cahokia,[56] and isolated wet years during this drought can be seen in the Central Plains time series (Figure 1, bottom panel). Other independently documented megadroughts are also in

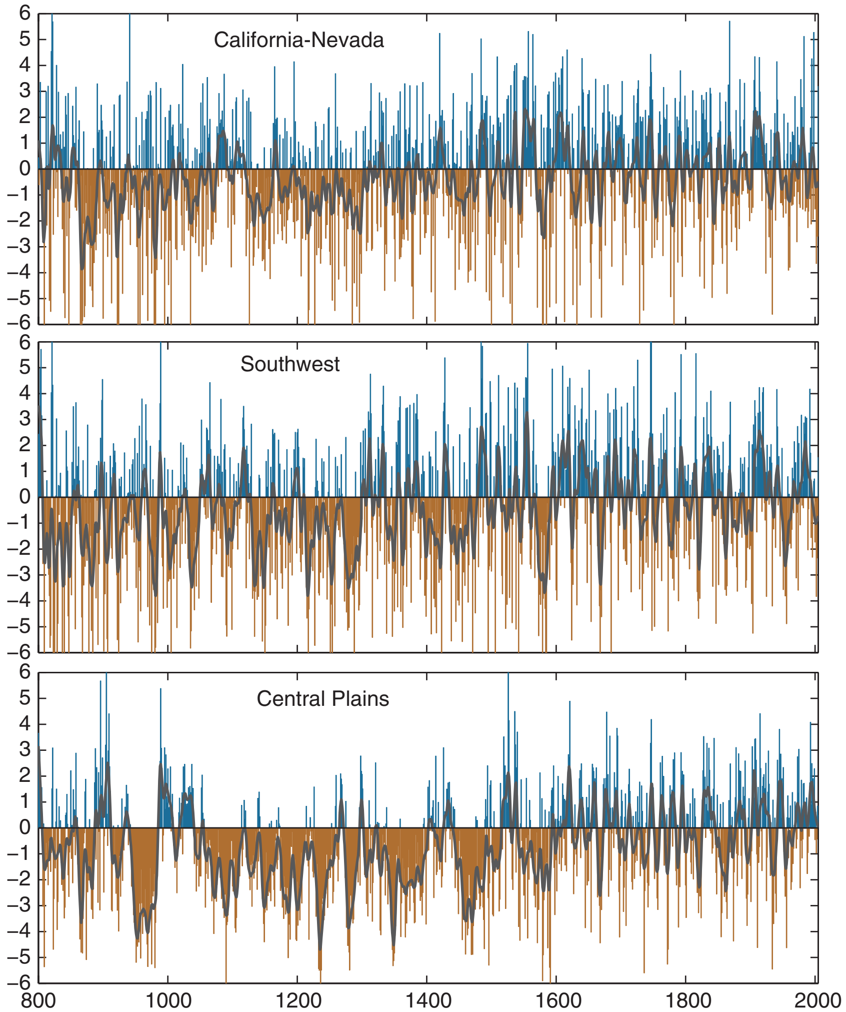

FIGURE 1 | Regional average PDSI time series from the updated version of the North American Drought Atlas: California–Nevada (32°N–41°N, 126°W–114°W), the Southwest (28°N–38°N, 114°W–103°W), and the Central Plains (33°N–45°N, 103°W–90°W). Gray line is a smoothed version of the PDSI time series, using a 10-year loess smooth.

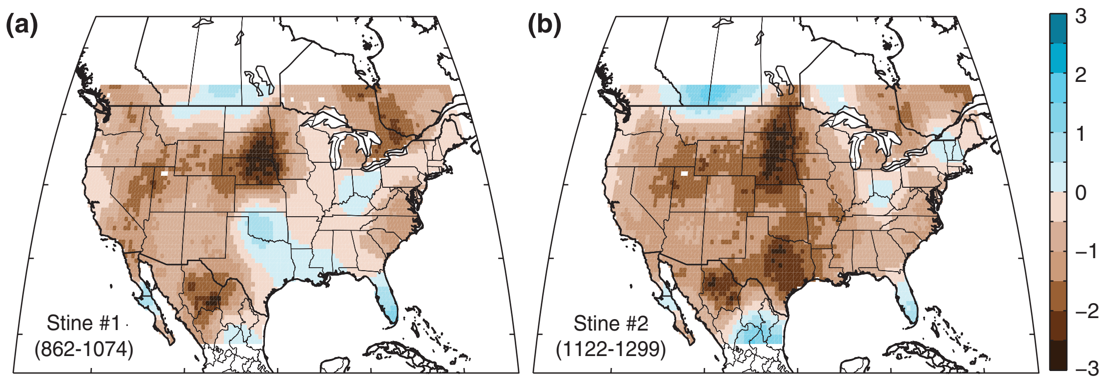

FIGURE 2 | Multiyear average PDSI from the updated drought atlas for the first (a) and second (b) of the centennial scale Stine megadroughts.

the updated NADA. In the late 900s (Figure 4(a)) much of the Southwest, Northern Mexico, and the Central Plains experienced intense drought conditions over a 20-year period. This drought is recorded in the onset of aeolian activity in the western portion of the Plains[57,58] and in lake sediment and alluvial records from Kansas to North Dakota.[6,59] As with the Stine droughts (Figure 2), however, tree-ring proxies are absent over the Central Plains for this period, giving less confidence in the interpretations of this event in the NADA for this region. Another major drought struck in the 1400s (Figure 4(b)), coinciding with extended low flows in the Colorado River.[27] The megadrought epoch ended with one of the most spatially extensive megadroughts in the late 16th century (Figure 4(c)), an event that afflicted nearly the entire West.[22,60]

Tree rings are possibly the best evidence for megadroughts during the Common Era, providing annually dated and spatially resolved reconstructions

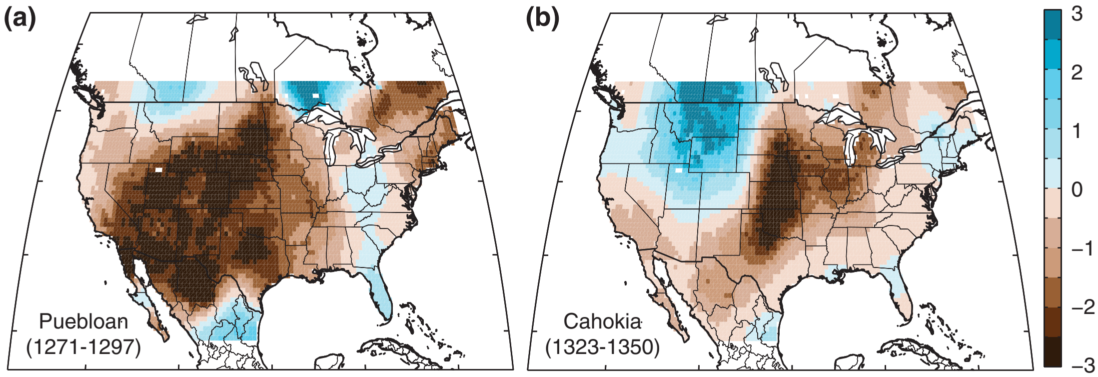

FIGURE 3 | As Figure 2, but for the periods coinciding with the abandonment of the Ancestral Puebloan (a) and Cahokia (b) Native American settlements.

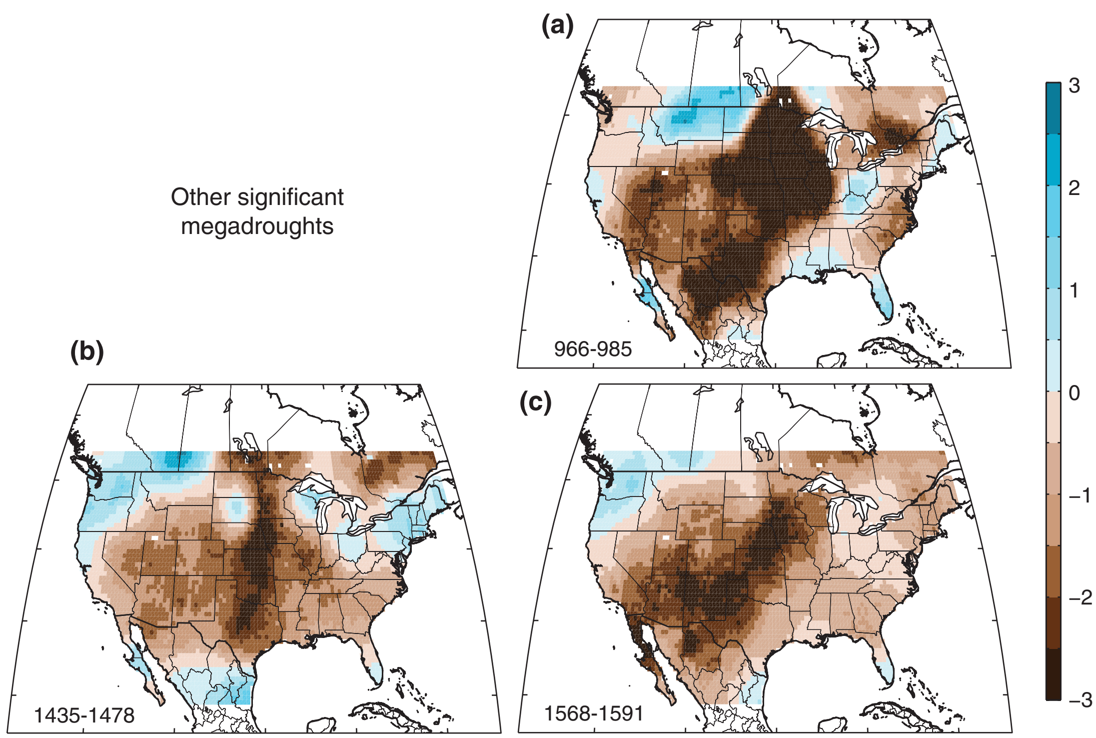

FIGURE 4 | As Figure 2, but highlighting other major megadrought periods.

that are critical for investigating the underlying dynamics.[50] There are major uncertainties, however, that may affect the interpretation of megadroughts in tree-ring-based reconstructions. Most notable is the previously mentioned sharp decline in proxy availability further back in time (Figure 5). This introduces significant sampling biases related to both the number of tree-ring series available at each site and the number of tree-ring chronologies available in each region. This issue is likely most important prior to 1000 CE and in regions like the Central Plains, where proxy density is low for most time intervals but also where some of the worst megadroughts are recorded in the NADA. Aside from the Central Plains examples highlighted previously (the Stine #1 drought in Figure 2; the 966–985 CE drought in Figure 4), another situation where these sampling uncertainties may be large is the Cahokia drought in Figure 3. Locally, the PDSI reconstruction for this event is based on only four tree-ring chronologies from Missouri and Oklahoma, areas peripheral to the most intense reconstructed drought anomalies. Uncertainties in this region in the NADA are thus likely to be much higher than for regions with a greater density of proxies, such as California and the Southwest. The shift in the spatial fingerprint of the Stine droughts compared to previous versions of the NADA[47] further highlights the sensitivity of these reconstructions to updates of the proxy network. The megadrought research community would therefore benefit from efforts to expand the proxy network over the more poorly sampled regions (e.g., the Central Plains) and time intervals (e.g., before 1000 CE). Success in this will depend on the discovery of relatively unaltered stands of old living trees and preserved dead wood, a difficult but not impossible task (e.g., juniper/pine on escarpment woodlands, subfossil oaks[61–63]).

Other biases in tree-ring based reconstructions may arise from the fact that most of the tree-ring proxy series are from current or previously living trees that survived the megadroughts for reasons that may be adaptive (e.g., a genetic predisposition toward drought resistance) or environmental (e.g., a local microclimate or groundwater access that would allow them to survive the drought, local protection from fire). The ultimate effect of this 'survivorship bias' is not well understood. One possible consequence is an underestimation of the true severity of some megadroughts because most trees would have

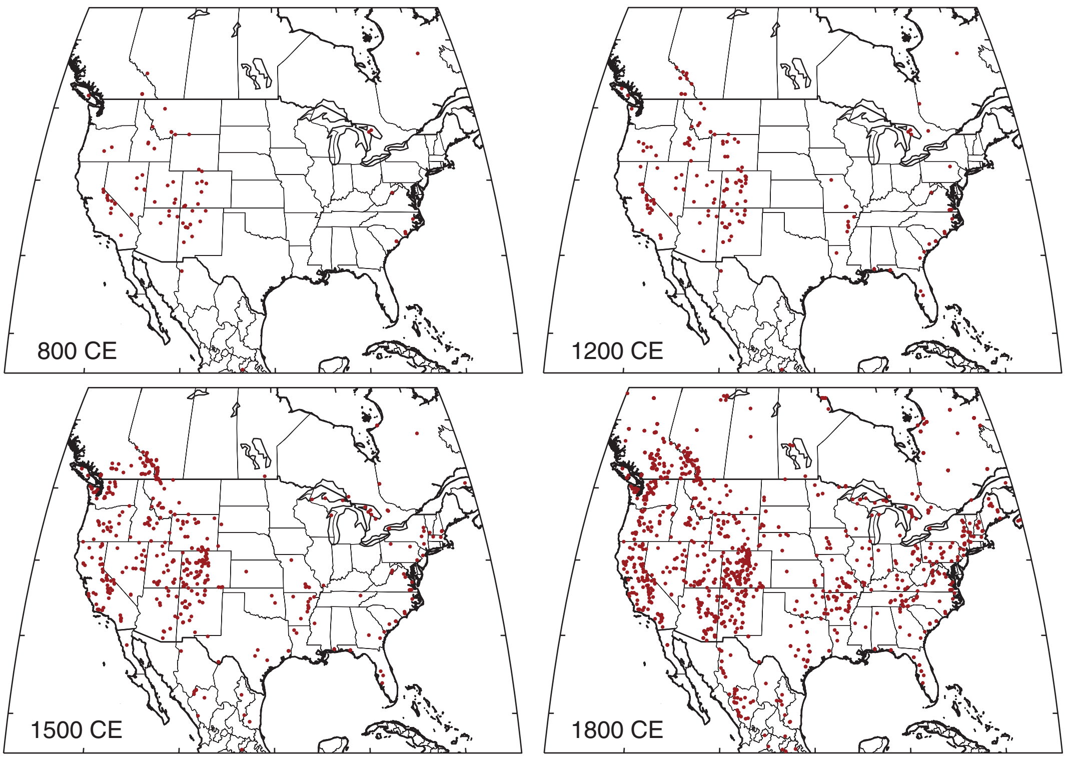

FIGURE 5 | Tree-ring chronology network for various years in the updated version of the North American Drought Atlas. The new network uses 1,936 chronologies.

died during these events, and thus gone unsampled. Alternately, recent work suggests there may be legacy effects in tree rings, where droughts may suppress growth for up to 4 years after a drought event.[64] In such cases, tree rings may overestimate drought persistence and severity, although this effect was found to be relatively modest (5–9% postdrought growth suppression).[64]

Even with these uncertainties, however, there is still significant independent evidence for exceptional aridity during the MCA and following centuries, confirming the story the trees tell. This includes increased wildfire frequency from independent dendrochronological information and charcoal accumulation in California and across the West,[65–67] widespread wildfires in the Rocky Mountains from charcoal in lake records,[68] dune mobilization and increased aeolian sediment deposition in Central Plains lakes,[14,15,69–71] elevated lake salinity in the Northern Plains,[59,72] vegetation banding and aeolian deposition in the Chihuahuan Desert,[73] decreased freshwater flows into San Francisco Bay,[74,75] episodes of river channel incision in the Central Plains,[76] and vegetation reconstructions indicating a greater prevalence of xeric species in Southern California.[77] The biggest uncertainties are thus likely to be in the details (timing, intensity, persistence, etc.), rather than the actual occurrence, of the megadroughts themselves.

Aside from their persistence, another attribute of these megadroughts is their apparent clustering in time during the MCA and the immediate centuries thereafter, leading to speculation that these phenomena may have been caused by anomalous forcing from increased solar activity and reduced volcanism. Enhanced aridity over North America during the MCA was only one regional piece of a global pattern of temperature and moisture departures at the time.[32,78,79] While some forced GCM experiments of the last millennium have simulated enhanced aridity during the MCA over North America,[80] none have been able to fully reproduce the time clustering of megadroughts.[81] Possible explanations for this model-observation divergence are that (1) the prescribed forcings (e.g., volcanic and solar) in the models are incorrect, (2) the model responses to these forcings are incorrect, or (3) the top of the atmosphere forcing during the MCA is simply not a significant contributor to the megadroughts. While top of the atmosphere forcing of the megadroughts remains an open question, recent advances in our understanding of historical era droughts and the availability of new GCM simulations have greatly expanded the opportunities to investigate the direct causes of the megadroughts themselves.

INTERNAL ATMOSPHERIC VARIABILITY

Anomalies in atmospheric circulation can be generated by interactions with the land or ocean surface[82,83] or through stochastic processes internal to the atmosphere.[84] For example, northward shifts of the jet stream, which often cause drought in the Southwest, typically occur during La Niña years,[85] but can also happen independent of any apparent SST forcing.[86] Such internal (unforced) atmospheric circulation anomalies have been implicated as at least partial contributors to several North American droughts, including the Dust Bowl,[33] the 2012 drought in the Central Plains,[2] the exceptional 1934 drought year,[87] and the ongoing drought in California.[88] This has led to some speculation that the Medieval-era megadroughts may have arisen through internal atmospheric variability, rather than being forced by exogenous processes, such as changes in top of the atmosphere forcing or persistent SST states.[81,86,89,90] In this section, we will specifically review the role of internal atmospheric variability unrelated to variations in SSTs. The contribution of coupled ocean–atmosphere variability to the megadroughts, either generated internally or forced from radiative changes at the top of the atmosphere, will be addressed in the next section.

Because extremes like droughts and megadroughts are rare by definition, analyses of multicentury GCM simulations can provide insight into the importance and ubiquity of different processes by allowing for sampling from a larger set of events than is typically available from the instrumental or even paleoclimate record. In a 10,000-year control run of the CSIRO Mark 2 coupled ocean–atmosphere model, multiple instances of model generated droughts and megadroughts were found over the Southwest,[89] Central Plains,[91] and Central America.[92,93] These droughts occurred frequently without any apparent connection to SST states in the Pacific and Atlantic that are typically associated with drought in these regions (see *SST Variability* section). Coats et al.[86] analyzed simulated megadrought occurrence for the Southwest region in forced (time-varying last millennium forcings) and unforced (fixed preindustrial control) simulations of the coupled ocean–atmosphere model ECHO-G. They found no difference in megadrought characteristics (duration, frequency, and intensity) between the two simulations and little coherency between the occurrence of megadroughts and different modes of ocean forcing, such as the El Niño Southern Oscillation (ENSO). In a follow-up analysis, Coats et al.[81] found similar results from additional models in the CMIP5 last millennium and preindustrial control simulations. They noted that, of all the models analyzed, only CCSM4 had a consistent association between modeled megadroughts and persistent ocean forcing in the form of cool conditions in the eastern tropical Pacific. The model experiments of Stevenson et al.[90] took a different approach, comparing simulated megadroughts in an atmosphere-only model simulation with fixed (prescribed) SST boundary conditions against results from a simulation using a coupled dynamic ocean model. They found no difference in frequency or intensity of megadroughts (defined as droughts lasting 15 years or longer) between the two simulations. From this, the authors concluded that internal atmospheric variability and the land surface were the dominant drivers of the model generated megadroughts, with ocean forcing acting in a secondary role.

The clear implication from these studies is that internally generated atmospheric variability, acting independent of the ocean and land surface, is capable of generating megadroughts similar to those observed in the paleoclimate record. However, even if atmospheric variability is capable of generating megadroughts, this does not necessarily mean it is the most likely mechanism to explain the actual events that occurred during the MCA. For example, all the aforementioned GCM experiments included an interactive land surface, even in the case of the atmosphere-only experiments of Stevenson et al.[90] Persistence in the model generated megadroughts thus may have come from land surface interactions which can impart considerable memory to the atmosphere and climate system.[94] In the case of studies with a coupled ocean,[81,86,89,91–93] it is also possible that the ocean may have still been playing a role in the models, just not via the standard mechanisms (e.g., ENSO) considered important for North American drought variability. The atmospheric variability hypothesis may also be dependent on the realism of model ocean–atmosphere teleconnections, where weak teleconnections or variability in important oscillatory modes (e.g., ENSO) may allow unrealistically strong persistence of atmospheric variability. This deficiency was noted in the ECHO-G analyses of Coats et al.,[86] where unrealistically weak (relative to observations) teleconnections between ENSO and the Southwest in the model allowed internally generated storm track shifts to persist for decades.

As mentioned previously, the enhanced megadrought activity over Western North America occurred during the MCA, a multicentennial interval of significant regional temperature and moisture anomalies across the world.[32,50,79] Stochastic atmospheric processes alone, however, are unlikely to create such a coherent, hemispheric-scale pattern of climate anomalies spanning the tropics and extratropics. This does not necessarily preclude a role for internal atmospheric variations in generating the regional North American megadroughts, but it strongly suggests that other processes capable of organizing climate across broader geographic areas were active at the time, such as ENSO or solar and volcanic forcing. We also note that no simulations to date have explicitly addressed the question of internal atmospheric variability and the most persistent of megadrought events, such as the centennial-scale events documented in Stine,[5] or the longer multidecadal droughts in the Southwest and Central Plains. Given the short memory inherent to the atmosphere, it appears unlikely that internal atmospheric variations alone would have been capable of sustaining such extreme events.

SST VARIABILITY

On interannual to decadal timescales, drought in Western North America is primarily modulated by modes of SST variability in the Pacific and Atlantic,[36,95] with ENSO being the most well understood. During cold-phase (La Niña) ENSO events, storm tracks over North America during the boreal winter and spring are shifted poleward[83,96] and winter and spring precipitation is suppressed across the Southwest and Southern Plains. Cold eastern tropical Pacific SSTs and La Niña conditions have been connected, at least in part, to many historical droughts, including the Dust Bowl,[97] the 1950s drought,[36,98] and the turn of the 21st century drought.[35,99] Less well understood, but still implicated as important drivers of decadal to multidecadal North American drought variability,[100,101] are the Pacific Decadal Oscillation (or related Pacific Decadal Variability) (PDO[102,103]) and the Atlantic Multidecadal Oscillation (AMO[104,105]). During winter and spring, negative phases of the PDO suppress precipitation across the Southwest and Southern Plains.[51,100,101,106,107] Importantly, while the PDO has been generally defined by its' extratropical SST anomaly pattern,[102,103] prevailing evidence indicates it is the tropical SSTs that force shifts in atmospheric circulation during different phases of the PDO.[108,109] The role of the AMO and Atlantic SSTs differs from ENSO and the PDO in that the teleconnections are primarily during the warm season. Positive values of the AMO (indicative of warm Atlantic SSTs) thus contribute primarily to drought in regions with warm season peaks in precipitation (e.g., the Central Plains[37]), but can also cause widespread drying across North America.[51,100,101,104,110]

There is broad, if somewhat fragmentary, evidence for persistently cool eastern tropical Pacific[41,111–114] and warm Atlantic[41,115–118] SSTs during the MCA that would have been conducive to megadroughts. Whether such SST anomalies during the MCA were forced by solar and volcanic radiative anomalies[119,120] or arose from internal variations of the ocean–atmosphere system is still unresolved. Some recent studies have even cast doubt on the idea that centennially averaged SSTs during the MCA were even anomalous.[121–123] Regardless, the potential for persistent SST states during the MCA offers a compelling hypothesis to potentially explain megadrought activity during this interval.

Meehl and Hu[124] investigated SST forcing of megadroughts in the Southwest using a 1360-year-long control run of a coupled ocean–atmosphere model. They found that model-generated megadroughts in the Great Basin region of Western North America were associated with multidecadal periods of anomalously cool SSTs in the eastern equatorial Pacific. Intriguingly, they found that these SST anomalies were physically distinct from ENSO variability in the model, and instead related to negative phases of the Interdecadal Pacific Oscillation, similar to the PDO, that suppressed precipitation in the midlatitudes. In this study, however, megadroughts were defined according to their precipitation deficits, and no specific comparisons were made with the paleoclimate record.

The SST-megadrought forcing hypothesis was picked up again in Seagar et al.[46] using an SST-forced (1320–1462 CE) 16-member ensemble of the CCM3 model.[125] In these experiments, SSTs were prescribed using coral proxy reconstructed SSTs over the tropical Pacific[111]; elsewhere, the atmosphere was coupled to a mixed layer ocean. The model was able to reproduce two periods (1350–1400 CE and 1430–1460 CE) of extended drought (defined as anomalously low model soil moisture) across the West. The drought patterns produced were similar to the NADA and other proxy records and consistent with the expected response to the prescribed cold eastern tropical Pacific SSTs from the coral reconstruction. There were, however, some substantial differences between reconstructed and model simulated droughts, possibly from errors in the tropical Pacific SSTs (estimated from a single coral proxy series) and potentially underrepresented impacts from Atlantic SST variability. Cook et al.[126] used the same global SST fields from these CCM3 experiments in a five-member ensemble of the GISS GCM,[127] focusing on the Central Plains megadroughts. In these experiments, the authors concluded that while the reconstructed SST anomalies could produce some drying over the Central Plains, it was insufficient to fully reproduce the magnitude and persistence of the Central Plains megadroughts as recorded in the NADA.

Feng et al.[44] conducted prescribed SST experiments to investigate the influence of both tropical Pacific and Atlantic basin SST anomalies on megadroughts during the MCA. They defined their megadrought period as 800–1300 CE, developing independent proxy reconstructed average SST anomalies for the tropical Pacific and Atlantic for these centuries. They found that, relative to a control simulation, the cool tropical Pacific and warm Atlantic conditions prescribed in the model were sufficient to suppress moisture transport into the Plains, reducing precipitation during the spring by 15–40%. They were also able to separately estimate the influence of the two ocean basins, and found that combined forcing from both basins explained most of the drought features. These simulations were, however, highly idealized: the prescribed SSTs did not vary from year to year and only 14 years of model output were analyzed (after a 1-year spin up). Additionally, comparisons by Feng et al.[44] between model output and the paleo record (i.e., the NADA) were only qualitative; the authors concentrated their analysis on precipitation and temperature anomalies in the model, rather than PDSI or soil moisture.

Investigations of SST-megadrought forcing have also used the past millennium and preindustrial control simulations from the CMIP5 archive, experiments in which the atmosphere is coupled to a freely evolving dynamic ocean model. The simulated SST history in the forced runs of the past millennium shows little consistency across the multimodel ensemble, and most models do not produce anomalously cool eastern tropical Pacific and warm Atlantic SSTs during the MCA.[128] Nonetheless, the models can be analyzed to determine to what extent the megadroughts that do occur (regardless of timing) are associated with persistent SST anomalies. The most comprehensive analysis of megadroughts and SST forcing in the CMIP5 archive to date was conducted by Coats et al.,[81] who found that only one model (CCSM4) had consistent associations between Southwest megadrought periods and cool (La Niña-like) tropical Pacific SSTs. They speculated that this was due, at least in part, to the relatively strong and stationary teleconnections between North America and the tropical Pacific in CCSM4 (much more stationary than in other CMIP5 models[129]) and the relatively large amplitude of variability in the tropical Pacific simulated by the CCSM4 model. Little consistency, however, was found between megadroughts and SST variability in other basins, including the Atlantic. Dynamics in these basins, and their impact on North American hydroclimate, are more poorly understood, especially in the models,[130] and only CCSM4 simulated warmer Atlantic SSTs during the MCA.[80] Landrum et al.[80] demonstrated that this Atlantic warming did enhance aridity over North America in the model, although they did not explicitly compare their model results with specific megadroughts in the paleoclimate record.

Ultimately, there is good evidence from models that persistent SST anomalies in the Pacific and Atlantic basins are capable of driving multidecadal megadrought periods in North America. Major uncertainties remain, however, regarding whether such persistent SST states actually existed during the MCA, and if they were forced from top of the atmosphere radiative anomalies or alternatively arose from unforced variability in the ocean–atmosphere system. Substantive progress regarding the SST-megadrought hypotheses will thus only occur once the SST state during the MCA is better constrained independently from the drought reconstructions and when the spatial pattern and intensity of reconstructed moisture conditions over North America are improved with additional tree-ring chronologies.

LAND SURFACE FEEDBACKS

Recent studies indicate that much of North America is a 'hotspot' for land-atmosphere coupling[131,132] a region where the state of the land surface (e.g., soil moisture, vegetation, etc.) has a strong influence on the overlying atmosphere. This close coupling allows for the development of potentially strong positive feedbacks that can amplify existing moisture and heat anomalies. Indeed, such processes have been implicated in historical droughts like the Dust Bowl[38,98] and 1988 drought,[133] and because of the substantial memory embedded in the land surface (via the slow evolution of soil moisture and temperatures[134]), this provides another set of hypotheses to test for the exceptional persistence of the MCA megadroughts.

Dry soils can limit evapotranspiration and latent heating, reducing moist static energy in the boundary layer and total moisture availability (i.e., precipitation recycling), suppressing precipitation[132] and extending moisture deficits. Reductions in vegetation cover can similarly reduce evaporative fluxes and precipitation[135,136] because roots are able to access deeper pools of soil moisture (normally disconnected from the atmosphere) and leaves increase the effective evaporative surface area. Over the Southwest, which is dependent on winter precipitation and summer (monsoonal) moisture, such positive feedbacks have been demonstrated for antecedent soil moisture[137–139] and vegetation conditions,[140] indicating a tendency for persistent dry (or wet) moisture anomalies from winter to summer. Other studies, however, have noted a negative feedback between above average snowpack and a weaker summer monsoon in the Southwest in models[141] and precipitation observations over the latter half of the 20th century.[142] This mechanism would instead favor out-of-phase cold and warm season precipitation and soil moisture anomalies in the Southwest. The observed seasonal anti-phasing in recent decades, however, is not a robust feature of the regional climate over the last 500 years,[143,144] and there is little evidence in models[143] or proxy reconstructions[144] for persistent dual season drought. The importance of land surface feedbacks for drought in the Southwest thus remains an open question.

While clear evidence for a land-surface feedback has been elusive in the Southwest, it appears to have played a more prominent role in influencing megadroughts in the Central Plains. In addition to being a region where direct soil moisture feedbacks have been important in historical drought events,[98] the Central Plains is also notable for the dynamic nature of its vegetation cover and landscape. This was demonstrated most clearly during the Dust Bowl drought, when widespread replacement of the native vegetation with annual (drought-vulnerable) crops and poor farming practices caused widespread crop failure and near unprecedented levels of wind erosion and dust storm activity.[145] This loss of vegetation reduced evapotranspiration from the land surface, shifting the surface energy balance to favor sensible heating and causing an increase in surface soil and air temperatures. Additionally, the increased dust aerosol loading in the atmosphere reduced surface net radiation and energy availability for convection, further suppressing precipitation during this drought.[38] Because similar changes to the landscape occurred during the MCA megadroughts,[12,14,15] there has been speculation that similar feedbacks may have contributed to these exceptionally persistent events. This was investigated in Cook et al.[126] in a series of GCM experiments where they prescribed paleoclimate estimates of SST forcing, loss of vegetation during the megadroughts, and dust aerosol sources over the Central Plains. They found that the addition of a dust aerosol source reduced surface energy availability, increasing stability in the boundary layer and suppressing warm season precipitation. Importantly, this reduction in precipitation enabled the model to reproduce the persistence of the megadroughts, something the experiments forced by SSTs alone were unable to do. There is thus clearly a role for land-atmosphere interactions and feedbacks in the Central Plains to have contributed to the exceptional character of the megadroughts. As with the other discussed hypotheses, however, there remain substantial uncertainties regarding the magnitude of the land surface changes during the megadroughts, as well as how generalizable these feedbacks will be across regions (including some where land-atmosphere coupling is weaker) and for some of the more exceptional events (e.g., the centennial Stine droughts).

MEGADROUGHTS AND CLIMATE CHANGE

The occurrence of megadroughts in the paleo record, extreme events far outside the realm of contemporary human experience, has motivated interest in the likelihood or risk of these events occurring in the future.[47] These concerns have been further amplified by a variety of recent studies suggesting that much of the West will likely get drier in the coming decades with anthropogenic climate change.[60,146–150] This projected drying arises as a function of anthropogenically forced reductions in surface moisture supply and increased atmospheric demand. On the supply side, there is good agreement across models that much of the Southwest and Southern Plains will see reductions in cool season precipitation,[146,149,150] part of a robust pattern of subtropical drying expected under increased greenhouse gas forcing.[151–153] Additionally, projected warming induced increases in the vapor pressure deficit are expected to increase evaporative demand and potential evapotranspiration (PET) in all regions.[154,155] These increases in PET are more widespread and robust across models than the precipitation responses, and are expected to intensify surface drying trends in areas where precipitation is projected to decline or remain neutral and even cause surface drying in some areas where precipitation will increase.[154] Indeed, there is some evidence that trends in temperature and PET may already be amplifying ongoing droughts in the West,[1,156,157] even as evidence for the emergence of anthropogenically forced changes in precipitation is ambiguous, at best.[35,88,158,159]

Studies have only recently begun to explicitly compare drought trends in 21st century projections to the full range of natural drought variability over the last millennium. In their analysis of the CMIP5 ensemble, Schwalm et al.[160] concluded that conditions during the 2000–2004 drought in Western North America will likely represent the 'new normal' by the end of the twenty-first century, matching the severity of the worst drought conditions of the last 1200 years. In their analysis, however, the authors only accounted for precipitation declines in the twenty-first century projections, ignoring warming induced increases in PET and likely underestimating future drying. They also averaged data over an exceptionally large region (25°–50°N, 100°–125°W), obfuscating important regional variability, like the the most intense drying in the Southwest. In an analysis of 27 GCMs in the CMIP5 database, Ault et al.[161] concluded that models are likely to underestimate the risk of persistent, multidecadal megadroughts in the Southwest. They attributed this to the fact that the models do not accurately capture the low frequency variability of precipitation reflected in observations and the paleoclimate record.[162] By adjusting the model frequency biases to be more consistent with observed variability, Ault et al.[163] concluded that there is a 10–50% likelihood of a 35-year or longer megadrought in the Southwest occurring in the next century under the business-as-usual RCP 8.5 emissions scenario. As with Schwalm et al.,[160] however, this work only considered projected changes in precipitation, ignoring any additional contributions to drying from warming.

Other studies have more directly analyzed the role of temperature in future drought dynamics and megadrought risk. Williams et al.[60] developed a Forest Drought Stress Index (FDSI) using precipitation and vapor pressure deficit. The authors reconstructed FDSI for the last millennium from tree rings and projected this index into the future using the CMIP5 ensemble. They concluded that by the 2050s, average drought stress in the Southwest will exceed even the worst megadroughts of the last millennium, caused primarily by warming induced increases in vapor pressure deficit and PET. Cook et al.[147] analyzed projected trends (RCP 8.5 scenario) in surface moisture availability in the Southwest and Central Plains using model calculated PDSI and model soil moisture near the surface (surface to 30 cm) and deeper in the soil profile (surface to 2–3 m). Their analysis indicated a much higher likelihood (>80%) of a megadrought occurring in these two regions during 2050–2099 than previous studies that considered only changes in precipitation.[163] Furthermore, the authors found that for most models and soil moisture indices, soil moisture conditions in 2050–2099 will likely be drier in these regions than even the most arid, megadrought-prone centuries of the MCA (1100–1300 CE).

There is thus a clear consensus in the projections for a large and significant shift toward drier conditions in the West under increased greenhouse gas warming. There remain substantial uncertainties, however, that need to be resolved in order to increase confidence in these projections. Notably, the land surface models within climate models, which are critical for evaluating terrestrial hydrological responses to climate change (e.g., soil moisture, runoff, etc.), are often highly parameterized, with significant variations in complexity and construction across modeling groups. This includes differences in soil column depths (e.g., <3 m in CanESM2 and >10 m in CCSM4), the number of soil layers simulated (e.g., 3 in CanESM2 and >20 in INMCM4.0), and even the level of sophistication in the treatment of vegetation growth and dynamics (e.g., fully dynamic vegetation in CCSM4 and fixed seasonal cycle in GISS-E2). These differences can be large enough that it becomes difficult to directly and meaningfully compare results across models, even when the simulations use the same set of forcings. To address this issue, many studies use output from the atmospheric model portion of the GCMs to calculate standardized drought indices[154,164,165] or drive offline hydrologic and land surface models.[166,167] Encouragingly, drought variability reflected in simplified standardized drought indices (such as PDSI) often correlates quite well with available soil moisture measurements[168,169] and more sophisticated model simulations, both offline[157,170] and in coupled GCMs.[147,154,171] Even within models, however, future trends may differ depending on the moisture balance metrics chosen. For example, in Cook et al.[147] the authors demonstrate that near surface and deeper soil moisture trends over the 21st century diverge over the Southwest in CanESM2 and over the Central Plains in ACCESS1.0. This may be due to the different seasons these moisture reservoirs integrate over (i.e., memory is longer in the deeper soil moisture pool) or other reasons, but it clearly highlights potential issues that may arise when trying to understand model drought trends.

Beyond the structural model issues, there are also process-based uncertainties that need to be better constrained. In most GCM projections, the drying signal over land is dominated by temperature-induced increases in evaporative demand acting to amplify evaporative water losses from the soil and surface. Because most terrestrial evapotranspiration occurs through plants via the process of transpiration (up to 80–90%[172]), however, one mechanism that may ameliorate warming induced evaporative water losses is the plant physiological response to increased atmospheric carbon dioxide concentrations ([CO_2]). Carbon and water exchange occurs at the leaf surface through stomata, pores that allow carbon dioxide to diffuse into the leaf during photosynthesis. While carbon dioxide diffuses in, water is lost from the plant to the atmosphere through the same openings. At higher [CO_2], however, the diffusion rate of carbon dioxide increases and plants can begin closing their stomata, reducing conductance and water loss while still maintaining relatively high levels of photosynthesis,[173] thus increasing their water use efficiency (i.e., the ratio of carbon gain to water loss). It is therefore conceivable that drought projections in greenhouse gas forced climate change scenarios may not adequately account for this process, leading to an overestimation of future drought trends.[174]

Models that include this effect in their land surface and vegetation models generally do see globally reduced rates of evapotranspiration at higher [CO_2], even at higher temperatures.[175–178] This effect is in fact becoming an increasingly standard process for inclusion in most GCMs, including many of those that participated in the CMIP5 intercomparison.[179,180] While the physiological effect of higher [CO_2] levels is quite well understood at the leaf level,[181] there are still large uncertainties regarding how this effect scales to individual plants, ecosystems, and the biosphere. One recent study[182] compared transpiration responses in two multiyear Free-Air CO_2 Enrichment (FACE) experiments at Oak Ridge National Laboratory and Duke Forest against simulations from 11 ecosystem and land surface models. In the experiments, where large stands of vegetation were exposed to elevated [CO_2] for multiple years, total transpiration declined at Oak Ridge but not at Duke Forest. In model simulations for the same sites, the authors found large differences across models and large declines in model simulated transpiration at Duke Forest, contrary to the FACE results. The authors attributed the disagreements across models, and between the models and FACE experiments, to differing model implementations of (1) coupling between photosynthesis and stomatal conductance at elevated [CO_2], (2) boundary layer treatment and canopy-atmosphere coupling,

(3) canopy interception and reevaporation of water, and (4) plant responses to soil moisture stress. Differences in the transpiration response are apparent across other CO_2 enrichment experiments as well, with many studies showing only modest, and often insignificant, changes in transpiration and soil moisture.[183–187] Observations of natural ecosystems find similar mixed results. Using nearly 30 years of remotely sensed vegetation data, Donohue et al.[188] concluded that [CO_2] fertilization effects contributed to an 11% increase in foliar coverage in warm, arid regions, attributing this to an increase in water use efficiency. This analysis did not, however, include an investigation of changes in total transpiration. More recently, in an analysis of carbon isotopes in tree rings across European forest sites, Frank et al.[189] found an overall increase in water use efficiency with [CO_2]. Despite this reduction in stomatal opening, however, they calculated a 5% increase in total forest transpiration, which they attributed to increased evaporative demand from atmospheric warming, increased leaf area, and lengthened growing seasons.

It is therefore clear that the role of elevated [CO_2] in future drought and soil moisture trends is highly uncertain. The Working Group II report of the IPCC ultimately concluded that the effect of elevated [CO_2] on runoff and transpiration is poorly constrained, and that temperature and precipitation are likely to remain the primary drivers of transpiration and soil moisture variability in the future.[190] This conclusion is generally supported by analyses of soil moisture trends in the CMIP5 models, which mostly incorporate at least some effect of elevated [CO_2] on model transpiration. For example, over the Southwest and Central Plains, Cook et al.[147] documented close year-to-year correlations and general agreement on future drying trends between model soil moisture in the CMIP5 ensemble and PDSI calculated from the same models, which has no elevated [CO_2] effect. Furthermore, it is likely that [CO_2] is more important as a limiting factor to vegetation at lower ambient levels than the modern era,[191] such as occurred during the transition into our current interglacial.

A final source of uncertainty in the future, especially at the regional level and on shorter (e.g., decadal) timescales, is internal climate variability that may act to enhance or diminish greenhouse gas forced trends.[192,193] A contemporary example is the recent decadal slowdown (or 'hiatus') in global surface temperature trends, a phenomenon attributed at least partially to natural variations in the Pacific[194] and connected to the ongoing drought in the Southwest.[35] Similar modes of natural variability are known to influence hydroclimate over North America, operating from interannual (e.g., ENSO) to multidecadal (e.g., AMO) timescales, and these modes will continue modulating North American drought dynamics in the future.[195,196] Although anthropogenically forced trends will eventually emerge above the variability embodied in these modes, on shorter timescales the natural variability will likely dominate. Combined with extant uncertainties regarding the roles played by these modes during past megadroughts, this highlights another major outstanding question regarding megadrought risk in the future, especially over the next several decades.

CONCLUSIONS

Droughts represent some of the most disruptive natural disasters in North America, and the impacts of historical[145,197] and more recent[2,198] events have been well documented. Given the often dramatic consequences of even single-year drought events,[2,87] and the ubiquity of multidecadal megadroughts in the paleoclimate record, it is perhaps fortuitous that North America has not experienced a megadrought in the last several hundred years. With emerging[1,156,157] and projected[146–150] trends toward increased desiccation across much of North America, improving our understanding of the causes of megadroughts is imperative in order to better understand the likelihood of their recurrence and impact in the future.

Various hypotheses for the causal mechanisms underlying megadroughts have been offered. While none have been definitively rejected, certain explanations are more plausible than others. The intrinsic memory timescale in the atmosphere (on the order of months), for example, is likely too short to allow internal atmospheric variability to act as the consistently dominant driver of multidecadal megadroughts, which have occurred repeatedly over the last millennium. To date, no study has completely isolated atmospheric variability, relying on models in which (1) the atmosphere is still coupled to sources of memory in the oceans or land surface[89,90] or (2) notable deficiencies exist in their ocean–atmosphere teleconnections over the megadrought regions.[86] Similarly, despite new ensembles of forced simulations over the last millennium, models still cannot produce the correct timing of the Medieval era megadroughts.[81,86] This makes it difficult to determine whether the apparent time clustering of events during and immediately after the MCA represents a real response to solar and volcanic forcing, or is simply coincidental. The alternative, that the ocean and land surface played pivotal roles, is supported by modeling evidence and the critical importance of these drivers for explaining persistent droughts during the historical era.

Understanding the risk of a megadrought event occurring in the current century will require an improved understanding of (1) natural drivers of megadroughts and (2) how these events will be superimposed on long-term anthropogenically forced hydroclimate trends. To point (1), we need new hypotheses to explain some of the truly exceptional events (e.g., the centennial-scale droughts first described by Stine), as well as improved constraints on the hypothesized mechanisms. We still lack credible high-resolution (annual to decadal) reconstructions of SST variability during the MCA, especially from the Pacific and Atlantic basins, or robust reconstructions of low-frequency climate modes relevant for drought, such as the PDO and AMO. For example, different reconstructions of the PDO generally show very little agreement or coherence prior to the 20th century, likely due to both variations in the PDO-related SST anomalies and nonstationary teleconnections between PDO SST anomalies and locations of the terrestrial proxies.[199] Improved reconstructions of these modes could provide better information on the important drought forcings during the MCA, and allow for better explicit testing of various megadrought hypotheses. To point (2), there remain appreciable uncertainties in the modeling of land surface and vegetation processes, as described earlier. These need to be resolved in order to increase confidence in the robust and severe drying trends projected under increased greenhouse gas forcing.

The paleoclimatic evidence for past megadroughts also needs to be carefully scrutinized and, where possible, improved. This can certainly be accomplished with expanded collections of living trees and dead wood, even from escarpment woodlands in the Great Plains, a region that appears to be especially prone to severe sustained megadrought but for which few tree-ring chronologies are available. Alternate hypotheses for some of the more extraordinary proxy evidence for past megadroughts also need to be tested. One recent study, for example, demonstrated that low frequency (decadal to centennial) variability in closed lake basins can be generated by interannual variability in climate.[200] The implication being that the interpretation of persistence in such proxy records needs to be viewed with a critical eye, as it may simply represent an artificial reddening of high-frequency climate variability. This is potentially relevant for discussions of the centennial Stine megadroughts, and whether inferences from the surface hydrology responses (i.e., low flow levels allowing establishment and survival of trees in the stream bed) accurately reflect climate variability at the time.

More generally, it may be worthwhile expanding the corpus of variables across which we define mega-droughts in the paleoclimate record and model simulations. Do these droughts manifest in similar ways (e.g., intensity and persistence) across the hydrologic cycle (precipitation, soil moisture, runoff, streamflow, etc.)? Or is our understanding biased by the previous focus on indicators responding to specific reservoirs such as soil moisture? Expanding this scope would be especially useful for relating megadrought events to variables that may be more relevant to water managers and stakeholders, such as winter snowpack or streamflow. Even with the need for improved understanding of uncertainties and detail, however, the current prognosis for water in the West is that of a steadily shifting baseline toward drier conditions as we move into a warmer future. It is therefore essential to better understand the potential for natural multidecadal and longer hydroclimate variability to return in the future, and what those events may look like superimposed on a drier (anthropogenically forced) mean state.

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