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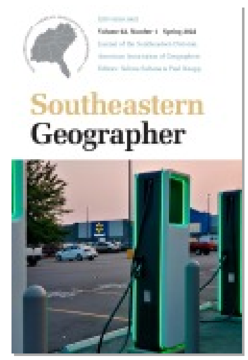

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Temporal Patterns of Drought Frequency and Severity in North Carolina, 1920–2019 and the Drought Gap of the 1960s–1970s

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HIGHLIGHTS

- An analysis of 100 years of drought in North Carolina shows that droughts are more frequent since 1970.
- Significant trends in drought severity in North Carolina are largely absent for recent 100–, 50–, and 30–year periods.
- Considerable spatiotemporal variability in drought frequency and severity exists across the state of North Carolina.

ABSTRACT: *Residents of North Carolina have endured the negative impacts of droughts for centuries. In this study, I examine spatiotemporal aspects of drought across North Carolina's eight climate divisions over a recent 100–year period (1920–2019). Using the Palmer Drought Severity Index, I define a drought event as any period of three or more consecutive months recording moderate to extreme drought conditions. I compare drought frequency, intensity, and length between early (1920–1969) and late (1970–2019) 50–year periods and test for trends in drought severity for the full 100–year study period and the most recent 50– and 30–year periods. For the majority of climate divisions, droughts are more frequent and longer in the late period. However, these differences were not statistically significant (*$p > 0.05$*) in any climate division or for the entire state. Similarly, trends in drought severity were generally absent, with only two climate divisions recording a significant trend toward drier conditions. Temporally, the long-term patterns reveal that droughts were largely absent statewide during the 1960s and 1970s. Considerable spatial variability exists within the state, with the southern coastal plain and Piedmont climate divisions the most anomalous for frequency and intensity.*

KEYWORDS: Drought events, Drought frequency, Drought severity, Palmer Drought Severity Index, North Carolina

INTRODUCTION

The impact of drought on residents of North Carolina goes back centuries, as the demise of the "Lost Colony" of Roanoke Island was shown via analyses of tree rings to be concurrent with an extreme drought in the late 1500s (Stahle et al. 1998). Thus drought was a likely contributing factor to this historical event. A climate reconstruction from bald cypress trees suggests that alternating periods of drought and wetness that last as long as three decades have been a component of North Carolina's climate since 372 CE (Stahle et al. 1988). While droughts in prior centuries were more persistent than droughts in recent decades (Seager et al. 2009), drought remains an important component of the climatology of North Carolina (Patterson 2014).

Studies of drought are often focused on single or multi-year events. For the southeastern United States in general and North Carolina specifically, two of the more heavily studied drought events occurred in 2007 (Flanders et al. 2007, Luo and Wood 2007, Clark et al. 2008, Manuel 2008, Maxwell and Soulé 2009) and 1986 (Bergman et al. 1986, Karl and Young 1987, Cook et al. 1988). The 2007 drought peaked in November, with all climate divisions in North Carolina experiencing a top-10-ranked drought, and three climate divisions experiencing the top-ranked November drought on record (Maxwell and Soulé 2009). The Southeast experienced a suite of impacts from this drought including limits on municipal water use, reduced agricultural productivity, significant drops in reservoir levels (Maxwell and Soulé 2009), and widespread economic losses (Flanders et al. 2007). Karl and Young (1987) examined the 1986 drought in the southeastern United States from both a hydrological and an agricultural perspective. They used an index that measures short-term variation in moisture available to examine conditions meaningful to agricultural activity and concluded that 1986 was the worst agricultural drought in the instrumental record, producing recurrence intervals as high as 979 years in the southern Piedmont region of North Carolina. For hydrologic conditions, they analyzed long-term data from the Palmer Hydrological Drought Index, which responds more slowly to changing moisture conditions than other drought indices (Soulé and Yin 1995) and concluded that hydrological drought conditions were not as severe as agricultural drought conditions, but still extreme, with a peak recurrence interval of 685 years in the southern Appalachian Mountains. Cook et al. (1988) also used recurrence intervals to place the 1986 drought in historical context, but they extended the record back to 1700 CE using tree-ring data and concluded it produced a recurrence interval of > 287 years. Bergman et al. (1986) note similar impacts for the 1986 southeastern drought (i.e., agricultural losses, water rationing), with some portions of North and South Carolina receiving less than 40 percent of mean precipitation from December 1985 through July 1986.

The drought literature also includes long-term examinations of drought for a region or state that delves into the spatial and temporal patterns (e.g., Eder et al. 1987, Tang and Piechota 2009, Maxwell et al. 2017, Tian and Quiring 2019). An excellent example for North Carolina was completed by Patterson (2014) using long-term (1895–2013) temperature, precipitation, and Palmer Drought Severity Index (PDSI; Palmer 1965) data. Patterson (2014) found that spatial variability of drought conditions among North Carolina's eight climate divisions was great enough to obscure statewide trends and that significant changes in drought severity were largely absent for the full period, but that drought severity had significantly increased in many divisions post-1960. For any study of drought reporting on trends, the period of record examined is crucial, as illustrated by the findings of Yin (1993), who report on significant increasing long-term moisture trends in the southeastern United States for 36 percent of the climate divisions they examined from 1895–1988.

According to Namias (1983), drought in the United States is typically associated with a synoptic pattern that produces prolonged subsidence of air. Persistent ridging and upper-level anticyclonic flow in one region are often teleconnected to anomalous pressure patterns upstream, with the large-scale forcing related to sea-surface temperature anomalies (Namias 1983). Winter droughts in the Southeast may be related to atmospheric perturbations associated with tropical Pacific anomalies (e.g., El Niño/La Niña), especially when analyzing longer-term records of drought supplied by tree rings, but summer drought "arises from internal atmospheric processes and is essentially unpredictable" (Seager et al. 2009, 5029). However, when examining subregions of the Southeast, Ortegren et al. (2014) found that drought in the Southeast Atlantic Coast Region (SACR), which includes all of North Carolina and South Carolina and much of eastern and central Georgia, is significantly related to several measures of large-scale atmospheric-oceanic variability, including the Bermuda High Index (BHI) (Stahle and Cleaveland 1992), suggesting a strong summertime controlling influence. The BHI measures the pressure difference between Bermuda and New Orleans, Louisiana and when negative relates to decreased southerly advection of moisture into the Southeast and thus a greater propensity for drought (Diem 2006, Labosier and Quiring 2013).

In this study, I use a 100–year record of drought in North Carolina's eight climate divisions to: 1) examine temporal patterns in the frequency of drought events and major drought events, 2) determine if there are significant trends in drought severity at 30–, 50–, and 100–year intervals, and 3) examine the temporal patterns of moderate and severe drought months. These analyses allow me to characterize the drought climatology of North Carolina during the instrumental record, identify how drought conditions have changed through time, and highlight the spatial variability of drought within the state.

METHODS

I obtained monthly values of the PDSI from the National Oceanic and Atmospheric Administration's (NOAA's) Physical Sciences Laboratory (NOAA 2020) for each of North Carolina's eight climate divisions (Figure 1). Although climate-division-level data are available back to 1895, the early portion of the record is volatile due to a lower number of stations included in averaging algorithms (Keim et al. 2003). Thus, I began my analyses in 1920 and ended in 2019 to yield a 100–year timeframe. The PDSI is a water balance-based measure of drought severity that is widely used to analyze spatial and temporal patterns of drought (e.g., Diaz 1983, Karl 1983, Soulé and Meentemeyer 1989, Soulé 1992, Maxwell and Soulé 2009, Patterson 2014, Ficklin et al. 2015). The PDSI accounts for the supply and demand of moisture through rainfall and evaporation, and values of a given month are highly dependent on moisture values of preceding months (Palmer 1965, Alley 1984). Thus, on the dry end of the scaling, PDSI values reported in an individual month (e.g., July) are reflective of the general nature of drought as a slowly developing climate phenomenon. PDSI values are centered on zero (positive values reflect wet conditions; negative values dry conditions) and normalized by the expected conditions within a given climate division.

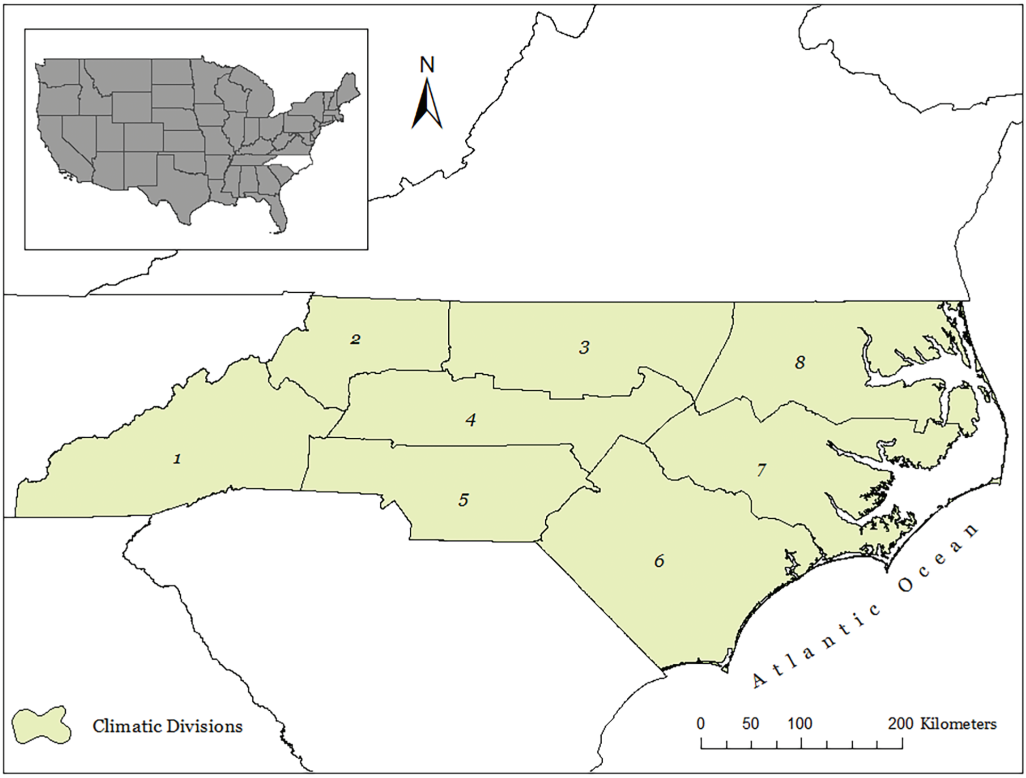

Figure 1. The study area showing North Carolina Climate Division 1 (Southern Mountains), 2 (Northern Mountains), 3 (Northern Piedmont), 4 (Central Piedmont), 5 (Southern Piedmont), 6 (Southern Coastal Plain), 7 (Central Coastal Plain), and 8 (Northern Coastal Plain).

I conducted all analyses for each of North Carolina's eight climate divisions. I began by using a definition of drought first proposed by Diaz (1983). Under this definition, a drought event occurs when a climate division has values of the PDSI < -2.0 for three or more consecutive months. Qualitatively, PDSI values of -2.00 to -2.99 reflect "moderate drought" (Palmer 1965). Similarly, a major drought event occurs when six or more consecutive months have PDSI values < -2.0. I split the 100–year record into an early period (1920–1969) and a late period (1970–2019). I tallied the total number of drought events and major drought events in each period, recorded the longest drought event, and calculated the mean length (months) and mean severity (mean PDSI) of drought for the early and late periods. I tested for significant ($p < 0.05$) differences in length, severity, the number of drought events, the number of major drought events, and the length of the longest drought events between the early and late periods using the non-parametric Mann-Whitney Test and a null hypothesis of no significant difference in the medians of the distributions.

I searched for the presence of significant ($p < 0.05$) drought trends using Mann-Kendall trend analyses for the full 100–year record, the last 50 years of record (1970–2019), and the last 30 years of record (1990–2019). For the trend analyses, I used data from January and July, the first full months of winter and summer. For graphical comparisons of drought conditions across the state, I created line plots of PDSI values from July, as summer drought is generally more critical to human activities than winter drought and fit a 10-year running mean through the patterns to be able to visualize short-term movements. For each year, I tabulated the number of months when PDSI values were < -2.0 (moderate drought threshold) and < -3.0 (severe drought threshold) and presented these patterns using vertical bar plots. For the number of moderate drought months annually, I used the Rodionov Regime Shift Analysis (RSA; Rodionov 2006) to identify regime shifts. I used a Huber's tuning constant of one, a cut-off length of three, and a *p*-value of 0.10. RSA allows for the detection of multi-year periods (i.e., regimes) where the means are statistically different from the preceding and/or following regimes. I presented the RSA patterns by using horizontal lines showing the means of regimes overlaid on the vertical bar plots depicting the number of months annually with moderate and severe drought conditions.

RESULTS AND DISCUSSION

Drought Events

In five of North Carolina's eight climate divisions, more drought events were recorded in the late period compared to the early period, in two climate divisions there were more droughts early than late, and in one climate division, it was tied (Table 1). For the state as a whole, there were 112 drought events recorded in the late period compared to 90 drought events recorded in the early period. While drought events were thus more frequent during the last 50 years of record, in no climate division was this difference statistically significant, or for the state as a whole ($p = 0.315$ from the Mann-Kendall test for the state). I found similar patterns for major drought events, with five of eight climate divisions having more frequent major drought events in the late period, two of eight in the early period with one tie, and no significant differences. Statewide, there were 59 major drought events in the late period compared to 46 drought events in the early period, but this difference was not significant ($p = 0.119$). For the longest droughts, six of eight climate divisions recorded the longest drought in the late period (mean of 24.8 months), one in the early period (mean of 20.4 months), with one tie (Table 1). Despite the tendency for longer droughts being recorded in the last 50 years of the record, there was no significant difference in median length of the longest drought between early and late periods ($p = 0.119$).

Spatially, there are generally more drought events occurring in the Piedmont of North Carolina (divisions 3, 4, and 5) and the fewest in the Coastal Plains regions (divisions 6, 7, and 8). The propensity of landfalling tropical cyclones to end droughts is greater in the Coastal Plains (Maxwell et al. 2012) and declines westward. Differences in the frequency of drought events between the mountain (1 and 2) and Piedmont climate divisions are small. The tendency for slightly more events in the Piedmont could be linked to orographic processes, which cause higher rainfall and snow amounts in the western part of the state, and when weather systems are tracking eastward, can cause minor rainshadow effects for the Piedmont (Soulé 1998). Similarly, the longest droughts were generally recorded in the Piedmont climate divisions, and this is likely a function of location as orographic processes in the mountains can reduce moisture advected eastward, and the propensity for landfalling tropical cyclones to end droughts decreases westward (Maxwell et al. 2012).

Drought Trends

Significant drought trends were largely absent across the state of North Carolina during the most recent 100, 50, and 30 years in the record examined (Table 2, Figure 2). Only divisions 5 and 6 in the southern Piedmont and Coastal Plain had any significant trends, and these were negative, indicating drier conditions or drought. In division 5 the 100–year trend during July was extremely weak, strengthened in the last 50–year period, and weakened to insignificant levels (although still negative) in the last 30 years (Table 2, Figure 2). NC 5 also had a significant negative trend in January (not shown graphically). I found a slightly weaker but still significant trend in January for Climate Division 6.

Drought Gap of the 1960s–1970s

One clear pattern that emerges when examining the temporal patterns of drought as measured by the number of months per year with PDSI < -2.0 and -3.0 is that drought conditions were largely absent statewide in the 1960s and 1970s (Figure 3). Also, the slightly greater frequency of drought conditions in the late (post-1970) period compared to the early period (Table 1) is evident for several climate divisions (e.g., 1, 4, and 5), but there exists substantive spatial variability across the state, as evidenced by Climate Division 6, which experienced a greater frequency of drought in the early period. Drought conditions were frequent in pulses during the 1920s, 1930s, and 1940s, and again in the 1980s, 2000s, and early 2010s. In terms of regimes, the pattern is largely consistent across the state. Except for climate divisions 6 and 8, where the regime shift picks up the pulse of droughts in the 1940s, there is an extended regime of low drought frequency from the 1930s to at least the 1980s (Figure 3). All divisions record drought regimes in the 1920s and 1930s, and again in the 2000s and 2010s, with the 2010s regime producing the highest mean frequency of drought everywhere except division 1.

While an examination of the causes of drought in North Carolina is outside the scope of this research, the general absence of drought statewide in the 1960s and 1970s is noteworthy. For example, Ortegren et al. (2014) present time-series graphs of the Atlantic Multidecadal Oscillation (AMO) and the BHI in relationship to the Palmer Hydrologic Drought Index. Although the graphs confirm their finding of a significant long-term relationship between drought and the AMO and BHI, their temporal pattern suggests that the high AMO/low BHI and drought relationship holds from 1940–1970, but lower/higher values of the AMO/BHI are recorded in the SACR beginning in about 1970 and

Table 1. A comparison of the number of drought events, major droughts, mean length of drought events, severity of drought events, and the longest drought events for North Carolina's eight climatic divisions between early (1920–1969) and late (1970–2019) periods. The p-values are from a Mann–Whitney test comparing drought length and severity between early and late periods.

	Climatic Divisions (E = early period - 1920-1969; L = late period - 1970-2019)															
Element compared	1E	1L	2E	2L	3E	3L	4E	4L	5E	5L	6E	6L	7E	7L	8E	8L
# Drought Events	11	14	13	13	11	17	11	20	9	17	14	10	12	9	9	12
# Major Drought Events	6	9	4	7	6	9	4	10	6	10	9	5	6	4	5	5
Mean Drought Length (months)	9.1	10	6.5	10.3	7.5	6	7.2	7.6	10	8.9	8.9	8.3	8.1	6.8	8	7.8
p-value length (comparing Early/Late)		0.69		0.24		1		0.72		0.42		0.68		1		0.67
Mean Severity of Droughts (months)	-2.8	-2.9	-2.8	-2.8	-2.9	-2.8	-3	-2.9	-2.8	-2.9	-2.9	-2.9	-2.9	-2.8	-3	-2.7
p-value severity (comparing Early/Late)		1		1		1		0.93		1		1		0.38		0.67
Longest Drought (months)	21	25	18	28	24	12	24	29	26	33	19	19	16	24	15	28

Table 2. Kendall's tau-b correlation r-values between January and July PDSI values and time series for 100-year (1920–2019), 50-year (1970–2019) and 30-year (1990–2019) intervals. Below are the associated p-values, with significant ($p < 0.05$) boldfaced.

	Climatic Divisions (month)															
Period	Div 1 Jan	Div 1 Jul	Div 2 Jan	Div 2 Jul	Div 3 Jan	Div 3 Jul	Div 4 Jan	Div 4 Jul	Div 5 Jan	Div 5 Jul	Div 6 Jan	Div 6 Jul	Div 7 Jan	Div 7 Jul	Div 8 Jan	Div 8 Jul
100 year	0.062	0.039	0.061	-0.008	0.062	-0.043	-0.02	-0.13	-0.055	-.134*	0.022	-0.019	0.001	-0.046	-0.005	-0.08
	0.362	0.565	0.368	0.903	0.362	0.532	0.77	0.055	0.418	**0.049**	0.748	0.786	0.993	0.501	0.945	0.244
50 year	-0.114	-0.078	-0.054	-0.031	-0.081	-0.056	-0.141	-0.149	-.248*	-.252*	-.211*	-0.113	-0.153	-0.066	-0.166	-0.042
	0.245	0.431	0.581	0.75	0.412	0.569	0.148	0.128	**0.011**	**0.01**	**0.031**	0.251	0.121	0.498	0.091	0.669
30 year	-0.22	-0.056	-0.118	0.079	-0.063	0.107	-0.182	-0.055	-0.198	-0.142	0.005	0.044	0.051	0.169	0.067	0.122
	0.09	0.668	0.363	0.544	0.63	0.411	0.159	0.668	0.125	0.276	0.971	0.734	0.694	0.192	0.604	0.344

peaking in about 1980. While the long-term relationships Ortegren et al. (2014) identify (e.g., low BHI concurrent with drought) may be a manifestation of the fact that North Carolina is part of a much larger region encompassing the SACR, the pattern change they present falls within the 1930s to 1980s low drought frequency regime identified for North Carolina in this study. Attributing the temporal patterns of drought specifically

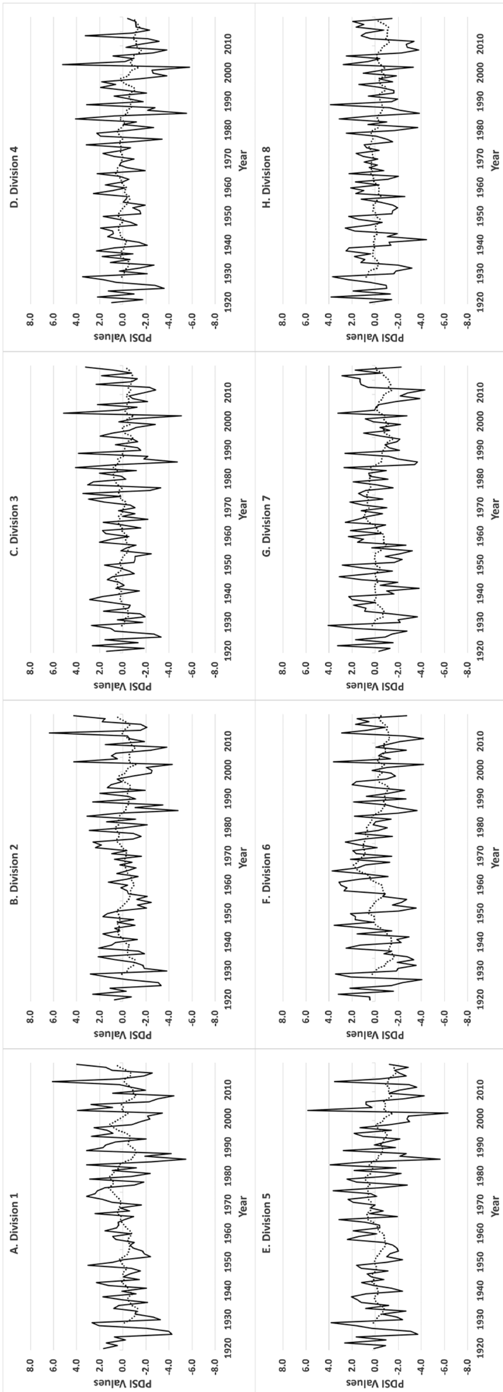

Figure 2. Annual values of the PDSI for July for North Carolina Climate Division 1 (A.) through 8 (H.) The dotted line is a 10–year running mean.

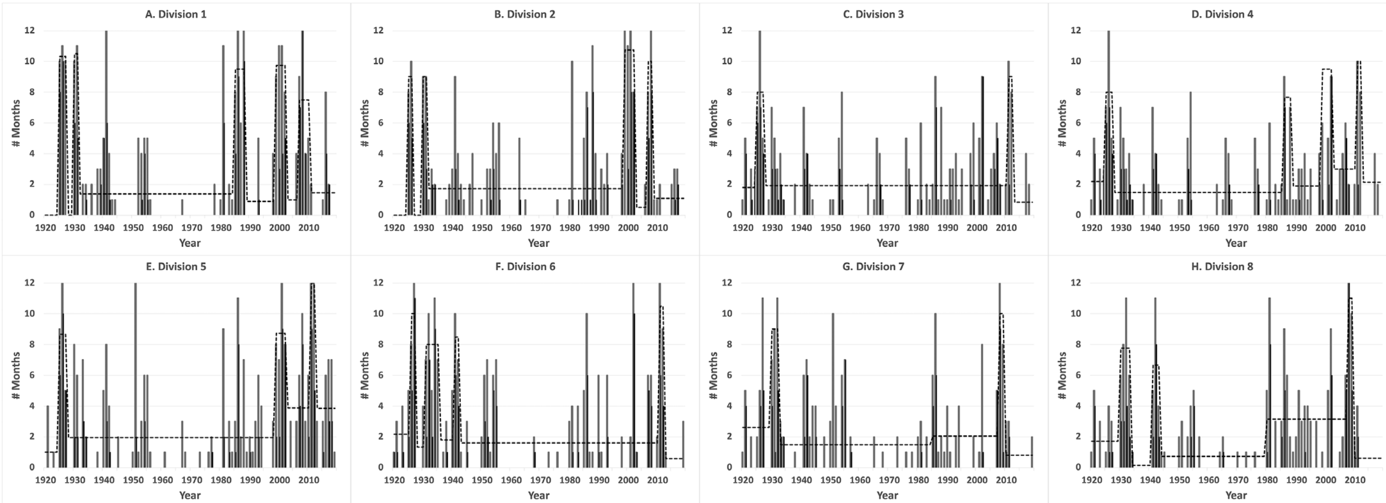

Figure 3. The number of months in a given calendar year recording moderate to extreme drought conditions (PDSI < -2; gray vertical bars), and severe to extreme drought conditions (PDSI < -3; black vertical bars), and the mean number of months for each regime identified using the Rodionov Regime Shift Analysis (dashed horizontal bars) for North Carolina Climate Division 1 (A.) through 8 (H.).

within the state of North Carolina to large-scale atmospheric forcing mechanisms is a topic worthy of future research.

Future Droughts

Drought remains a frequent topic of research in the United States and our understanding of drought patterns and processes continues to evolve (e.g., Abatzoglou et al. 2017, Heim 2017, Basara et al. 2019, Christian et al. 2019, Noel et al. 2020, Ault 2020). While not as extreme as other regions of the United States, Global Circulation Models predict an overall decrease in soil moisture and increase in drought severity (Dai 2013) and an increase in the spatial extent of summertime drought in the southeastern United States (Ahmadalipour 2017). From 1980–2013, droughts in the United States produced the second-most economic losses ($199 billion) of any form of natural disaster, trailing only tropical cyclones (Smith and Matthews 2015). As residents and ecosystems of North Carolina experience negative impacts from multiple meteorological hazards, increasing our awareness of historical patterns of drought in the state is useful for any entity involved in water resource management and planning as we move forward in the 21st century. Further increases in population coupled with future droughts will further stress the finite and variable water systems residents of North Carolina rely on.

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