

Megadroughts in the Common Era and the Anthropocene

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Abstract

Megadroughts, often lasting multiple decades, have caused major ecological and societal disturbances in the past. While most research has focused on megadroughts in North America, the concept has gained increased international attention in recent years. In this Review, we discuss shared causes and features of Common Era and future megadroughts. Paleoclimate reconstructions spanning the last 2,000 years document the occurrence of megadroughts on every continent, save Antarctica. Megadroughts are often linked to decadal variations in sea surface temperatures, with radiative forcing and land-atmosphere interactions acting as secondary factors. Anthropogenic climate change has already contributed to recent megadroughts in southwestern North America and Chile-Argentina and will likely increase future megadrought risk and severity in many regions. Notably, future megadroughts will be differentiated from past events through higher temperatures, which act as the main driver of increased risk, severity, and impacts. Major deficiencies in our understanding of natural and anthropogenic megadrought processes remain, however. These include 1) sparse high-resolution paleoclimate information over some regions, 2) incomplete representations of internal variability and land-surface processes in climate models, and 3) the undetermined capacity of water-resource management systems to manage megadrought impacts. Resolving these key uncertainties will be necessary to increase confidence in projections of future megadrought risk and resiliency planning.

Key points

1. Broadly speaking, *megadroughts* are persistent droughts that exceed the length of typical droughts during the 20th century, the period of climate observations serving as the basis for modern water-resource management and infrastructure.
2. While a more quantitative megadrought definition is challenging to establish, we recommend that the term be reserved for *persistent, multi-year drought events that are exceptional in terms of severity, duration, or spatial extent when compared to other regional droughts during the instrumental period or the Common Era*.
3. Past megadroughts caused major ecological and societal disturbances over the last two millennia, and were forced primarily by persistent ocean states, with possible secondary contributions from internal atmospheric variability, volcanic and solar forcing, and land-atmosphere interactions.
4. The most active megadrought regions in the past (e.g., western North America) are areas where climate change is projected to enhance future drought risk through declines in precipitation, increases in evaporative demand, and changes in plant water use.
5. Future megadroughts would substantially strain many modern water-management systems, though our understanding of the risks of such events, and their ultimate impacts, is still limited by uncertainties in observations and models.

Introduction

While the origin of the term “megadrought” is unknown, the concept itself came to prominence with Common Era (CE; Year 1 to the present) paleoclimate drought research over western North America^{1–6}. These studies documented multi-decadal periods of extreme aridity (*megadroughts*) across western North America before 1600 CE, intervals characterized by large moisture deficits across the hydrologic cycle^{1–5}, widespread ecological disturbances^{6–8}, and disruptions to ancient societies^{9–12}. Recurrent and persistent droughts are an intrinsic feature of North American hydroclimate variability, but these megadroughts were primarily distinguished by their much greater persistence (e.g., multiple decades) compared to even the most extreme decadal-length instrumental-era droughts during the 1930s and 1950s^{13,14}.

Recently, especially persistent or severe drought events in many regions around the globe have been increasingly referred to as megadroughts, despite the absence of any formal or universally accepted definition. These include multi-decadal periods of enhanced aridity in Australia^{15,16}, South America¹⁷, Europe¹⁸, Central Asia^{19,20}, and Mesoamerica²¹; a multi-season drought in 1540 CE over Europe²²; spatially extensive multi-year droughts in India²³; the late Ming Dynasty drought in China^{24,25}; and a recent decadal drought in Chile and Argentina^{26–28}. Furthermore, with anthropogenic warming expected to increase drought severity and risk in many regions of the world^{29,30}, the term has been increasingly applied to droughts with clear climate change contributions, both in recent observations^{26,31} and in model projections^{32,33}.

There is nevertheless little consistency in the application of the megadrought label and there are no currently applicable objective criteria that define when a drought becomes a megadrought or when a period of moisture deficit becomes persistent enough to represent a shift in the mean state, rather than a discrete transient event. Moreover, while there have been several reviews of megadroughts in the literature^{34–36}, these have overwhelmingly focused on North America and predate recent advances in our understanding of natural drought variability and the role of climate change in contemporary and future events. Therefore, it is worth revisiting the megadrought concept from a global perspective and incorporating recent insights into the working understanding of megadrought definitions, causes, and future risk.

This review synthesizes recent advances in our understanding of megadrought dynamics over the past 2,000 years and into the future, leveraging the latest state-of-the-art paleoclimate reconstructions, detection and attribution studies, and climate model simulations. We develop a more formal definition for megadroughts, and demonstrate that regions on all continents outside Antarctica have experienced drought intervals in the past that qualify. We summarize new evidence that strengthens previous hypotheses that many past megadroughts were forced by ocean-atmosphere interactions, and discuss how climate change is likely to increase drought risk and severity in many of the most megadrought-prone regions in the world. Finally, we discuss some of the extant uncertainties that must be better constrained to improve our understanding of past megadroughts and increase our confidence in projections of future megadrought risks and impacts.

Drought Variability and Defining Megadroughts

Common Era Drought Variability

Data on droughts over the last two millennia are available from proxy-based reconstructions, including lake sediments³⁷, corals³⁸, and tree rings³⁹. Tree-ring based “drought atlases” have been especially informative for quantifying spatiotemporal drought variability and specific drought events^{40–46}. These annually resolved, gridded reconstructions of summer season Palmer Drought Severity Index (PDSI; a soil moisture index) cover the last one to two millennia and have been critical for informing our understanding of drought variability and dynamics at large spatial scales^{34,42–50}. At present, these drought atlases cover most of the Northern Hemisphere^{40–44}, South America⁴⁵, and eastern Australia and New Zealand⁴⁶. Here we combine updated and existing versions of these datasets into a pseudo-global drought atlas to investigate the inherent temporal scales of drought variability over the last millennium.

Despite differences in regional climate dynamics, summer soil moisture shows large year-to-year persistence during recent centuries (1400–2000 CE), indicative of a strong tendency for soil moisture anomalies (deficits or surpluses) to carry forward from one year to the next. Positive autocorrelation at a one-year lag is nearly universal, with values over +0.5 for many regions (**Figure 1a**). Positive autocorrelation $>+0.3$ extends into year 2 in some areas (**Figure 1b**), including the classic North American megadrought regions of the Central

Plains, Southwest, and Mexico. A major exception to this global tendency toward strong persistence is the west coast of North America, where autocorrelation is weak or even negative over California. This tendency for year-to-year reversal of soil moisture anomalies in California is likely due to large inter-annual variability and high-frequency, quasi-cyclic variations in cool-season precipitation in the region^{51,52}.

Strong persistence of summer soil-moisture anomalies and droughts is also evident in analyses of the slopes of the power spectra⁵³⁻⁵⁵. Within the filtered periods, positive slopes indicate higher proportional variance at lower frequencies and longer timescales, while negative slopes are indicative of higher proportional variance at higher frequencies. Slopes of the power spectra in the drought atlases filtered for 2-50 year periodicities are positive across most regions covered by the drought atlases (**Figure 1c**). This is consistent with the strongly positive autocorrelation documented previously and suggests that extended periods of persistent wetter or drier soil moisture states are common in much of the world. When the power spectra are filtered to remove sub-decadal timescales (focusing on 10-50 year periodicities), slopes remain positive in many regions, indicating higher power at multi-decadal compared to decadal bands in these areas (**Figure 1d**). This includes regions with some of the longest documented megadroughts in the paleoclimate record, including the Central Plains, Southwest North America, and Central Europe. Consistent with the autocorrelation results, California and the west coast of North America stand out with flat or negative slopes, indicative of variability dominated by higher frequencies.

Defining Megadroughts

These results demonstrate that strong inter-annual persistence in summer soil moisture anomalies is apparent worldwide, while also highlighting the large inter-regional differences in lower frequency (decadal to multi-decadal) variability. These regional differences in drought variability underscore the difficulty in establishing a universal megadrought definition. For example, while a decade-long drought in California would be highly abnormal given the typical high-frequency (inter-annual) variability in the region, such an event would not stand out as exceptional in Mexico and the southwestern United States (US), where decadal variability is larger. This cautionary note extends to analyses of megadroughts in climate model simulations, with the added complication that climate models may have characteristic variability that diverges substantially from the observations.

Any useful definition of megadrought therefore needs to be contextualized relative to the background drought variability of the region being analyzed. However, defining megadroughts is further complicated by the myriad methods used in the literature to determine when an event, whether a normal drought or megadrought, begins and ends^{56,57} (**Box 1**). These include criteria based on consecutive dry or wet years^{58,59}; multi-year to multi-decadal average drought anomalies^{32,33,60,61}; methodologies that combine both perspectives^{62,63}; or joint criteria that incorporate duration and spatial extent⁶⁴. Even once defined, there are often substantial differences from one study to the next regarding which characteristics of these events are analyzed, including duration, magnitude, severity, spatial extent, or even impacts. Methodological choices may therefore strongly affect how megadrought events are defined and discussed, with little consistency across studies, regions, and time periods.

In recognition of the methodological diversity employed by the drought research community and informed by the analyses of drought variability in the previous section, we argue that megadroughts should be defined as *persistent, multi-year drought events that are exceptional in terms of severity, duration, or spatial extent when compared to other regional droughts during the instrumental period or the Common Era*. This definition is flexible enough to recognize that different methodologies may be used to define drought or quantify characteristics of droughts, but also emphasizes that for an event to be considered a megadrought, it must be explicitly compared to other droughts in the available instrumental or paleoclimate records using the same metrics. Such comparisons are critical for establishing the exceptional nature of a megadrought relative to a long-term baseline, ensuring that the term “megadrought” refers to the most extreme events.

Megadroughts Over the Last Two Millennia

Megadroughts have been documented in the paleoclimate record on every continent outside of Antarctica over the last two millennia (**Figure 2**). As noted previously, no formal or quantitative definition of megadrought is typically applied in the literature, but the events that we highlight are all consistent with our definition of megadroughts as being exceptional in terms of severity, duration, or spatial extent when compared to background drought variability.

North America

North America is the most well-studied region in megadrought research, in part because of its rich availability of drought-sensitive paleoclimate archives². This research began with the early 20th-century work of AE Douglass, who pioneered the science of dendrochronology and was the first to describe the 13th-century megadrought (which he referred to as the “Great Drought”) in the southwestern US^{65,66}. More recent research started with a study documenting multi-centennial periods of low runoff and streamflow in California’s Sierra Nevada Mountains from the mid 800s to the mid-1000s and from the early 1100s to the late 1200s⁵. Paleo-drought research in western North America advanced rapidly following this work, with studies documenting multi-decadal megadroughts across nearly every part of western North America^{2,34–36,48} during the Medieval era and the centuries immediately following^{2,34,36} (800-1600 CE). These include especially notable megadroughts across the southwestern US during the 1100s and 1200s³⁶; in the mid-1100s over the Colorado River Basin^{67,68}; and across the southwestern US, Mexico, and Central Plains during the late 16th century^{31,69–72}.

The ecological and societal consequences of these megadroughts are well documented in archaeological, historical, and paleoecological records. The late 1200s megadrought likely contributed to the depopulation of the Mesa Verde cliff dwellings in southwestern North America, which had been built and occupied by the Ancestral Puebloans for more than 100 years^{65,66,73,74}, and possibly the collapse of the Cahokia settlements in the Mississippi River Valley⁷⁵. The late 16th-century megadrought was recorded in English and Spanish colonial records^{69,76} and caused the abandonment of Native American settlements in the southwestern US⁷⁷. Across western North America, the megadroughts caused increased wildfire activity across^{78,79}, mass forest mortality events^{6,7,71}, and desertification that resulted in large-scale increases in dune mobilization and dust storm activity^{80–83}.

Mexico and Central America

Mexico was another major center of megadrought activity, events often coinciding with megadroughts in the Southwest US and Central America. Major multi-decadal megadroughts affected the Toltec (1149-1167 CE) and Aztec (1378-1404 CE) civilizations^{21,44}, the former coinciding with the decline of the Toltec capital at Tula. The Terminal Classic megadrought during the decline of southern Maya polities (see below) also may have extended into Central Mexico for several decades (897-922 CE). Megadroughts also occurred in the region during the Spanish Conquest (1514-1539 CE)²¹, followed by a mid-1500s event in central Mexico that predated the late 16th-century megadrought in the southwestern US and likely contributed to an outbreak of hemorrhagic fever in 1576 that caused ~2 million deaths in Mexico^{10,69}.

The most well-known megadrought in Central America was the event associated with the decline of the southern Maya kingdoms marked by the Terminal Classic Period, ca. 800-1000 CE. While the extent to which this megadrought contributed to the putative ‘collapse’ of the Maya is strongly debated⁸⁴, the paleoclimate record offers strong evidence for a major extended drought event or events at the time. Centered over the Yucatán Peninsula and modern-day Guatemala and Belize, this megadrought is recorded in lake records^{37,85–88}, speleothems⁸⁹, and coastal sediments⁹⁰. Average annual precipitation deficits during the Maya megadrought are estimated to have ranged from 25-40%⁹¹ or even 41-54%⁹² below average, with precipitation during the driest intervals declining by as much as 52-70%^{89,92}.

South America

Patagonia in South America experienced a multi-decadal megadrought coincident with the first major California megadrought of the Common Era⁵. Similarly, seven other distinct Medieval era megadroughts in Central Chile were concurrent in time with megadroughts over Southwestern North America¹⁷. The end of the 15th century was characterized by a decadal drought in Patagonia⁴⁵, and extended periods of enhanced aridity over central Chile and central-western Argentina occurred in the middle of the 16th, 18th, and the beginning of

the 21st centuries⁴⁵. Two decadal and longer megadroughts from 1615–1637 CE and 1684–1696 CE were recorded in the South American Altiplano region, followed by an extreme five-year drought from 1800–1804, referred to as the “Silver Mine” drought⁹³. While relatively short compared to other megadroughts, the Silver Mine drought was one of the driest intervals during the ~200 years of intensive Spanish mining in the region and was especially widespread, extending from the Altiplano in Bolivia and into central Argentina⁴⁵. Since the mid-1970s, hydroclimatic tree-ring reconstructions from the Altiplano recorded the driest conditions of the past 6-7 centuries^{94,95}, an apparent shift towards arid conditions concurrent with the rapid warming and retreat of the tropical Andes glaciers during the late 20th century^{96,97}. Less detailed information on Common Era hydroclimate is available for lowland tropical South America. Extended periods of reduced South American Summer Monsoon precipitation during the Medieval era and over the last century are recorded in a 2300-year lake sediment record from the Central Andes⁹⁸. Multi-centennial tree-ring based precipitation reconstructions⁹⁹ also highlight prolonged drought periods in the mid-19th century and late-18th century in the eastern Amazon.

Africa

In the Mediterranean region of North Africa, tree rings have been successfully employed to reconstruct frequent and severe multidecadal droughts during the 13th and 16th centuries¹⁰⁰. However, high-resolution Common Era paleoclimate records are only sparsely available over Africa outside the Mediterranean, making it challenging to resolve droughts on timescales shorter than several decades or even a century. Most evidence is from lake records, which often have limited precision age models and act as low-pass filters on climate signals, making it difficult to identify the timing and severity of major hydroclimate events. This is especially true before the 18th century, after which information from higher resolution proxies, historical records, and documentary evidence is more widely available.

Despite these issues, lake records do highlight several multi-decadal to centennial-scale periods of enhanced aridity over East Africa during the first millennium of the Common Era that could cautiously be interpreted as megadroughts^{101–103}. These include persistent periods of low flows into Lake Turkana and reduced precipitation over the Ethiopian highlands from 200 BCE to 300 CE¹⁰⁴; reduced rainfall from 0–200 CE at Lake Challa¹⁰⁵; and several multi-decadal droughts at Lake Edward between 400–890 CE¹⁰⁶. The Medieval era was especially dry in East Africa, with significant megadroughts recorded in declining lake levels between 1000–1250 CE^{105,107,108}. While East Africa became substantially wetter in the following centuries, humid west Africa experienced a ca. 300-year megadrought from 1450–1750 CE that was likely the driest in the region during the late Holocene^{109–113}.

Megadroughts affected the Sahel and Guinea Coast in 1765–1780 CE and 1789–1798 CE¹¹⁴, with nearly the entire continent transitioning into a major episode of aridity that lasted from the late 18th century through the first half of the 19th century^{115,116}. These decades were some of the most arid in East Africa of the last millennium, with exceptional declines recorded in lake levels^{105,115,117,118}. This period was followed by another major drought in the 1880s and 1890s over Ethiopia^{115,119,120} that caused a severe famine from 1888–1892¹²¹.

Europe and Asia

Europe experienced several multi-century megadroughts over the last two millennia, including one in Central Europe from the mid-400s to 600 CE^{122,123} and another from 1000–1200 CE⁴² that was centered in Germany and Fennoscandia. The duration and magnitude of the 1000–1200 CE event were similar to the California megadroughts that occurred from the early 800s to the late 1000s^{5,34}. Two other centennial-scale events occurred in Central Europe during the Spörer and Dalton solar minima from 1400–1480 CE and 1770–1840 CE, respectively¹⁸. Within these periods, especially intense multi-decadal droughts⁴² were recorded over north central Europe from 1437–1473 CE and 1779–1827 CE, with 1798–1808 CE being especially dry over England and Wales. The western Mediterranean experienced several decades of severe drought in the mid-1600s, recorded in tree-ring reconstructions¹²⁴ (1620–1640 CE) and pro pluvial rogation documentary proxies from Catalonia¹²⁵ (1626–1650 CE). Over the Iberian Peninsula, extended drought also occurred from 1680–1700 CE, the coldest interval of the Little Ice Age during the Maunder Minimum, and from 1760–1800 CE¹²⁶.

India experienced a series of multi-decadal megadroughts during the 14th and 15th centuries associated with 20–30% declines in monsoon rainfall, including at least one event that was 30 years long^{127,128}. Megadroughts occurred in Southeast Asia around the same time, most notably two multi-decadal events in the mid-1300s

and early 1400s that may have contributed to the collapse of the Angkor civilization in modern-day Cambodia¹²⁹ (**Box 2**). Decadal-scale megadroughts occurred regularly in Northern China over the last millennium CE¹³⁰: 1146–1155 CE, 1240–1249 CE, 1483–1492 CE, 1578–1587 CE, and 1634–1643 CE. The 17th-century drought contributed to widespread famine that led to the deaths of 20 million people and is widely believed to have helped motivate the peasant uprising that ended the Ming Dynasty¹³¹.

While most of the extreme megadroughts in Asia have been regionally focused, extreme multi-region events did occur. These include the “Strange Parallels” drought from 1756-1768 CE that affected peninsular India, Southeast Asia, and central Russia⁴³ and the Great Victorian drought from 1876-1878 CE that affected India, Southeast Asia, and China^{43,132,133}. The latter event, occurring during the height of British global colonialism, contributed to widespread famine, 12.2-29.3 million deaths in India, and 19.5-30 million deaths in China¹³⁴. In arid Central Asia, tree-ring chronologies provide evidence for a severe 16-year megadrought from 1175-1190 CE, a turbulent period characterized by warfare on the Mongolian steppe, as well as a longer and more intense 19-year megadrought starting in 804^{19,20}.

Australia

Much like Africa, mainland Australia has very few local paleoclimate proxies with sufficient temporal resolution to develop detailed estimates of Common Era drought variability. Consequently, most hydroclimate reconstructions use non-local proxies, assuming some degree of stationarity in climate teleconnections and covariability across regions. Examples include tree rings from Tasmania and New Zealand⁴⁶, ice cores from Antarctica¹³⁵, and corals along the east coast of Australia³⁸. More recently, significant advances have been made to develop local proxy records, including new tree ring reconstructions extending back over 600 years in western Australia¹⁵.

Ice core records suggest Southwestern Australia was especially drought-prone in the mid-1300s¹³⁵ and during the 18th and 19th centuries. Tree-ring records corroborate some of these events, indicating the occurrence of major multi-decadal megadroughts from 1755-1785 CE, 1828-1859 CE, and 1889-1908 CE¹⁵. Records for northern Australia also point to an extended dry period for the first half of the 19th century from 1825-1847 CE¹³⁶. The early 1800s event may have been especially extreme. Coral records from Queensland indicate that 1827-1856 CE was likely the driest 30-year period for streamflow in the region since the 1600s³⁸, while tree rings in western Australia recorded a megadrought around the same time, suggesting this may have been an especially widespread event¹⁵.

Southeast Australia experienced multiple extended periods of drought, including multi-centennial periods of aridity with below-normal precipitation during the 12th and 13th centuries^{137,138} and major decadal-scale megadroughts in the early 1500s, late 1700s, and 1820s to 1840s^{46,139-142}. Southeastern Australia experienced moderately dry summer conditions for the extended period from 1550-1600 CE with a more severe but shorter dry period from 1670-1704 CE¹⁴³. The central coast in eastern Australia (southeast Queensland) also experienced eight major megadroughts over the last millennium^{16,144}, including a 39-year event from 1174-1212 CE¹⁶.

Natural Drivers of Common Era Megadroughts

External Forcing

External forcing hypotheses are motivated strongly by the observation that many Common Era megadroughts occurred during periods of anomalous solar and volcanic forcing^{17,24,48,86,117,145}. For example, megadroughts in western North America primarily cluster in time during the Medieval era^{2,48}, a period of enhanced solar forcing and reduced volcanic activity¹⁴⁶. Proposed mechanisms include increased local temperature responses that enhance evaporative demand¹⁴⁷, reductions in land-sea temperature gradients causing weaker monsoons^{148,149}, and forced sea surface temperature (SST) changes in ocean basins with strong teleconnections to regional drought^{18,61,150-152}.

However, evidence is still mixed on the role of these forcings on megadroughts in North America and elsewhere. For example, while the temporal clustering of North American megadroughts appears higher than predicted from random noise alone, the evidence that this clustering was specifically caused by external forcing is much weaker^{153,154}. Hydroclimate responses to forcing can also vary spatially. For example,

volcanic eruptions are linked to drought in some regions¹⁵⁵ (tropical Africa) and pluvial periods in others^{156–158} (Mediterranean, Southeast Asia). Finally, while there is some evidence that climate model experiments can generate megadroughts in response to forcing changes^{17,24,61,147}, climate models can also generate megadroughts analogous to events in the paleoclimate record through internal variability alone^{59,159–162}.

Atmosphere-Ocean Dynamics

Hydroclimate variability on interannual to multidecadal time scales often results from complex interactions between the ocean and atmosphere. Anomalous SSTs create diabatic heating anomalies that generate atmospheric wave trains and shift storm tracks and mean circulation features, causing droughts, pluvials, or floods in distant land regions¹⁶³. Because of the strong persistence and relatively slow evolution of SST anomalies, which arises from both the thermal inertia of the ocean and slowly varying ocean circulation, the ocean is a likely contender for driving persistent drought. For megadroughts, tropical Pacific and Atlantic SSTs may be especially important because of the strong interannual to multi-decadal variability in these basins and because of the ability of tropical oceans, especially the Pacific, to drive teleconnections that influence climate worldwide¹⁶³. This tropical ocean driving can cause persistent hydroclimate states that would be unlikely to be sustained by atmospheric dynamics alone^{17,147,164,165}.

There is strong support for SST variability as a primary driver of Common Era megadroughts across multiple continents. Climate models generate megadroughts in response to low-frequency variations in Pacific and Atlantic SSTs that have similar characteristics to events in the paleoclimate record^{17,147}, even if the timing is inconsistent^{58,166}. Megadroughts on one continent have also been observed to co-occur in time with megadroughts or other persistent hydroclimate anomalies on other continents^{147,43,70,150,167}, patterns unlikely to occur through stochastic atmospheric variability alone¹⁵⁹, especially when the co-occurrence is between hemispheres. For example, the late 16th-century megadrought in southwestern North America co-occurred with a major pluvial in eastern Australia⁷⁰ and concurrent megadroughts in North and South America are common in the paleoclimate record^{5,17,168,169}, telltale signs strongly implicating the tropical Pacific as the common driver.

Decadal-scale cold Pacific SST anomalies are associated with many of the Medieval-era megadroughts in North America^{147,165} and South America¹⁷. Cold SST anomalies cool the tropical atmosphere and displace the jet streams and storm tracks in each hemisphere poleward. Additionally, Rossby wave teleconnections from the reduced precipitation above the cold equatorial waters create anomalous high pressure in the extratropical Pacific west of North and South America. This resembles the atmospheric response to interannually-varying La Niña conditions and diverts precipitation-bearing storms poleward of the drought regions. These same SST anomalies also drive longitudinal shifts in the location of deep convection and associated shifts in the zonal overturning circulation in the tropics. It is warm central Pacific SSTs, often related to positive phases of the Interdecadal Pacific Oscillation, that have been strongly linked to megadroughts in eastern Australia^{16,46,138} and Asia⁴³ as the locus of convection in the Indo-Pacific sector shifts east.

Across the Atlantic sector, warm SSTs likely contributed to the megadroughts over North America^{17,147}, two events from ca. 1000-1200 CE and 1500-1700 CE in west Africa¹¹², and the megadrought in Central America during the Terminal Classic period¹⁷⁰. Over central Europe, megadroughts were linked both with a cold state of the North Atlantic Ocean and long-lasting winter atmospheric blocking activity over the British Isles and western part of Europe¹⁸. Megadroughts in Eastern China are driven by a weakening of the East Asia summer monsoon (EASM), linked to weakening of the western Pacific subtropical high and a rising atmospheric pressure pattern in central-eastern Asia, and the strengthening of the East Asia Winter Monsoon (EAWM), in response to the strengthening of the Aleutian Low¹⁷¹. The Indian Ocean has can also contribute to multidecadal drought, especially when acting synergistically with west Pacific SSTs^{100,172}.

Uncertainties remain, however, regarding the extent to which these megadrought related SST and large-scale circulation states were externally forced^{17,18,147,150} or a consequence of exceptional periods of internal climate variability^{58,166}. For example, the dynamical thermostat mechanism has been invoked to explain how enhanced radiative forcing (increased solar and weak volcanism) during the Medieval era could have shifted the eastern tropical Pacific into a persistent cold state^{151,152}, which would have increased megadrought risk in western North America. However, as discussed above, megadroughts in the Americas do not easily line-up in time with radiative forcing as would be expected if they were largely mediated by a forced La Niña-like tropical Pacific response to positive radiative forcing. However, a shift to a stronger zonal SST gradient

across the tropical Pacific has been observed in recent decades, possibly in response to increased radiative forcing from rising anthropogenic greenhouse gas concentrations¹⁷³ a period that has also gone along with a shift in the American West to a claimed megadrought^{31,62} though any dynamical connection is far from clear. However, internal ocean-atmospheric variability during recent decades and past megadroughts cannot be ruled out^{58,166,174}.

Land-Atmosphere Interactions

Land-atmosphere interactions can significantly affect drought severity and persistence. For example, declining soil moisture during droughts increases sensible heat fluxes and decreases latent heating and evapotranspiration¹⁷⁵. Feedbacks from these changes at the land surface can amplify surface drying by increasing atmospheric aridity and evapotranspiration¹⁷⁶ or suppressing precipitation¹⁷⁵, though not in all cases¹⁷⁷. Additional feedbacks can occur through surface vegetation responses and wind erosion or dust aerosols¹⁷⁸. Such processes likely contributed to major historic droughts of the 20th century, including the Dust Bowl of the 1930s¹⁷⁹ and the multi-decadal Sahel drought from the 1970s to the early 1990s¹⁸⁰. Despite the strength of land-atmosphere interactions in many megadrought-prone regions^{176,181}, the importance of these mechanisms during megadroughts over the last two millennia has not been extensively studied.

There are two megadroughts where research has demonstrated that land-atmosphere interactions may have played some role. The first is for the Medieval era megadroughts over the Central Plains of North America. Geomorphological evidence shows that these droughts caused widespread declines in vegetation coverage, which drove high levels of wind erosion and dust storm activity⁸³. When these land surface changes were integrated into climate model experiments, it was found that the vegetation decline and associated increase in dust aerosols had a strong warming effect on summer temperatures and significantly suppressed early summer precipitation¹⁸². These factors increased the severity and persistence of the simulated megadroughts compared to simulations using SST forcing alone¹⁸².

The second is the Terminal Classic megadrought in Central America from 800-1000 CE. Prior to the arrival of Europeans, Mexico and Central America were home to millions of people^{183,184}, populations that converted large areas of forest to cropland^{184,185}. When various estimates of deforestation during this interval were integrated into climate models, the models generate pronounced declines in precipitation, especially during the wet season. One idealized climate model experiment found a 15-30% reduction in July precipitation with complete deforestation of Mesoamerica¹⁸⁶. Another study¹⁸⁷, using an empirically constrained estimate of Pre-Columbian land use in the region¹⁸⁸, found that deforestation could cause a 10-20% reduction in late summer precipitation, contributing to an overall 5-15% decline in annual precipitation¹⁸⁷ across southern Mexico and the Yucatán. Therefore, deforestation could potentially account for a substantial fraction of total estimated precipitation declines during the Terminal Classic megadrought⁹¹.

Anthropogenic Climate Change and Megadroughts

The imprint of anthropogenic climate change on terrestrial hydroclimate is already detectable at the global-scale^{47,189-192}, manifesting primarily through the intensification of existing wet-dry patterns^{47,191}. Consequently, climate change has already contributed significantly to the severity of many recent droughts through anthropogenically forced changes in precipitation^{189,190,193}, snow^{194,195}, and evaporative demand and evapotranspiration¹⁹⁶. Climate change has intensified soil moisture droughts over California^{197,198} and southwestern North America³¹; snow and streamflow droughts across the western United States¹⁹⁹⁻²⁰⁵; and precipitation droughts in the Mediterranean²⁰⁶⁻²⁰⁸, Central America²⁰⁹, the Caribbean²¹⁰, Chile²⁶, southern Africa^{211,212}, Central Asia²⁰, and southwest Australia^{206,213}. Included in these events are recent or ongoing extended droughts in southwestern North America⁶² and central Chile and central-western Argentina²⁶ that could be considered megadroughts. With continued warming, it is expected that drought and megadrought risk and severity will continue to increase with future warming for many of these regions^{29,214}.

The Southwestern North America Megadrought (ca. 2000-ongoing)

Since the beginning of the 21st century, southwestern North America has experienced drought conditions that are unprecedented at least back to 800 CE^{31,62}. Beginning in 2000 CE and extending at least through the most recent summer of 2021 CE^{62,215}, this extended drought has caused severe declines in water resources^{62,216,217}, major economic and agricultural losses²¹⁸, and widespread wildfire activity^{219,220}. Regional average

reconstructed soil moisture during 2000-2021 CE ranks as the driest 22-year soil moisture anomaly of the last 1200 years. In terms of both duration and regional average severity, this event is only comparable to the multi-decadal megadroughts that afflicted the region prior to 1600 CE.

There is strong evidence that climate change contributed to the severity, duration, and spatial extent of the soil moisture deficits during this drought (**Figure 3a,b**). There is no obvious evidence of a downward trend in precipitation in the region over the last century and precipitation deficits during this event are certainly strongly influenced by natural variability^{174,221}. Specifically, a swing towards the cool tropics phase of Pacific Decadal Variability at the turn of the century, which has persisted on and off since, drove a drying tendency across the southwest that contributed to the 21st century drought^{174,221,222}. This decadal shift is analogous to prior decadal shifts in tropical Pacific SST and precipitation over the southwest and likely a result of natural Pacific decadal variability^{222,223}.

However, the region has also experienced significant increases in vapor pressure deficit because of warmer temperatures and declines in specific humidity²²⁴⁻²²⁶. The warming is largely attributable to anthropogenic warming^{225,227} and has exacerbated the drought that would have occurred due to precipitation changes alone. When the 2000-2021 CE mean summer soil moisture was recalculated after removing anthropogenically forced climate trends, it was estimated that anthropogenic climate change accounted for ~42% of the soil moisture deficit during this 22-year period⁶².

The large effect of climate change is apparent when comparing the spatiotemporal evolution of the observed drought against a counterfactual version with the effects of climate change removed. In the absence of anthropogenic forcing, 2000–2021 would have likely been composed of two distinct droughts, with much more moderate cumulative soil moisture deficits up through 2021⁶². Additionally, the most extreme soil moisture deficits would have been localized in southern California and Arizona, consistent with the drought pattern expected of predominantly cool-phase conditions in the tropical Pacific, instead of the much more spatially extensive observed drying. Climate change therefore likely turned what would have been a moderate drought, with characteristics typical of recent historical variability in the region and only some areas experiencing extreme drought severity, into a widespread and extended event representing one of the worst megadroughts of the last 1200 years.

The Chile-Argentina Megadrought (ca. 2008-ongoing)

Since 2008, Chile and Argentina have experienced extreme decadal-scale drought conditions that have severely affected water resources^{27,228,229}, wildfire²³⁰, and vegetation health²⁷ across the region. Precipitation declines have been especially extreme and widespread, reaching 20-40%^{26,27,231} below normal in some locations and years. These precipitation deficits have propagated across the hydrologic cycle, causing 7-25% decreases in lake areal extent²³², declines in streamflow of up to 90% in some regions^{27,228}, and major impacts on snow and glaciers in high alpine areas^{27,233}. The severity of this drought, and its largely unprecedented string of consecutive dry years, has motivated several authors to declare this event a megadrought^{26,27,234}.

Central Chile and central-western Argentina, in particular, experienced a significant drying trend during the 20th century^{45,206,229,235,236}, and the recent megadrought stands out as exceptional in both the historical record and paleoclimate reconstructions of the last millennium (**Figure 3c,d**). Extreme single-year droughts in the region are common, but persistent decadal-scale droughts are rare^{26,27} and this megadrought has the longest consecutive run of significant dry years during the 20th century²⁶. While there are several decadal periods in the paleoclimate record analogous to the contemporary megadrought^{27,45}, numerous reconstructions suggest that this event is the driest, or near-driest, decadal-scale drought of the last thousand years^{26,27,234,235}.

Decadal variations in tropical Pacific SSTs are the main natural driver of megadrought in Chile, both in the past¹⁷ and for the current event²⁶. However, there is some evidence that anthropogenic climate change may be intensifying the precipitation deficits^{206,237}. In the Southern Hemisphere, strong anthropogenic forcing from greenhouse gas driven warming and stratospheric ozone depletion have contributed to positive trends in the Southern Annual Mode (SAM), a poleward expansion of the Hadley Cell, and a poleward shift of the southern hemisphere storm tracks and jet stream. This poleward shift and expansion of climate regions reduces winter precipitation in the mid-latitude region of megadrought. Anthropogenic warming has also likely contributed to warmer ocean temperatures in the subtropical southwest Pacific Ocean, which may have amplified ridging and drying over the region²⁸. Estimates of the anthropogenic contributions to the severity of

the Chilean megadrought range from 20-50%^{26,27,231,238}, and likely acted in concert with natural Pacific SST variability to amplify precipitation deficits during this megadrought.

The Future of Megadrought Risk

Many of the most megadrought-prone regions during the Common Era are also locations highlighted in the Sixth Intergovernmental Panel on Climate Change (IPCC) assessment report (AR6) as areas expected, with at least *medium confidence*, to experience increased drought severity and risk with climate change (Chapter 11²³⁹, *Figure 11.8*). These include western North America, Central America, the Caribbean Islands, Europe and the Mediterranean, Chile, and southern Australia. Consistent with recent droughts, future increases in drought risk and severity are expected to occur in response to season-specific precipitation declines^{240,241}, decreased snowpack storage^{195,205,242,243}, and increases in evaporative demand²⁴⁴ and plant water use^{245,246}. In most regions, increased drought risk occurs as a direct response to warming because of the much more uncertain precipitation responses in models. The exception is in Mediterranean-climate regions, where drought risk driven by robust reductions in cool season precipitation related to anomalous high pressure occurring within an adjustment of planetary-scale stationary waves^{206,247–250}.

In western North America, climate model experiments project large and robust increases in megadrought risk with warming. One study using the CMIP5 generation of climate models found a 60-80% likelihood of decadal (11-year) and multi-decadal (35-yr) megadroughts occurring over the Southwest and Central Plains of the US by the end of the 21st century under both moderate and high warming scenarios³³. More recent analyses using the CMIP6 generation found a ~50% increase in the likelihood of events analogous to the 2000-2020 megadrought occurring by the end of the 21st century across low, medium, and high warming scenarios⁶⁰. Model projections in CMIP6 under moderate warming (SSP2-4.5) indicate that many of the Common Era megadrought regions will experience substantial increases in multi-decadal megadrought risk in the latter half of the 21st century (**Figure 4**). This conclusion is supported by analyses of several climate model large ensembles which found that, under a high-emissions climate scenario, multiple regions (e.g., western North America, western Europe, southern Africa, and Australia) would transition into soil moisture states meeting or exceeding megadrought definitions for the entirety of the 21st century²¹⁴.

If realized, these changes would likely mean an unprecedented level of megadrought activity compared to even the most arid centuries of the Common Era. However, there is evidence that lower forcing scenarios would partially mitigate projected increases in megadrought risk and severity³². This is because the increases in risk are attributable to background trends and shifts in the mean state, which scale strongly with the magnitude of forcing, and not changes in decadal or multidecadal hydroclimate variability²¹⁴. Moreover, uncertainty in projected megadrought risks for regions like the southwest US remain sensitive to internal climate variability even under high forcing; large initial condition ensembles of climate simulations are therefore necessary to better constrain uncertainties in future regional megadrought risk estimates^{251,252}. Even in analyses where mitigation did not substantially reduce the occurrence of megadrought periods, lowered warming still substantially decreases the severity of individual drought years⁶⁰. Therefore, climate mitigation is likely to offer critical benefits for moderating megadrought severity and risk, even if future increases cannot be entirely avoided.

Summary and Future Perspectives

In this review, we argue for a more formal definition of *megadroughts*, reserving the term only for events that are distinguished by their exceptional nature compared to more typical droughts in the instrumental or paleoclimate records. By this definition, megadroughts have occurred on every continent outside of Antarctica during the Common Era, and have been most strongly linked to SST variability, especially in the tropical Pacific and Atlantic basins. Climate change has already amplified the severity of recent megadroughts in southwestern North America, central Chile, and central-western Argentina and could increase future megadrought risk to largely unprecedented levels by the end of the 21st century. Future megadroughts will present significant challenges to water resources²¹⁶ and ecosystem resilience²⁵³, though climate mitigation can potentially reduce event risk and severity compared to the most extreme warming scenarios³².

Despite progress in understanding natural and anthropogenic megadrought drivers, our confidence in projections of megadrought risk is undermined by uncertainties in estimates of natural drought variability. This is especially true for regions where hydroclimate proxy coverage during the Common Era is sparse (e.g., the Amazon), where there is heavy reliance on remote proxies (e.g., mainland Australia), or where most information comes from low temporal resolution archives (e.g., lake records) with significant time uncertainties (for example, Sub-Saharan Africa before 1700 CE). These limitations make it difficult to fully constrain natural drought variability, the past occurrence of megadroughts, and the characteristics of these events. Addressing these limitations will require prioritizing new efforts to collect and develop seasonally and annually resolved proxies and synthesize these new records into spatially resolved reconstructions over regions that have historically been poorly sampled. Concerns regarding natural variability also extend to climate models that may significantly underestimate natural hydroclimate variability and therefore underestimate future megadrought risk^{53,54,254}. Changes to the atmospheric general circulation, often linked with shifts in regional hydroclimate, also differ across climate models²⁵⁵. While it is difficult to know what changes are needed to improve these models, more comprehensive evaluations against the much longer paleoclimatic record may offer insights into where and why the models are failing.

With temperature playing an increasingly important role in modern and future droughts^{18,256–262}, past megadroughts are likely to be imperfect analogues of future events. Higher temperatures are a major, direct driver of increased soil moisture, streamflow, and snow drought risk and severity and can fundamentally change the manifestation of these events. For example, anthropogenic warming has allowed a turn-of-the-21st-century megadrought to emerge across a broad swath of southwestern North America, even though drought-promoting circulation anomalies have likely not been as severe or persistent during this ongoing event as they were during the megadroughts that occurred before 1600 CE⁶². Warmer temperatures during droughts are likely to amplify drought impacts on ecosystems^{6,263}, though by how much is unclear because of the complex and uncertain responses of vegetation to climate and atmospheric carbon dioxide concentrations^{245,246,264}. Much of this uncertainty is centered in the representation of land surface and vegetation processes within climate models, which are often highly parameterized and simplified. Moving forward, it will be critical to understand and improve how these process representations affect model sensitivities, mean states, fluxes, and the underlying manifestation of drought events²⁶⁵.

To address these future challenges, more explicitly considering megadroughts in drought planning exercises will be required. Many water resource management plans center on what is often termed the “drought of record”, usually the single worst drought event in the historical record designed to represent a potential worst-case scenario for drought resiliency planning. Texas, for example, uses the 1950s drought as their drought of record^{266,267}, an event that led to the creation of the Texas Water Development Board and new reservoir construction across the state^{266,268}. Given the much more persistent and severe megadroughts in the paleoclimate record and model projections, however, a more informed approach may be to use these paleoclimatic records to define new droughts of record^{39,138} or at least develop model exercises to assess how current plans would fare under these much more extreme scenarios^{269,270}. These approaches are already being considered and applied to water resource management in California, the Colorado River Basin, and the Missouri River Basin. Such exercises should also consider that a megadrought-prone future may also mean shorter or less frequent wet intervals that may limit recovery between droughts, especially for groundwater and larger reservoirs. These issues are already beginning to manifest in the western US, where persistent and frequent drought periods have impeded groundwater and reservoir recovery during the short intervening wet intervals^{62,271,272}.

With ongoing climate change and the associated increases in drought severity and risk, it is plausible, or even likely, that some regions in the coming decades will experience a major megadrought that will significantly stress regional adaptive capacities. One major challenging aspect will be that much of the increased megadrought risk in the future occurs because of a shift of regional climates to more arid mean states²¹⁴ characterized by higher temperatures and, in some cases, reduced precipitation. In these cases, megadrought effectively becomes the new climate normal and it can be questioned whether the term ‘megadrought’ - which, by definition, refers to a dry anomaly - will at some point need to be retired in favor of other terms, like aridification²¹⁶. Studies of the paleoclimate record and model projections, however, can be used to better constrain and contextualize future changes in hydroclimate and megadrought risk, allowing us to more proactively develop resiliency plans to reduce the impact of the events.

Figure legends

Figure 1. **Characteristics of soil moisture (PDSI) drought variability in the tree-ring based drought atlases from 1400-2000 CE, the common interval across all datasets.** Data over North America come from the Living Blended Drought Atlas³⁴ and the Mexican Drought Atlas⁴⁴. Southern Hemisphere reconstructions are the South American Drought Atlas⁴⁵ and the Australia New Zealand Drought Atlas⁴⁶. The reconstruction over Eurasia is an updated and combined version of the Old World Drought Atlas⁴², the European Russia Drought Atlas⁴¹, and the Monsoon Asia Drought Atlas⁴³. **a,b** | Autocorrelation at 1- and 2- year lags. Most regions show high year-to-year persistence, indicative of a strong tendency for multi-year drought or pluvial periods in most regions. **c,d** | Slopes of the power spectra, filtered for 2-50 year and 10-50 year periodicities. Widespread positive slopes in the 2-50 year band indicate higher power concentrated at decadal to multi-decadal frequencies. Results are more spatially heterogeneous in the 10-50 year band, but highlighting many regions with higher power at multi-decadal relative to decadal frequencies. **Analyses of the paleoclimate record demonstrate that the underlying characteristics of drought variability in recent centuries are highly regional, especially at lower frequencies, highlighting the difficulty of establishing a globally universal definition for megadrought.**

Figure 2. **Megadroughts have occurred on every continent outside of Antarctica during the Common Era.** In some regions, these were isolated events (Central Asia), while other regions experienced extended, centennial-scale periods of recurrent megadrought activity (Western North America, Chile and Argentina). **Western North America:** Cliff Palace at Mesa Verde, a cliff dwelling abandoned during the late 13th-century megadrought. **Central America:** Tikal, center of one of the most powerful Maya conquest states that was abandoned following the Terminal Classic Drought. **Chile and Argentina:** Laguna Acuelon, a popular tourist destination near Santiago, Chile that completely dried out in 2019 during the ongoing megadrought in the region. **Europe:** A “hunger stone” marker in the Czech Republic, embedded into streambeds during periods of intense drought and famine. **West Africa:** Lake Bosumtwi in Ghana, where megadroughts lead to extreme persistent low water levels. **East Africa:** Lake Edward, which experienced major lake level declines during megadrought periods from 1000-1200 CE. **Central Asia:** Chinggis (Genghis) Khan, who consolidated power in Mongolia in the late 1100s, during a period of intense regional conflict coinciding with a severe drought. **India:** Dandak Cave in peninsular India, site of speleothem records that recorded major megadroughts during the 14th and 15th centuries. **Northern China:** A major megadrought in the mid-1600s contributed to widespread famine and contributed to the eventual collapse of the Ming Dynasty. **Southeast Asia:** Much of Greater Angkor was abandoned following a series of major hydroclimate events that significantly damaged their hydraulic infrastructure. **Western and Eastern Australia:** Australia is especially drought-prone, and both regions of the continent have experienced major megadroughts during the past millennium. **Megadroughts are an intrinsic part of natural hydroclimate variability during the Common Era, affecting regions on every continent outside of Antarctica, with often large effects on ecosystems and societies.**

Figure 3. **Climate change has contributed to early 21st century megadroughts over southwestern North America and central/southern Chile and Argentina.** **a** | Cumulative summer season soil moisture anomalies over southwestern North America associated with the driest 22-year mean anomalies in the soil moisture reconstruction (800-2021 CE). The magnitude of the recently observed drought (2000-2021 CE; red) is nearly twice as severe as the same event when the effect of anthropogenic climate change (ACC) is removed (blue). **b** | Cumulative soil moisture anomalies over southwestern North America associated with the development of all droughts at least 15 years in length. In the absence of climate change, the start of the contemporary drought would have been delayed to 2007 CE, with a much more modest accumulated soil moisture deficit. Figures a,b adapted from Williams et al, 2022⁶². **c** | Observed summer soil moisture (PDSI) anomalies²⁷³ were extremely dry across central and southern Chile and Argentina (dashed black lines; 68°W-76°W, 28°S-56°S) from 2008-2021 CE. **d** | Compared to a reconstruction extending back to 1400 CE⁴⁵, regional average soil moisture for 2008-2021 CE ranks as the single driest 13-year period during the last six hundred years, supporting recent work suggesting that climate change has amplified the severity of this event^{26,28,231}. **Consistent with model projected drought responses to warming, there is clear evidence that climate change has already amplified megadrought severity in two regions of the world.**

Figure 4. **Regional multi-decadal megadrought risk in the CMIP6 projections under a moderate warming (SSP2-4.5) scenario.** These calculations use an ensemble of 22 models (Supplementary Table 1) and regional average, standardized (baseline 1851-1950 CE) summer total column soil moisture. In this analysis, megadrought risk is defined as the fraction of 21-year mean soil moisture anomalies in the pooled ensemble that are drier than the fifth percentile estimated during the 1851-1950 CE baseline. While relatively simple, this is a conservative definition, as 21-year drought anomalies would be considered extreme compared to past events in most regions. The baseline (1851-1950 CE) risk is indicated in the light pink shading in the probability density plots. Standardized soil moisture values (density plots) and megadrought risk (inset percentages) from the multi-model ensemble for the late 20th (1951-2000 CE; blue distributions) and 21st (2051-2100; red distributions) centuries are also shown. On the map, regions with highest levels of risk in the late 20th and 21st centuries (red circles) experience mean shifts in the multi-model ensemble towards drier conditions. In regions with more moderate risk during these intervals (blue circles), the small increases in megadrought risk are associated with subsets of models in the ensemble that trend drier, rather than any coherent ensemble-mean shift. **In the same regions of active megadrought activity during the Common Era, warming in the CMIP6 projections increases megadrought risk.**

Box 1 | Defining Droughts and Megadroughts

Characteristics of droughts and megadroughts are highly sensitive to the calculation of their start and termination dates. We demonstrate this by applying three different methods of drought-event detection to a single reconstructed soil moisture time series (800-2021 CE) from Southwestern North America⁶² (data available from: <https://doi.org/10.25921/8pt9-hz08>). Williams et al.⁶² defines extended droughts as having at least 10 consecutive years with negative 10-year trailing mean values, trimming the start and end dates to avoid starting or ending the events with consecutive annual (non-smoothed) positive anomalies, and dismissing events shorter than 5 years. Meehl & Hu⁶³ base their definition on consecutive, negative 11-year centered mean values. Coats et al.⁵⁸ begin droughts with two consecutive negative annual values, continuing the event until two consecutive positive values occur.

Focusing on extended (5-year or longer) droughts, *Williams* identifies 30, *Meehl* identifies 41, and *Coats* identifies 56. Many of the worst megadroughts are detected by all three methods, with minor and sometimes large differences in their start and end dates. For example, while all three methods found the same start date for the late 13th-century megadrought, *Coats* terminates this event a decade earlier compared to *Williams* or *Meehl* (box figure, upper left). Consequently, while the duration and cumulative severity of this event is similar between *Williams* and *Meehl*, this megadrought is much shorter (box figure, bottom left) and more moderate (box figure, bottom right) using *Coats*. Even larger differences can be seen in the late 16th-century megadrought (box figure, upper right).

More generally (bottom panels), we find that droughts based on the *Williams* method have longer durations and higher overall severity, the *Coats* method characterizes droughts that are shorter because drought termination is easier, and the *Meehl* defined events have lower overall severity because this method allows for inclusion of wet years during the beginning or end of the drought. In addition, each of the three methods of drought event detection could lead to varying results depending on the time period used to define baseline conditions when the long-term mean drought anomaly is set to zero. While there is no clear argument that any of the approaches are superior, this highlights the importance of consistently defining the drought identification methods and an awareness of the underlying assumptions and limitations associated with the chosen methodology.

Box 2 | Portrait of a megadrought: the Angkor Drought (ca. 1344–1367 CE)

The Angkor Drought in Southeast Asia triggered a series of events that contributed to the demise of the Angkor civilization¹²⁹, evidenced in archaeological excavations and LiDAR scans²⁷⁴. During this drought, streamflow in the Mekong was ~2–3 standard deviations below normal²⁷⁴, causing Angkor's rulers to seal off reservoirs to minimize water losses. The modified infrastructure had much less hydraulic capacity and was subsequently heavily damaged by a severe flood in 1375^{129,274}. With this loss of water storage capacity, Angkor could not sustain itself during the next major drought (ca. 1399–1404 CE) and flood sequence, and much of the Greater Angkor region was eventually abandoned.

Analyses of regional average soil moisture (PDSI; box figure, a) over Southeast Asia (box figure, b; 93°–110°N and 80°–24°E) from an updated version of the Monsoon Asia Drought Atlas⁴³ highlight how extreme the 1344-1367 CE drought was (box figure, c). Using a simple definition requiring at least 5

consecutive dry years, we identified 21 total extended drought periods, highlighted in yellow. The Angkor drought (highlighted in orange) spans 24 years from ca. 1344–1367 CE, the single longest drought event in the record. This was the third most spatially extensive extended drought, with negative time-average soil moisture anomalies affecting 89% of the regional land area during this period. The single most severe soil moisture deficit of any extended drought occurred during the Angkor drought (1363 CE), and the time average soil moisture anomaly ranks as the fourth driest overall. From these analyses, and the criteria established in our review, this event qualifies as a megadrought, exhibiting exceptional *severity* and spatial *extent* compared to other droughts in the region over the last ~800 years.

Glossary

ARIDIFICATION

A long-term change in a region from a wetter to a more arid climate. Aridification is differentiated from drought because, while the latter is a temporary period of reduced water availability, aridification represents a more permanent change in the baseline climate.

DROUGHT

A temporary or transient period of reduced water availability, typically measured in terms of deficits in precipitation, soil moisture, runoff, streamflow, or snow.

MEGADROUGHT

persistent, multi-year drought events that are exceptional in terms of severity, duration, or spatial extent when compared to other regional droughts during the instrumental period or the Common Era.

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