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Drought during early European exploration and colonization of North America, 1500-1610CE: A comparison of evidence from the archives of societies and the archives of nature

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Abstract. This article presents the historical evidence concerning the occurrence of drought in North America from 1510-1610CE based on a comprehensive review of original written records concerning all early European expeditions into the present US and Canada. It compares this evidence from the archives of societies with maps and time series of drought generated from the tree ring-based North American Drought Atlas (NADA). This comparison demonstrates the reliability of early colonial historical records as sources of evidence concerning drought, as well as the applicability of the NADA to the scale of local and regional human historical events. The comparison further verifies the occurrence and societal impacts of certain major droughts previously identified in dendroclimatological studies, but suggests that some summer hydrological deficits indicated in the tree ring record reflect a deficiency of summer rather than winter precipitation. Finally, this review of evidence from both the archives of societies and archives of nature highlights the extraordinary challenges faced by early European explorers and colonists in North America due to climatic variability in an already unfamiliar and challenging environment.

1 Introduction

The frequency and severity of regional droughts before the instrumental period may be reconstructed on the basis of either the archives of nature or the archives of societies. The former, which comprise natural records containing proxies for precipitation or soil moisture, such as tree ring width or isotopic variations in speleothem layers, are usually employed for the more distant past and for world regions without detailed historical records. The latter, which comprise descriptions and observations of natural phenomena left by people, are usually employed for the past five to six centuries in regions with abundant personal records and official archives, such as Western Europe and China. In some cases, however, reconstructions of both types may be combined or compared in order to achieve a level of continuity, homogeneity, resolution, spatial extent and/or seasonal coverage lacking in one type of archive alone, as well as to cross-check their respective results. This approach may be particularly useful where the archives of societies are plentiful enough to provide useful data but insufficient for a complete independent reconstruction of historical drought (e.g., Mendoza et al., 2006; Stahle et al., 2007).

This article presents the evidence concerning the occurrence and the human impacts of droughts in North America (present US and Canada) during the first century of European exploration and colonization of the continent, 1510-1610CE, based on an original comprehensive review of the primary historical sources for those expeditions. It compares this evidence from the archives of societies with drought reconstructions based on archives of nature, principally reconstructions of summer Palmer drought severity index (PDSI) from the tree ring-based North American Drought Atlas (NADA). This reconstruction and comparison serves the following four purposes: (1) to test the objectivity and reliability of these historical observations, and thus the potential for exploration and colonization records to be used in drought reconstruction; (2) to crosscheck the NADA reconstructions—including those for extreme events reconstructed during the 16th and early 17th centuries—and the NADA's applicability to the scale of human historical events; (3) to gain further insights into the seasonality and severity of historical droughts found in each type of evidence; and (4) to better understand the human impacts of droughts during this critical and vulnerable phase of North American exploration and colonization. By 1610—with the foundation of enduring

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colonies at St. Augustine, Santa Fe, Quebec, and Jamestown—the basic geography of Spanish, French, and English colonial claims to different parts of the continent had been established, marking a significant turning point in North America's history.

The investigation of historical droughts, including reconstruction and impact studies utilizing the archives of societies, is a growing and evolving field. Nevertheless, a recent review has identified North America as one of the least studied regions (Brazdil et al., 2018). Although the present-day US and Canada contain abundant personal and official records dating back to the colonial period, many of the them containing information on weather and climate, few researchers have used them to reconstruct the frequency or severity of historical droughts (Mock, 2012; White, 2018).

On the other hand, American dendroclimatology is relatively well developed, and tree ring-based studies have been increasingly utilized in historical research. David Stahle and colleagues first pointed out prominent droughts in the tree-ring record—including major droughts during the late 1500s in the Southwest and early 1600s in Virginia—and their likely impact on early North American colonization (Stahle and Cleaveland, 1994; Stahle et al., 1998). In 2007, Stahle and colleagues proposed that "the integration of the [NADA] PDSI reconstructions with historical information on environmental conditions and the activities of Euroamerican and Native American societies is a largely unexploited opportunity that promises significant new insight into American history and environmental change" (Stahle et al., 2007).

Archaeologists have reviewed physical and written evidence for the role of droughts and other extreme weather during the first century of European expeditions in several regional contexts, particularly the Chesapeake (Blanton, 2000; Blanton, 2003; Blanton, 2004; Rockman, 2010), the interior Southeast (Burnett and Murray, 1993), Florida (Paar, 2009; Blanton, 2013), and New Mexico (van West et al., 2013). A few historians have begun to incorporate climatic perspectives into accounts of early North American exploration and colonies (Kupperman, 2007a; Grandjean, 2011; Wickman, 2015; Wickman, 2018), and a 2017 monograph has provided a comprehensive narrative of the role of regional climate differences and climatic variability in early Spanish, French, and English exploration and colonization of the present US and Canada (White, 2017). These historical studies have indicated that many expeditions suffered from unexpected extreme cold as well as drought. This article provides the first concise, continent-wide overview of the evidence concerning drought from both human and natural archives presented for historical climatologists and paleoclimatologists.

2. Sources and Methods

2.1. Archives of Societies

A search was made for all primary historical records surviving from or directly relevant to every known European expedition that spent time in the present US and Canada from 1510-1610 CE. This search resulted in several thousand documents contained in roughly one thousand published volumes as well as electronic collections and unpublished archival series in the Archivo General de Indias (Spain) and National Archives (UK), most available online (see Supplementary Material). The author read each of these personally and, where possible, in their entirety. Some documents were consulted in English translations, but in those cases almost all descriptions of weather, climate, or climatic impacts were read again in their original languages (French, Spanish, German, Italian, Latin, and Dutch) to correct any mistranslations and to ensure accuracy. All dates were converted from the Julian calendar into modern calendar dates with the new year beginning on January 1. Descriptions of weather, climate, and climatic impacts were never extracted from their context and compiled separately but always considered contextually, meaning that the study took into account: (1) the description's context within the individual document and its larger corpus; (2) the conditions of the observation and of its recording and publication; (3) the background of the author or authors, including his or their subjective sense of 'normal' weather or climate; and (4) the genre of writing in which any description appeared. (For a complete book-length account of the historical context of climate observations in the course of early exploration and colonies, see White, 2017.). Whenever possible this study has attempted to verify accounts against each other and against external evidence, such as archaeological investigations.

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The relevant surviving records fall broadly into six such genres: private correspondence, official correspondence and memoranda, correspondence of religious orders, pamphlets, travelogues, and finally chronicles and other second-hand compilations of information, which could be used only with caution. Each of these genres has been used in historical climatology and each presents particular strengths and weaknesses as a source of weather, climate, and impact evidence (Pfister, 2018; Pfister and White, 2018). However, the unique conditions under which early colonial records were compiled endow them with peculiar advantages and disadvantages compared to other similar records from the archives of societies. On the one hand, events during the exploration of new lands and the colonization of new territories were unusually well recorded, and those records have been more carefully sought out, preserved, and analyzed by scholars concerned with the historical and environmental significance of colonialism. Moreover, observers present in unfamiliar environments and concerned with prospects for resource extraction, trade, colonization, or missionization usually devoted more attention to environmental features, including weather and climate, than those at home (Taylor, 1993; White, 2015b; Zilberstein, 2016). Europeans on early colonial expeditions were also acutely vulnerable to climatic variability and extremes. On the other hand, colonial observations necessarily predate the establishment of regular institutions or practices that could produce regular records containing climate proxies, such as officially prescribed annual harvest dates. Furthermore, the novelty of colonial environments made it difficult for observers to determine what was normal weather or climate or to identify reliable phenological markers of variability or extremes. Adding to their confusion, early European explorers and colonists expected climates to align with latitudes, overlooking the differences between Europe's predominately maritime climates and North America's predominately continental ones (Kupperman, 1982; Rockman, 2010). This study aims to evaluate whether the advantages of these sources outweigh their potential drawbacks when it comes to reconstructing past weather and climate.

This study has identified four main types of evidence concerning drought in the archives of societies for early colonial North America: (1) *Phenological descriptions*, including the growth of crops and conditions of rivers provide the most objective indicators of drought, but they are not common in all sources. (2) *Narrative accounts*, describing a lack of rainfall or giving general descriptions of dry seasons, are found more frequently but provide less certain indicators of the presence or absence of drought. (3) *Societal impacts* attributed to drought, particularly famine, also appear frequently in the sources, and may provide confirmation that conditions were unusually severe. However, these descriptions need to be considered in the context of societal vulnerabilities, which varied according to the colony or Native American society in question. Most of the populations discussed in this study relied heavily on crops of maize, which in turn depended on adequate summer rainfall and a lengthy frost-free growing season. (4) Finally, *rain-making ceremonies* represent a peculiar but potentially valuable type of evidence for drought. Measuring the occurrence and scale of officially sanctioned rain prayers, known as rogation ceremonies, has been demonstrated as a reliable method of drought reconstruction in Spain and Spanish America (Domínguez Castro et al., 2008; Domínguez Castro et al., 2018). Historians have identified similar ceremonies outside Spain in many different religious and cultural traditions, but these have not yet been tested in the same fashion. In the colonial North American context, many early European expeditions reported performing rain prayers, being asked by Native Americans to perform rain prayers, or observing indigenous communities performing rain-making ceremonies. Some historians have argued that such accounts could have been biased or even falsified by early European observers eager to present Native Americans as simple pagans ready to be won over to Christianity. However, a close review of the context and consistency of these accounts across sources has indicated that most were probably based on actual events (Kupperman, 2007b; White, 2015a).

All evidence was analyzed year by year for each expedition. The results were for each evidence type are presented in Table 1 below.

2.2. Archives of Nature

Most high-resolution reconstructions of drought in North America for the pre-instrumental period have relied on measures of the variation in the width of growth rings in trees whose growth has been limited by soil moisture during the growing season.

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The NADA is a set of June-August PDSI reconstructions at annual resolution based on 1,845 tree-ring chronologies estimated on a 286-point (2.5˚x2.5˚) grid, which covers most of North America for the past several centuries (Cook et al., 1999; Cook et al., 2010). Major droughts for this period found in the NADA have also been reproduced in independent tree-ring studies (e.g., Grissino-Mayer et al,. 2002; Harley et al., 2017). Relevant precipitation proxies found in other archives of nature are discussed in the results and discussion sections below.

Summer PDSI is a function of both precipitation and evapotranspiration; the seasonality of precipitation signals embedded within the NADA thus varies according to region. Although both summer and winter precipitation influence summer PDSI in all parts of the continent, the NADA has been found to have a dominant winter signal in the Southwest and Florida and a dominant summer signal in most of the rest of the continent. However, the signal at any given location may depend on local conditions and the proximity of tree-ring samples (St. George et al., 2010). For this reason, variations in PDSI over large regions reconstructed by the NADA cannot always reveal past meteorological droughts (deficiencies in precipitation) or agricultural droughts (insufficient precipitation and/or moisture for the development of crops) in any particular season and location as indicated in the archives of societies. In some cases, sub-annual ring components may be used as distinct proxies for summer and winter precipitation in the Southwest (Stahle et al., 2009; Griffin et al., 2013).

Using the visualization tools at http://drought.memphis.edu/NADA/ this study produces: (1) maps of PDSI for each region of travel for any colonial expedition that stayed long and left enough documentation to indicate the presence, absence, or impact of drought 1510-1610CE in regions of North America where evidence of drought was found; and (2) time series of PDSI variation at all locations in which any European colony remained for long enough and left enough documentation to indicate the presence, absence, or impact of drought in North America 1510-1610CE in regions of North America where evidence of drought was found.

3. Results

The following section presents first an overview of findings from the archives of societies for all expeditions, then findings for each major expedition, combining information from the archives of societies and archives of nature.

3.1. Overview: Archives of Societies

Table 1 provides a concise overview of each expedition by region, summarizing the location and four types of evidence concerning droughts explained in section 2.1. Evidence for droughts occurs in expeditions in the Southeast, Southwest, and Chesapeake region, but not in any expeditions to California, New England, or Canada during this period. It should be noted that colonists and religious missionaries did record evidence for drought and the occurrence of rain prayers in New England and Canada during the 1620s and 1630s (White, 2015a; Grandjean, 2011), which suggests that the absence of evidence during the expeditions under study here likely reflects a lack of observed droughts rather a failure to recognize droughts in these environments. Compared to very frequent descriptions of cold and storms (White, 2017) descriptions of droughts are relatively uncommon in the sources, but still appear in roughly half the expeditions to the Southeast, Southwest, and Chesapeake.

{Table 1 here; caption: A summary of information concerning the presence or absence of drought, and impacts attributed to drought, for each European expedition to North America during 1510-1610CE drawn from the archives of societies. An explanation of sources and types of evidence is provided in section 2.1. A question mark indicates that the evidence is uncertain, as explained for each instance in the relevant part of the section 3.2.}

3.2. Integrated results for each expedition

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For each expedition presenting written evidence of drought, the following sections compare the evidence from the archives of societies with that from the archives of nature, particularly the NADA, as described in section 2.2.

3.2.1. Cabeza de Vaca

The first, brief Spanish colonial expeditions to the Southeast, led by Juan Ponce de Léon in 1513 and 1521 and Lucas Vázquez de Ayllón in 1526, left no evidence concerning drought, although second-hand sources concerning each expedition describe encountering an unexpectedly cool climate. The earliest written indication of a drought in North America comes from Álvar Núñez Cabeza de Vaca, one of the few survivors of an ill-fated expedition begun in 1528 under the leadership of Pánfilo de Narváez. In his lengthy but often confusing account of the survivors' wanderings in the American Southwest, Cabeza de Vaca described being asked by Native Americans in what was likely present-day south Texas to pray for rain to avert a drought, probably in 1535. This episode does not appear in the other surviving eye-witness testimony of these travels. A comparison with the NADA map of PDSI for that year (Figure 1), indicates dry, but not extreme, conditions in that region in 1535, but not elsewhere on Cabeza de Vaca's itinerary.

{Figure 1 here; caption: NADA JJA PDSI reconstruction for 1535, American Southwest}

3.2.2. Soto Expedition

During 1539-1542 a large Spanish expedition originally led by Hernando de Soto began in northern Florida and subsequently moved throughout the present southeastern United States before traveling down the Mississippi River and returning to New Spain. Despite multiple detailed independent descriptions of extreme cold during the expedition, no historical sources left direct descriptions of drought. The only evidence of drought comes from a 1541 episode, described by multiple eye-witnesses, in which Native Americans in present-day northern Arkansas asked Soto pray for rain to avert a drought and crop failure. The NADA map for 1541 (Figure 2a) indicates a drought centered on northeast Arkansas during 1541, while the rest of the region traversed by the Soto expedition had above average soil moisture at this time. The NADA time series for the approximate site of this rain-making ceremony (Figure 2b) indicates that 1541 was the start of a longer drought at this location, as measured by PDSI.

{Figure 2a here; caption: NADA JJA PDSI reconstruction for 1541, Soto expedition}
{Figure 2b here; caption: NADA JJA PDSI reconstruction time series for 1530-1550 at approximate location of 1541 observed rain-making ceremony}

3.2.3. Coronado Expedition

During 1540 and 1541, a large expedition from Mexico led by governor Francisco Vázquez de Coronado occupied first the Zuni pueblos of today's western New Mexico, then various Puebloan towns of the central Rio Grande valley. Of the many surviving official and personal accounts of the expedition, several mentioned heavy winter snows and none mentioned drought, even though most members of the expedition were expecting a Mediterranean climate and not New Mexico's Southwestern desert climate. This evidence for above-normal winter precipitation during the expedition matches well with the NADA composite reconstruction for region during 1540-1541 (Figure 3a), showing exceptionally moist conditions, as well as the time series for the approximate location of the Spanish occupation around present-day Bernalillo, New Mexico during 1540 and 1541 (Figure 3b).

{Figure 3a here; caption: NADA JJA PDSI reconstruction for 1540-1541, New Mexico}
{Figure 3b here; caption: NADA JJA reconstruction time series for 1530-1550, Bernalillo, NM}

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3.2.4. Luna Expedition

In late summer 1559, Spanish conquistador Tristán de Luna y Arellano led over 1,500 soldiers and colonists to settle in Pensacola Bay, Florida, where a hurricane soon destroyed most of their ships and supplies. Unable to live off the land and facing famine, the colony retreated inland to central Alabama, while a detachment explored the region of northeast Alabama and northwestern Georgia, thought to be more promising for settlement. The expedition's breakdown left ample official documentation, including many complaints about the region's environment and climate. These mentioned the frequency and unpredictability of rains—in contrast to those of Mediterranean climates on the same latitude across the Atlantic—but not drought. The NADA composite map of the area in 1559-1560 (Figure 4a) indicates somewhat below-average moisture around Pensacola Bay and above-average moisture in northeastern Alabama and northwestern Georgia, with average conditions in central Alabama, as also indicated in the time series for the approximate location of the colony in that region (Figure 4b).

{Figure 4a here; caption: NADA JJA PDSI reconstruction for 1559-1560, Luna expedition}
{Figure 4b here; caption: NADA JJA PDSI reconstruction time series for 1550-1570, central Alabama}

3.2.5. French and Spanish Florida colonies

Between 1562 and 1565, French Huguenots attempted to establish colonies on the coast between present-day South Carolina and northern Florida. These were over-run by the Spanish, who established the permanent colony of St. Augustine, Florida, as well as several outlying posts including St. Elena, South Carolina, which lasted until 1587. The French colonies, as described in several personal accounts by eye-witnesses, suffered from frequent shortages and sometimes famine caused by poor supplies, shipwreck, and inability to obtain food from local indigenous communities. The Spanish presence left a much more complete documentary record testifying to droughts during 1565-66 in the region between South Carolina and northern Florida, and drought and/or harvest failures at the St. Augustine colony in 1588-89 and 1598-99. Multiple sources include a description of Native Americans asking the colony's governor at St. Augustine to pray for rain in 1566.

The NADA composite map for 1565-1568 (Figure 5a) indicates a severe drought centered on South Carolina during those years. The time series of PDSI variation at St. Augustine during 1560-1580 (Figure 5b) indicate that the worst years of the drought there occurred in 1566 and 1569; a time series of PDSI variation at St. Augustine in 1580-1610 (Figure 5c) indicates that the worst local droughts in that period occurred in 1586-1589 and 1598-1599, again closely matching the evidence from the archives of societies. Lesser droughts, for which there is not apparent written evidence, occurred locally in 1583 and during the early 1590s.

{Figure 5a here; caption: NADA JJA PDSI reconstruction for 1565-68, French and Spanish Florida}
{Figure 5b here; caption: NADA JJA reconstruction time series for 1560-1580, St. Augustine}
{Figure 5c here; caption: NADA JJA reconstruction time series for 1580-1610, St. Augustine}

3.2.6. Ajacán

In 1570, a small group of Spanish Jesuit missionaries attempted to establish an outpost in approximately the same region as the later English colony of Jamestown, Virginia. In the scarce documentation that survives from the expedition, they reported that the land was "punished with six years of sterility and death," and that both maize and wild plants had died or were inaccessible due to intense cold and snows. Native Americans massacred the priests in early 1571. Stahle et al. 1998 first identified a regional drought in the eastern Virginia and North Carolina tree-ring record during the six years leading up to the colony's founding, which also appears in the NADA composite map for Virginia 1565-1570 (Figure 6a). The time series of

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PDSI variation for the approximate location (Figure 6b) indicates persistent if not always severe drought since 1562, with the worst year (PDSI=-3) occurring in 1566.

{Figure 6a here; caption: NADA JJA PDSI reconstruction for 1565, Virginia
{Figure 6b here; caption: NADA JJA PDSI reconstruction time series for 1560-1580, approximate location of Ajacán}

3.2.7. Roanoke

Between 1585 and 1588, English investors led by Sir Walter Raleigh made several attempts to colonize Roanoke Island in the Carolina Outer Banks, before losing all contact with the final "lost colony." A settler in 1586 described a drought that withered Native American maize and reported being asked to pray for rain to end that drought. During the following year, colonists were unable to obtain maize from indigenous communities by threats or barter, and they therefore suffered famine. Stahle et al. 1998 identified 1587-1589 as the deepest drought in the eastern Virginia and North Carolina tree-ring record; and the NADA composite map for 1585-1588 (Figure 7) shows a major drought in eastern North Carolina, although not specifically for Roanoke Island, which lacks its own tree-ring record.

{Figure 7 here; caption: NADA JJA PDSI reconstruction for 1585-1588, eastern North Carolina}

3.2.8. New Mexico 'Rediscovery'

During 1581, 1583, and 1590-1591, three small officially unauthorized expeditions entered New Mexico from New Spain. Each remained only a few weeks or months, made no enduring colony, and left only a few written testimonies by eye-witnesses. The first in 1581 mentioned a "climate like that of Castile": a likely indication of more winter than summer precipitation. (Spanish explorers also compared the seasons of coastal southern California, which has a Mediterranean climate, to those of Castile, but did not make this comparison for seasons of the Southeast.) Testimonies reported witnessing a Puebloan rain-making ceremony, although it is not clear whether this was a normal seasonal ritual or a specific response to a drought. The second expedition in 1583, described heavy snows early in the year but reported Puebloans refusing to share maize due to a "lack of rain" and poor harvest that summer. The third in 1590-1591 traveled mainly during the winter months and left detailed descriptions of exceptional cold and heavy snows but no evidence of drought.

Tree ring-based reconstructions have identified a "mega-drought" centered on northwestern Mexico and the Southwestern United States, with shifting spatial patterns, during the 1560s-1590s (Meko et al., 1995; Stahle et al., 2007; Margolis et al., 2011). A similar mega-drought appears in a precipitation reconstruction based on band thickness in an annually banded speleothem in New Mexico (Asmerom et al., 2013). These expedition records provide some of the very few direct written environmental descriptions of that region during this period. The NADA maps of PDSI in New Mexico indicate little drought in 1581 (Figure 8a), severe drought across the present-day state in 1583 (Figure 8b), and severe drought across the present-day state in 1590 (Figure 8c). The written testimonies from the 1583 expedition appear to confirm that the hydrologic drought in the tree-ring record was also a meteorological and agricultural drought with societal impacts, while the evidence from all three expeditions suggests inconclusively that there may have been a greater deficit in summer than winter precipitation—i.e., a failure of the Southwestern summer "monsoon." However, a tree ring-based reconstruction attempting to distinguish winter and summer precipitation signals using early- and latewood measurements has concluded that the regional mega-drought affected both seasons (Stahle et al., 2009).

{Figure 8a here; caption: NADA JJA PDSI reconstruction for 1581, New Mexico}
{Figure 8b here; caption: NADA JJA PDSI reconstruction for 1583, New Mexico}
{Figure 8c here; caption: NADA JJA PDSI reconstruction for 1590, New Mexico}

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3.2.9. Oñate expedition

A 1598 invasion from Mexico led by Juan de Oñate occupied present-day New Mexico and subjugated the Pueblos of the region. In 1601, the expedition nearly collapsed when a large number of officers and settlers defected. Narratives of Oñate's campaign, as well as disputes arising from the colony's near collapse, left a large body of personal and official evidence concerning conditions in New Mexico. The earliest indication of a drought occurs in a description of Native Americans asking colonists to pray for rain in 1598; however, this episode appears only in one unreliable source. Colonists during 1599 and 1600 compared the climate to that of Castile, with predominately winter precipitation. Abundant written evidence for extreme summer drought appears in 1600 and 1601, along with descriptions of starvation when the Pueblo maize crop failed and livestock died for want of pasture. However, descriptions also indicate that the winter of 1600-01 was exceptionally snowy and icy and late frost occurred the following spring. Moreover, sources agree that the colony's crop of irrigated winter wheat succeeded.

Tree ring-based reconstructions have identified a serious three- to five-year regional drought beginning in 1598 (Grissino-Mayer et al., 2002). The NADA composite map for New Mexico during 1598-1601 (Figure 9a) indicates significant deficits in summer soil moisture, particularly in the central and northern parts of the present-day state, where the expedition settled. The NADA times series for the location of Oñate's first colony at present Okhay Owingeh pueblo (Figure 9b) indicates droughts in 1598 and 1600-1601, but not as significant as those of the earlier mega-drought evident during the early 1580s.

{Figure 9a here; caption: NADA JJA PDSI reconstruction for 1598-1601, New Mexico
{Figure 9b here; caption: NADA JJA PDSI reconstruction time series for 1580-1610, Okhay Owingeh, New Mexico}

3.2.10. Jamestown colony

The English colony at Jamestown, Virginia suffered through multiple environmental disasters, conflict with Native Americans, and high mortality from its founding in 1607 through 1610, when it was rescued by a large infusion of new settlers and supplies. Abundant evidence from the archives of societies testifies to exceptional summer drought throughout these first years at the colony. Settlers' summer grain crops failed repeatedly, and Native Americans reportedly faced shortages of corn. In summer and autumn, saltwater apparently intruded into the James River as far as Jamestown, where it was described as "at flood verie salt, at low tide full of slime and filth"; salt poisoning may have contributed to the exceptional mortality at the colony (Earle, 1979). In 1608 or 1609, a leader of a nearby indigenous community asked colonists to pray for rain to end the drought. During the "starving time" in winter 1609-1610 roughly three quarters of the remaining settlers died of famine and related diseases. During the period 1607-1610, sources also describe the winters as exceptionally cold, with much frost and snow.

Stahle et al. 1998 identified 1606-1612 as the driest 7-year period in the past 770 years in the eastern Virginia and Carolina tree-ring record. The NADA composite map for 1606-1610 (Figure 10a) indicates a moderate drought over southeastern Virginia. The NADA time series of PDSI variation for 1600-1620 at the location of Jamestown (Figure 10b) indicates a deficit of soil moisture each summer during 1606-1612, with a severe drought (PDSI=-3) in 1610. The evidence from the archives of societies suggests that hydrologic drought indicated in the tree-ring record reflects a summer meteorological and agricultural drought, rather than a deficit in winter precipitation. A study of oxygen isotope variations in speleothems from West Virginia caves also suggests a regional shift from summer to winter precipitation (i.e., precipitation less enriched in ^{18}O) ca.1600CE (Hardt et al., 2010).

{Figure 10a here; caption: NADA JJA PDSI reconstruction for 1606-1610, eastern Virginia and North Carolina}
{Figure 10b here; caption: NADA JJA PDSI reconstruction time series for 1600-1620, Jamestown, VA}

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4. Discussion

This study finds broad agreement between the evidence from the archives of societies and that from the archives of nature concerning the occurrence and severity of droughts in North American during 1510-1610CE. The results indicate that the written historical records correctly identified drought in most locations and years during which substantial written observations were made, and conversely that the records did not incorrectly identify droughts for any time and location where the archives of nature identified a positive hydroclimate anomaly. This convergence of evidence suggests that early colonial records may provide useful indicators for the presence, absence, and impacts of drought in regions for which there is little other written evidence. The advantages of early colonial sources for historical climatology, including their authors' interest in environmental factors and vulnerability to environmental extremes, appear to balance out their disadvantages, such as unfamiliarity with local climates. This finding may encourage further historical climate research into records of colonial North America as well as Australia and other regions for which early colonial records may fill a gap in evidence concerning droughts (e.g., Gergis et al., 2010). These early colonial records may also be used to shed light on the climatic vulnerabilities and adaptations of indigenous peoples before their societies were transformed by colonialism and introduced pathogens (e.g., White, 2014; Wickman, 2018) and thus to test hypotheses of proto-historic climate-driven depopulation or migration based on the archaeological record and paleoclimate proxies (e.g., Anderson, 1994; Bird et al., 2017).

The results also suggest that the NADA reconstructions provide data useful at the level of human historical events. In contrast to historians' findings that the corresponding Old World Drought Atlas has been unable to reproduce well-verified historical climate anomalies (e.g., Collet, 2018: 74), the NADA appears to consistently identify droughts found in the archives of societies. In this case, the hydrologic droughts indicated in NADA also appear as summer meteorological and agricultural droughts in historical records.

Written records for the late 1500s and early 1600s in the Southwest and Virginia confirm that summers were exceptionally dry but indicate that winters were snowy. This suggests that the NADA summer PDSI reconstruction may be more sensitive to summer precipitation at some precise locations (a possibility acknowledged in St. George et al., 2010). Thus these early colonial records provide some confirmation, if only anecdotal, of widespread exceptional spring-summer droughts and societal impacts during the late 16th and early 17th centuries indicated in studies of several regions of the North Hemisphere mid-latitudes, including North America, the Middle East, and China (Alfaro-Sánchez et al., 2018).

Finally, the evidence presented here highlights the significant impact of drought on many early European colonial expeditions. Drought was not the only environmental challenge during these expeditions, and did not affect expeditions to all parts of continent. European explorers and colonists also faced challenges resulting from the extreme cold and storms described in many sources as well as non-environmental factors such as poor leadership, poor planning, and confusion over the conditions they would face in the New World. Nevertheless, the evidence reviewed in this study confirms that drought occurred with unusual frequency and severity during expeditions to the Southeast, Southwest, and Chesapeake regions, and that drought created multiple stressors for these expeditions, including failure of crops, competition with Native Americans for scarce remaining provisions, and poor water quality and related illnesses. It seems reasonable to conclude that the outcome of many early expeditions—and therefore the timing and geography of the European colonization of North America—would have been substantially different had those expeditions not encountered droughts.

5. Conclusion

This study has presented evidence concerning drought and its impacts based on a comprehensive review of written historical evidence concerning all early European expeditions to North America 1500-1610CE as well as a comparison of this evidence to tree-ring based NADA PDSI maps and time series. It has found that the information on drought drawn from the archives of societies is consistent with that from the archives of nature. The comparison between the two demonstrates the potential

usefulness of early colonial records for drought reconstruction and the applicability of NADA results to the scale of human historical events. Written historical evidence indicates that major JJA hydrologic droughts in the Southwest and Chesapeake region reconstructed in the NADA reflect summer meteorological and agricultural droughts that had major societal impacts and almost certainly influenced the outcome of colonial expeditions.

The author reports no conflicts of interest.

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Table 1: A summary of information concerning the presence or absence of drought, and impacts attributed to drought, for each European expedition to North America during 1510-1610CE drawn from the archives of societies. An explanation of sources and types of evidence is provided in section 2.1. A question mark indicates that the evidence is uncertain, as explained for each instance in the relevant part of the section 3.2.

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Region	Year	Expedition/Colony	Location	Phenology	Description	Impact	Rain Prayer
Southeast	1513	Ponce de León	Florida coast		cool and wet		
	1521	Ponce de León	Florida coast				
	1526	Ayllón	Carolina coast				
	1528	Narváez	Florida Gulf coast				
	1529	Cabeza de Vaca	Texas Gulf coast			famine	
	1535	Cabeza de Vaca	south Texas?				Y
	1539	Soto	Florida				
	1540	Soto	interior SE				
	1541	Soto	Mississippi				
	1541	Soto	Arkansas				Y
	1559	Luna	Mississippi				
	1560	Luna	Mississippi		frequent heavy rains		
	1562	Charlesfort	S Carolina				
	1563	Charlesfort	S Carolina				
	1563	Fort Caroline	Florida				
	1564	Fort Caroline	Florida			famine	
	1565	Fort Caroline/St. Augustine	Florida			famine	
	1566	St. Augustine	Florida			famine	Y
	1567	St. Augustine	Florida				
	1588	St. Augustine	Florida	poor harvest			
	1589	St. Augustine	Florida	poor harvest			
	1591	St. Augustine	Florida	poor harvest			
	1598	St. Augustine	Florida	poor harvest			
	1599	St. Augustine	Florida	poor harvest			
Chesapeake	1524	Verrazzano	Atlantic coast				
	1570	Ajacán	Virginia			"sterility and death"	
	1585	Roanoke	N Carolina				
	1586	Roanoke	N Carolina	corn whiters	"extraordinary drought"		Y
	1587	Roanoke	N Carolina			famine	
	1588	Roanoke	N Carolina				
	1607	Jamestown	Virginia	saltwater intrusion into James River; late planted crops fail		famine and high mortality	
	1608	Jamestown	Virginia	poor harvest			Y
	1609	Jamestown	Virginia	poor harvest			
	1610	Jamestown	Virginia	poor harvest		famine	

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New England	1602	Gosnold	New England coast				
	1603	Pring	New England coast				
	1605	Waymouth	New England coast				
	1604	St. Croix	Maine				
	1605	St. Croix	Maine				
	1608	Sagadahoc	Maine				
Southwest	1540	Coronado	New Mexico		heavy snow		
	1541	Coronado	New Mexico		heavy snow		
	1581	Chamuscado-Rodríguez	New Mexico		"climate like that of Castile"		Y?
	1583	Espejo	New Mexico		heavy snow in March; "lack of rain" in July	shortage of corn	
	1590	Castaño de Sosa	New Mexico				
	1598	Oñate	New Mexico				Y?
	1599	Oñate	New Mexico		climate like Castile; dry summer; winter snows		
	1600	Oñate	New Mexico	irrigated wheat fields successful; summer corn poor			
	1601	Oñate	New Mexico	(as in 1600)	"no rain this year"	famine	
California Coast	1542	Cabrillo	California coast				
	1587	Unamuno	California coast				
	1595	Cermeño	California coast				
	1596	Vizcaíno	California coast		"climate and sort of winter…the same as that of Castile"		
	1602	Vizcaíno	California coast		summer and winter compared to those of Castile		
	1603	Vizcaíno	California coast				
Canada	1534	Cartier	Gulf of St. Lawrence				
	1535	Cartier	Gulf of St. Lawrence				
	1536	Cartier	St. Lawrence				
	1541	Cartier	St. Lawrence				
	1542	Cartier	St. Lawrence				
	1542	Roberval	St. Lawrence				
	1543	Roberval	St. Lawrence				
	1598	La Roche	Sable Island				
	1599	La Roche	Sable Island				
	1600	La Roche	Sable Island				
	1601	La Roche	Sable Island				
	1602	La Roche	Sable Island				
	1603	La Roche	Sable Island				
	1600	Tadoussac	Tadoussac				
	1601	Tadoussac	Tadoussac				
	1606	Port-Royal	Nova Scotia				

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	1607	Port-Royal	Nova Scotia				
	1608	Champlain	Quebec city area				
	1609	Champlain	Quebec city area				
	1610	Champlain	Quebec city area				

Figure 1: NADA JJA PDSI reconstruction for 1535, American Southwest

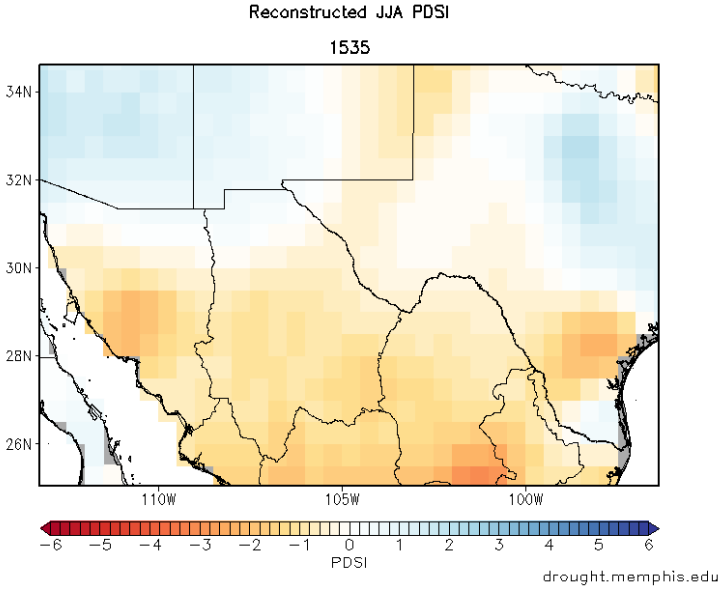

Figure 2a: NADA JJA PDSI reconstruction for 1541, Soto expedition

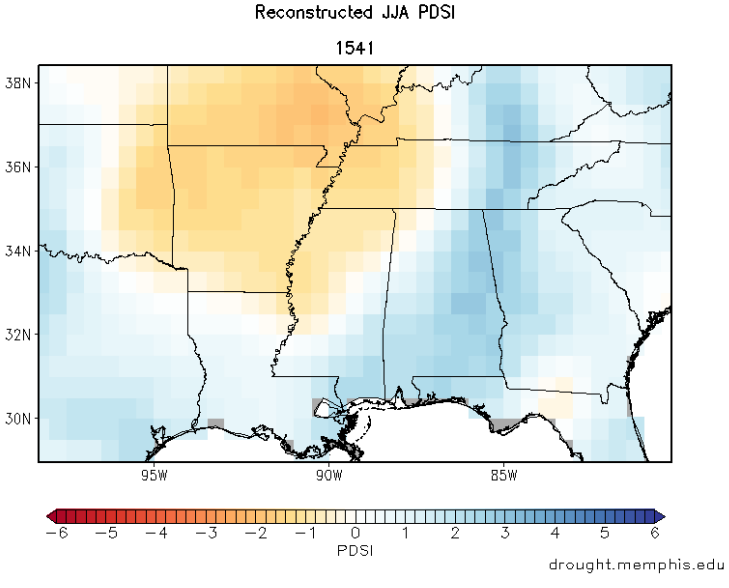

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Figure 2b: NADA JJA PDSI reconstruction time series for 1530-1550 at approximate location of 1541 observed rain-making ceremony

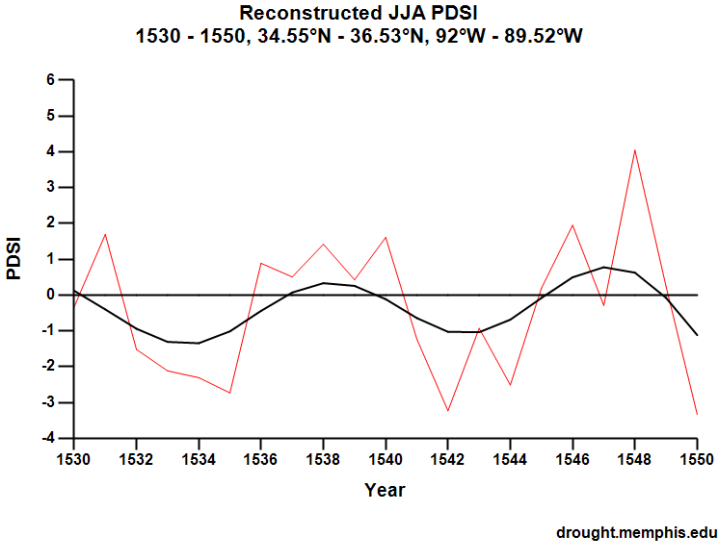

Figure 3a: NADA JJA PDSI reconstruction for 1540-1541, New Mexico

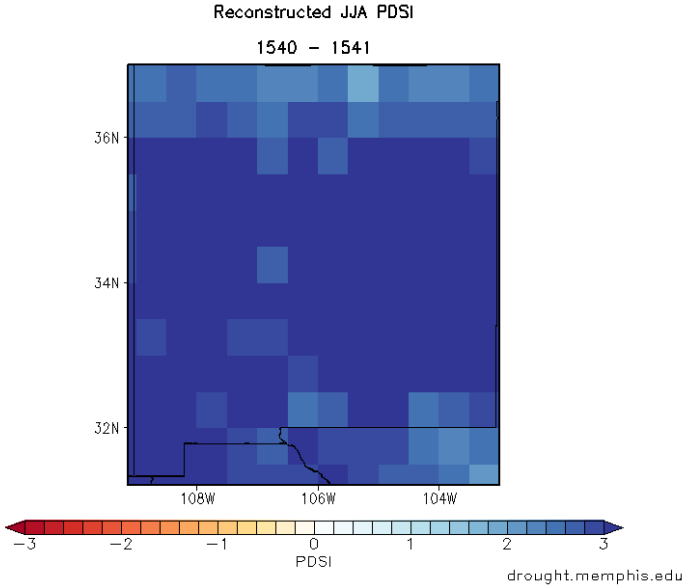

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Figure 3b: NADA JJA reconstruction time series for 1530-1550, Bernalillo, NM

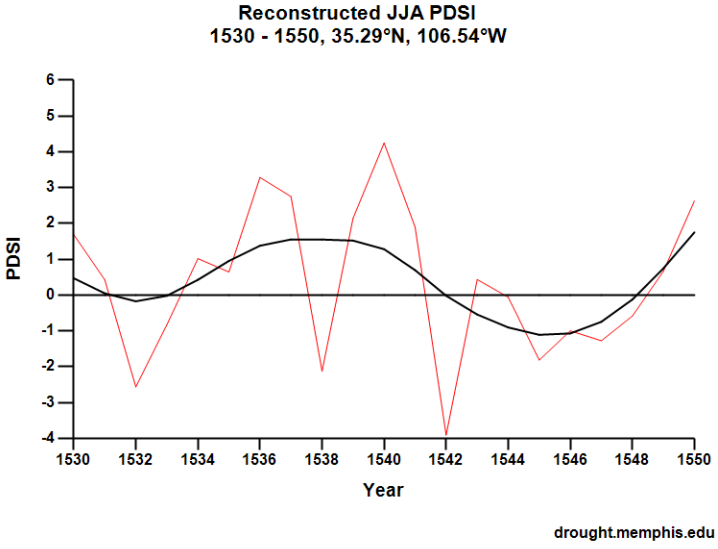

Figure 4a: NADA JJA PDSI reconstruction for 1559-1560, Luna expedition

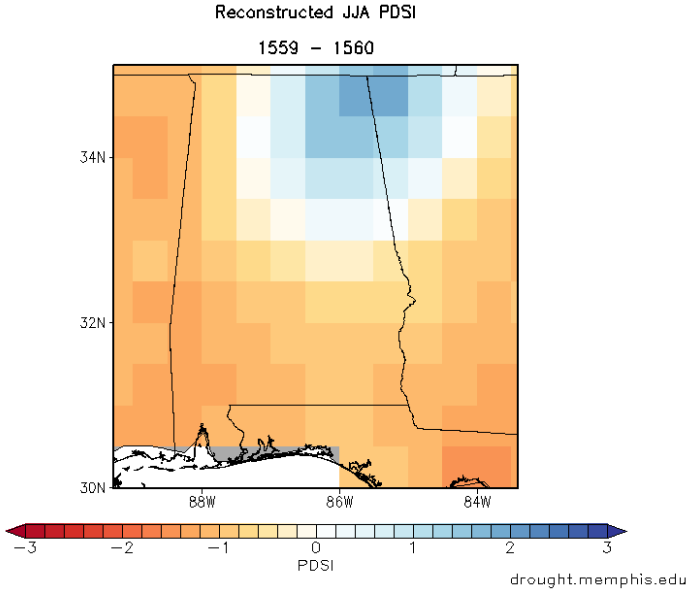

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Figure 4b: NADA JJA PDSI reconstruction time series for 1550-1570, central Alabama

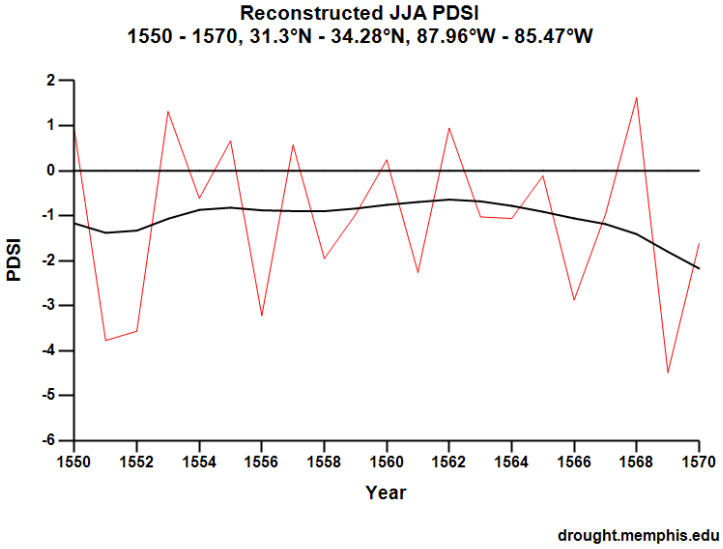

Figure 5a: NADA JJA PDSI reconstruction for 1565-68, French and Spanish Florida

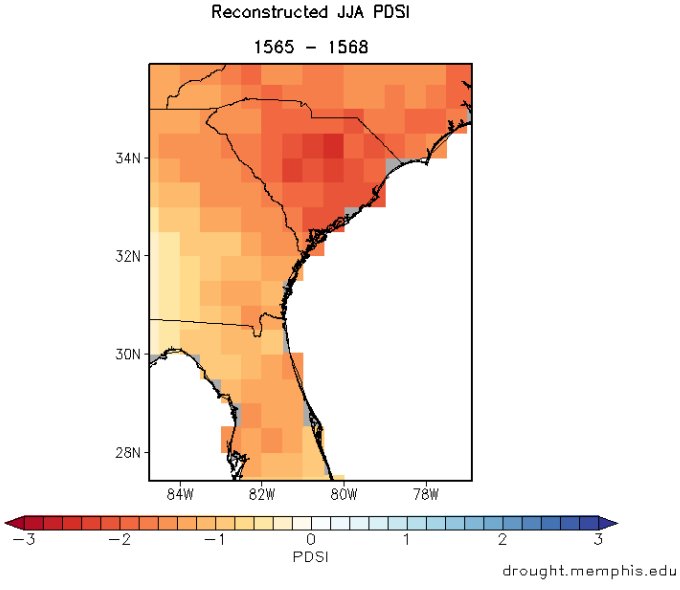

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Figure 5b: NADA JJA PDSI reconstruction time series for 1560-1580, St. Augustine

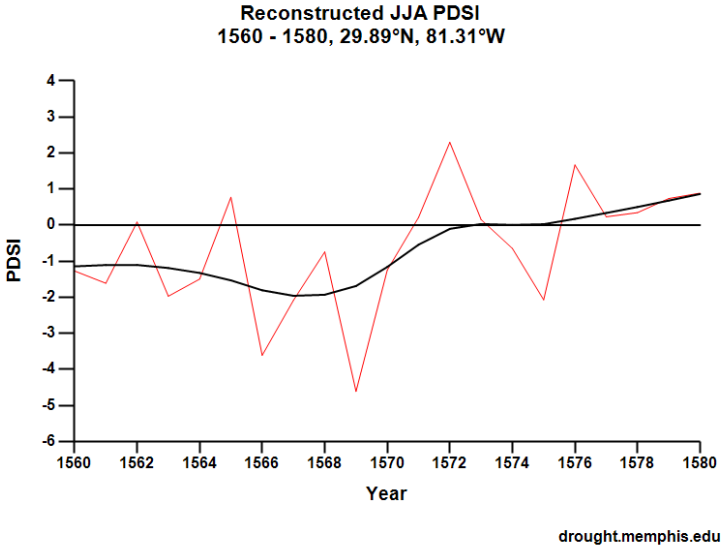

Figure 5c: NADA JJA PDSI reconstruction time series for 1580-1610, St. Augustine

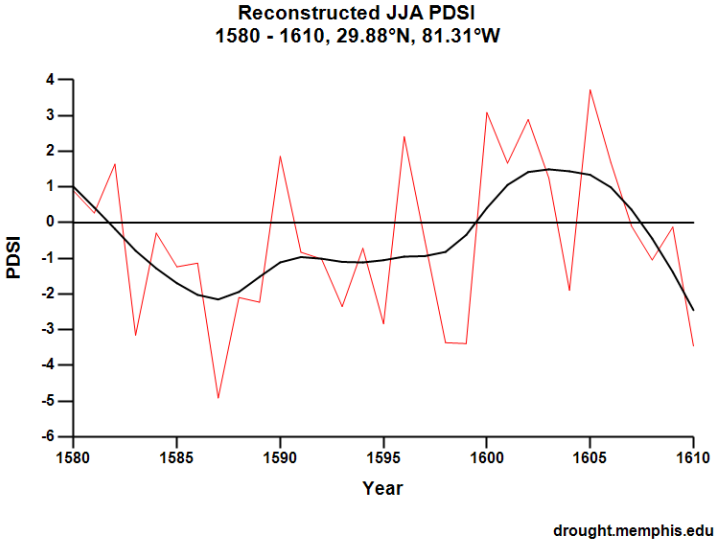

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Figure 6a: NADA JJA PDSI reconstruction for 1565, Virginia

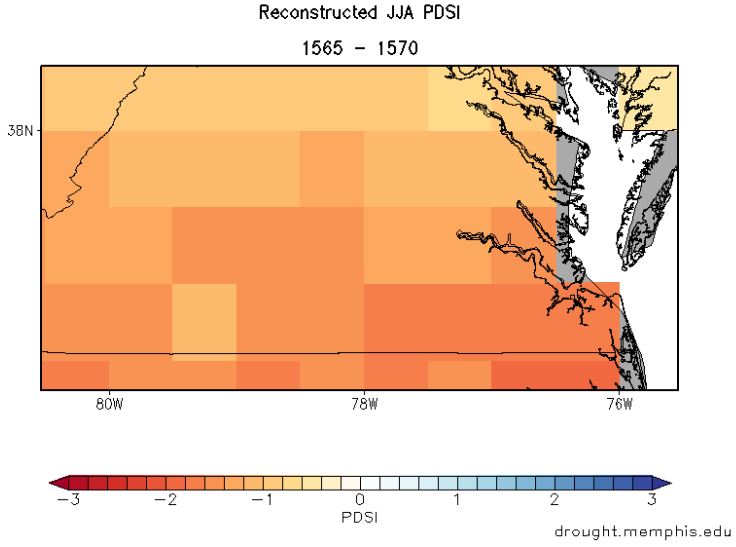

Figure 6b: NADA JJA PDSI reconstruction time series for 1560-1580, approximate location of Ajacán

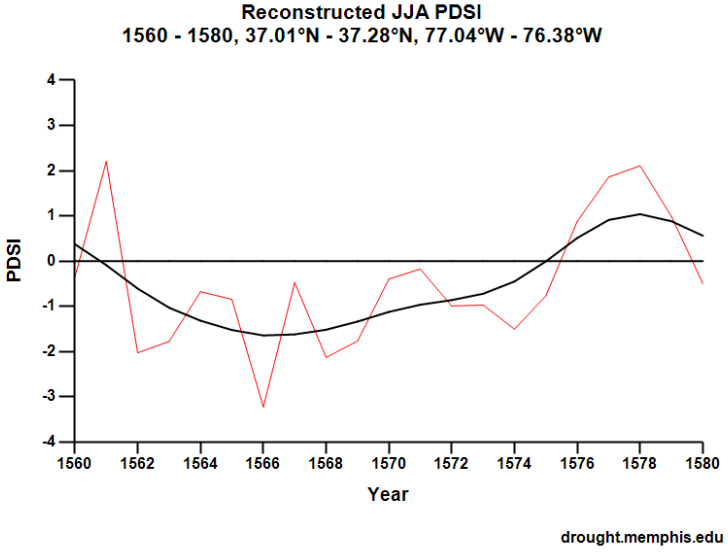

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Figure 7: NADA JJA PDSI reconstruction for 1585-1588, eastern North Carolina

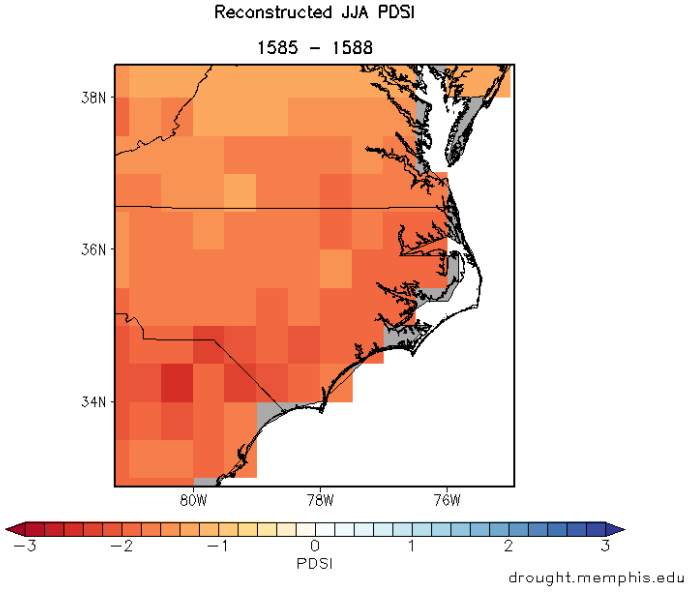

Figure 8a: NADA JJA PDSI reconstruction for 1581, New Mexico

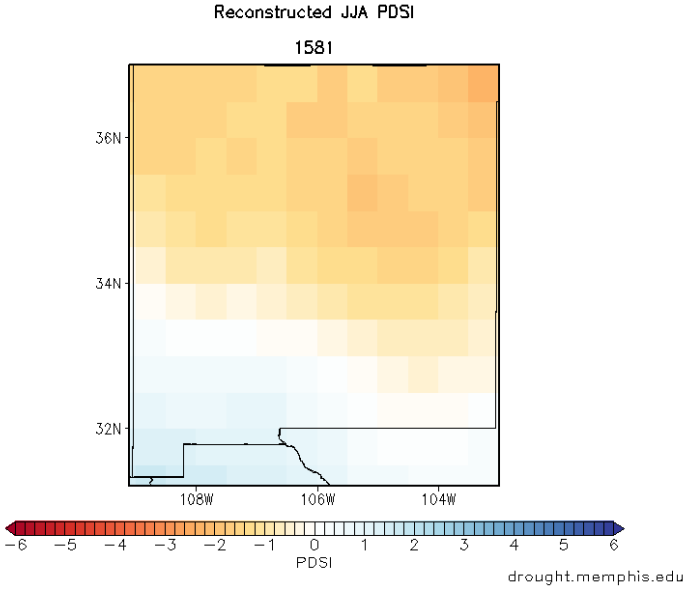

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Figure 8b: NADA JJA PDSI reconstruction for 1583, New Mexico

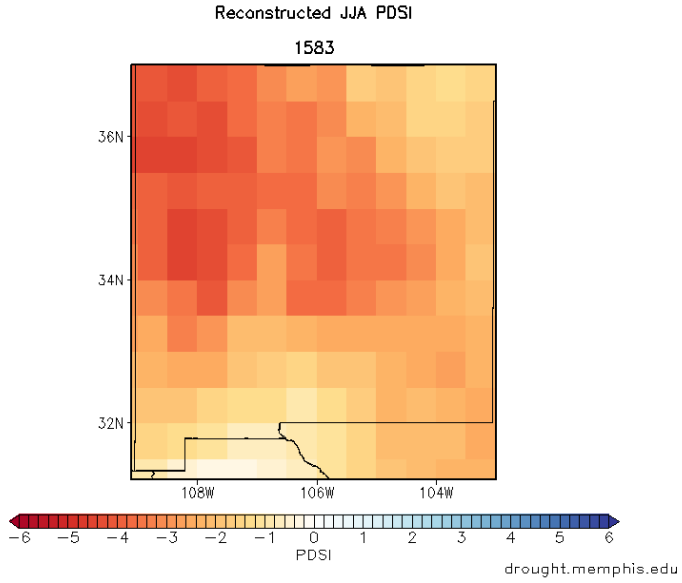

Figure 8c: NADA JJA PDSI reconstruction for 1590, New Mexico

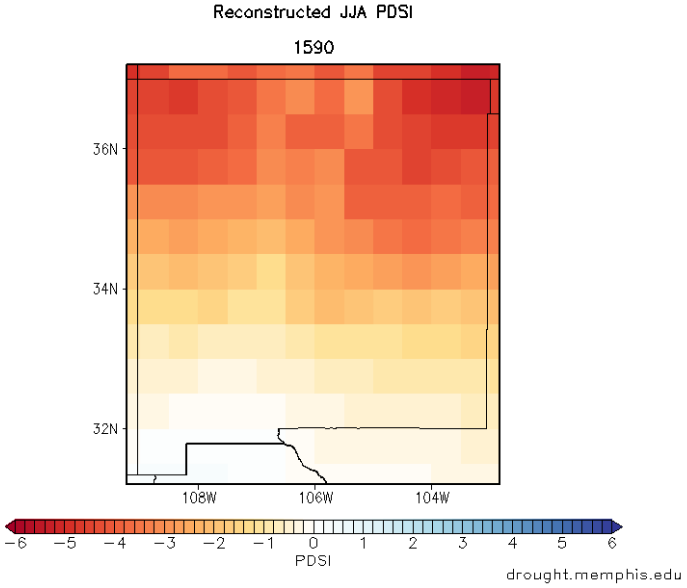

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Figure 9a: NADA JJA PDSI reconstruction for 1598-1601, New Mexico

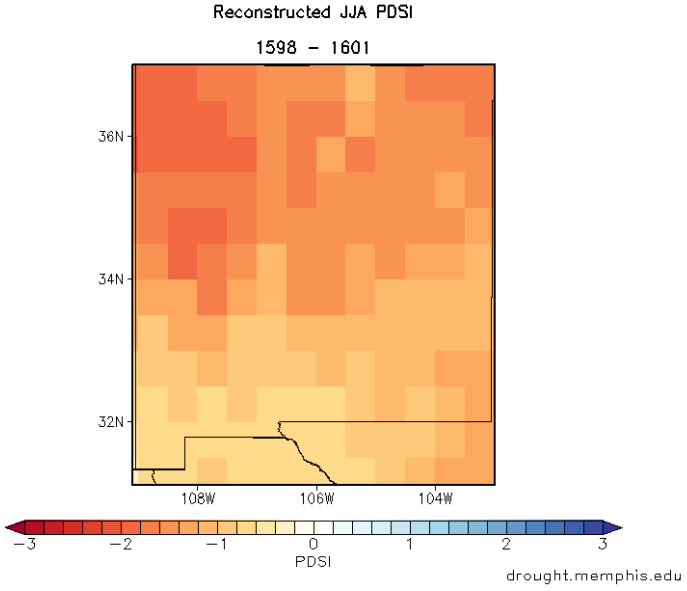

Figure 9b: NADA JJA PDSI reconstruction time series for 1580-1610, Okhay Owingeh, New Mexico

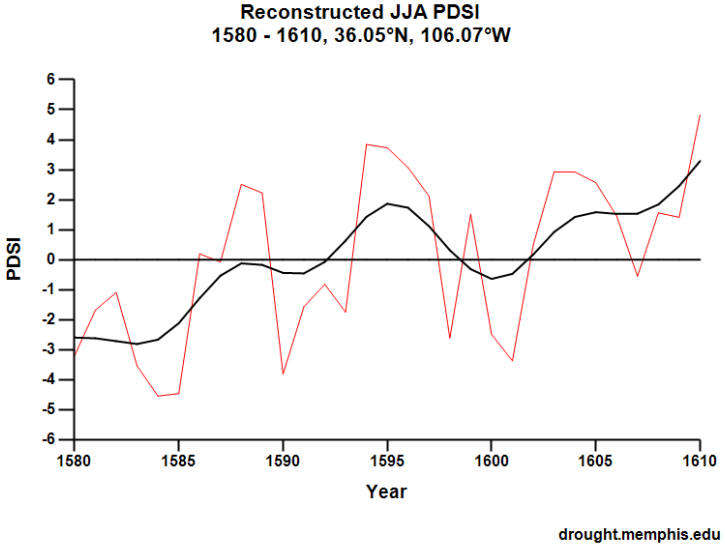

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Figure 10a: NADA JJA PDSI reconstruction for 1606-1610, eastern Virginia and North Carolina

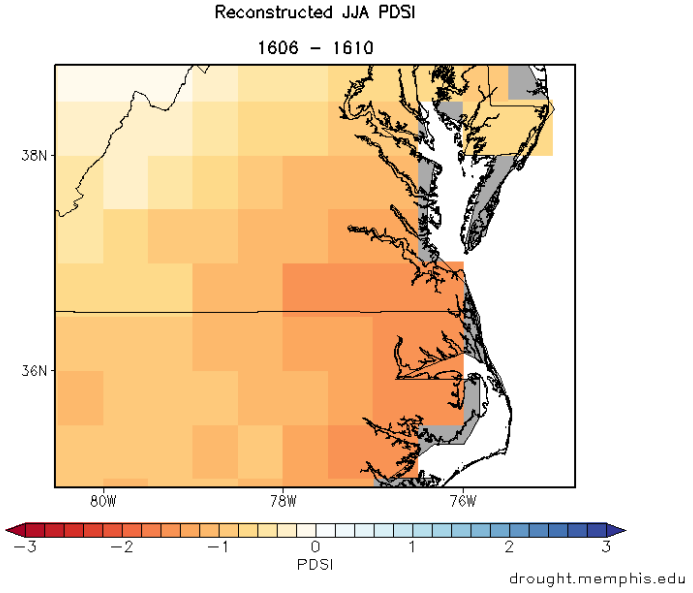

Figure 10b: NADA JJA PDSI reconstruction time series for 1600-1620, Jamestown, VA