Tropical Cyclones and Drought Amelioration in the Gulf and Southeastern Coastal United States

JUSTIN T. MAXWELL

Department of Geography, Indiana University, Bloomington, Indiana

JASON T. ORTEGREN

Department of Environmental Studies, University of West Florida, Pensacola, Florida

PAUL A. KNAPP

Department of Geography, University of North Carolina at Greensboro, Greensboro, North Carolina

PETER T. SOULÉ

Department of Geography and Planning, Appalachian State University, Boone, North Carolina

(Manuscript received 19 November 2012, in final form 25 April 2013)

ABSTRACT

Precipitation from land-falling tropical cyclones (TCs) has a significant hydroclimatic influence in the southeastern United States, particularly during drought years. The frequency with which TCs ended drought conditions was examined for southeastern coastal states from Texas to North Carolina during 1895–2011. The region was divided into the Gulf Coast states (GCS) and the southeastern Atlantic coast states (ACS). The spatiotemporal patterns of tropical cyclone drought busters (TCDBs) were analyzed. Larger-scale ocean–atmosphere influences on TCDBs were examined using chi-squared analysis. The ACS experienced TCDBs more frequently and farther inland compared to the GCS. The number of TCDBs has significantly increased with time in the ACS. TCDBs numbers in the GCS did not exhibit significant increases, but the area alleviated of drought conditions increased significantly in the last 117 years. The dominant larger-scale ocean–atmosphere forcing of TCDBs was a combination of a warm Atlantic Ocean [positive Atlantic multidecadal oscillation index (AMO+)] and weak westerlies [negative North Atlantic Oscillation index (NAO−)]. AMO+ leads to an increase in the number of TCs throughout the North Atlantic basin, and NAO− increases the likelihood of TC landfall by controlling the steering of TCs toward the southeastern United States.

1. Introduction

Land-falling tropical cyclones (TCs; tropical depressions, tropical storms, and hurricanes) and droughts have well-documented economic and ecological impacts in the southeastern United States (e.g., Seager et al. 2009; Nogueira and Keim 2010, 2011; Ortegren et al. 2011). Most of the societal impacts of these events are perceived negatively, as both TCs and droughts often impose high economic costs. Specifically, land-falling TCs are associated with loss of human life, coastal property damage, and inland flooding from extreme precipitation events (Lyons 2004; Emanuel 2005; Crossett et al. 2008; Pompe and Rinehart 2008). Persistent droughts in the southeastern United States can have severe economic impacts, particularly in the form of agricultural losses (Morehart et al. 1999; Ortegren et al. 2011). Additionally, warm-season droughts often lead to reductions in streamflow and reservoir levels, which may have substantial ecological ramifications (Morehart et al. 1999). Maxwell et al. (2012) documented the ability of land-falling TCs during 1950–2008 in the Atlantic Coast region of the southeastern United States to act as tropical cyclone drought busters (TCDBs), abruptly alleviating soil moisture deficits and ending both short- and long-term droughts. They found

Corresponding author address: Justin T. Maxwell, Department of Geography, Indiana University, Student Building 120, 701 E. Kirkwood Ave., Bloomington, IN 47405.
E-mail: maxweljt@indiana.edu

DOI: 10.1175/JCLI-D-12-00824.1

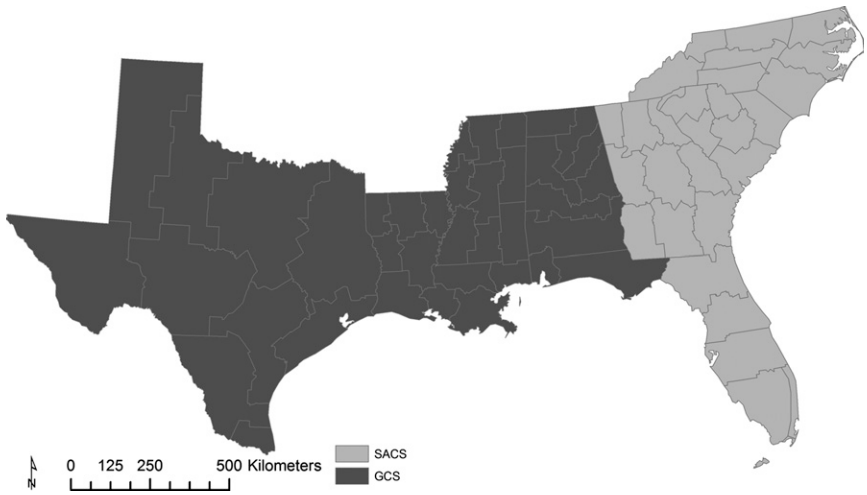

FIG. 1. Study area showing climate division boundaries and assignment of climate divisions to either the southeastern ACS (light gray) or the GCS (dark gray).

that in three-fourths of the climate divisions, at least 20% and up to 41% of all droughts were ended by TCs. They also found that the phase of the North Atlantic Oscillation influenced the probability of a TCDB occurring in the region.

The interactions between regional drought and TC landfall variability and the spatiotemporal properties of these interactions have received little attention (e.g., Sugg 1968; Maxwell et al. 2012). Here we expand our prior research by examining the occurrence of TCDBs along the coastal states of Texas–North Carolina (Fig. 1) during AD 1895–2011 and investigating the hydroclimatic influence of TCDBs within this region. Expanding the dataset used in Maxwell et al. (2012), we discuss the larger-scale ocean–atmosphere influences that affect these TCDBs in terms of areas impacted, occurrence frequency, and trends that have occurred in these metrics during the 117-yr study period.

a. *Interdecadal TC landfall and TC precipitation variability*

Interdecadal differences in regional TC rainfall totals exist in the southeastern United States. For example, a comparison of 1931–60 and 1961–2007 for the entire eastern United States revealed a significant increase in TC rainfall in the latter period for the Gulf Coast states (GCS) and Florida that was concurrent with a decreasing trend in TC rainfall in Georgia and South Carolina (Nogueira et al. 2013). However, a separate analysis found that in coastal regions of the Southeast, TC rainfall was greater during 1931–60, while inland TC rainfall was greater during 1961–2007 (Nogueira and Keim 2011). Anomalously low TC rainfall occurred for the entire Southeast during 1973–84 (Nogueira and Keim 2010).

Both the total area affected by TC rainfall, as measured by the number of weather stations receiving TC rainfall, and the amount of TC rainfall received in the Southeast exhibit interdecadal variability associated with well-known features of North Atlantic climate variability. The slow variation between above- and below-average sea surface temperatures in the North Atlantic Ocean [i.e., the Atlantic multidecadal oscillation (AMO)] is correlated with the amount of TC rainfall received in the Southeast. Ultimately, the AMO appears to be driven by variations in the North Atlantic component of the oceanic thermohaline circulation (Dima and Lohmann 2007). Warm phases of the AMO (AMO+; e.g., ~1940–60 and ~1995–present) are associated with increased TC landfall frequency, greater inland TC rainfall, and greater total area impacted by TC rainfall for the eastern United States. (Nogueira and Keim 2010).

During cool phases of the AMO (AMO−), TC rainfall is below average in the higher latitudes of the U.S. East Coast, from North Carolina to New England, and above average in the Gulf Coast region, from the Florida panhandle to south Texas (Nogueira et al. 2013). TC rainfall in the southeastern Atlantic coast states (ACS) is significantly correlated with the AMO, due in part to a substantial increase in TC landfall frequency in the region during AMO+ (Nogueira et al. 2013). By contrast, the primary influence on land-falling TCs and TC rainfall in Texas is associated with ENSO conditions. La Niña conditions favor TC activity while El Niño years are associated with reduced activity (Gray et al. 1994).

The North Atlantic Oscillation (NAO) is quantified by an index that documents the seesaw pattern of sea level pressure differences between Iceland and the Azores islands. The NAO influences the tracks of TCs over the

North Atlantic Ocean (Elsner and Kara 1999; Elsner and Kocher 2000; Keim et al. 2004; Elsner et al. 2006; Elsner and Jagger 2006; Dailey et al. 2009). Additionally, there is evidence of reductions in winter precipitation in the southeastern United States during NAO− phases (Stenseth et al. 2002), although some studies indicate an insignificant relationship between the NAO and precipitation in the southeastern United States during other seasons (Stahle and Cleaveland 1992; Henderson and Vega 1996; Katz et al. 2003; Tootle et al. 2005; Hurrell and Deser 2009). Maxwell et al. (2012) identified the NAO as the only significant variable affecting the likelihood of a TCDB impacting the southeast ACS during the period 1950–2008.

The NAO influence on TC tracks further emphasizes the out-of-phase relationship in interdecadal TC landfall probability between the Atlantic and Gulf of Mexico coasts (Elsner et al. 2000). Regional variations in TC landfall likelihood are associated with low-frequency variability in the location of the steering winds on the south and west flanks of the Bermuda high. In a positive NAO phase (NAO+), the western ridge of the Bermuda high typically shifts farther north and east, and TC activity increases (relative to NAO− phases) at higher latitudes on the U.S. East Coast (Elsner et al. 2000; Katz et al. 2003). When the Bermuda high shifts farther south and west (NAO−), TCs experience less recurving and are steered into the Gulf of Mexico, resulting in TC landfall frequency increases in the Gulf Coast states and decreases along the U.S. East Coast (Elsner et al. 2000).

While the AMO appears to influence the number of TC landfalls, their interdecadal spatial variability, and the amount of TC rainfall, the NAO influence is limited to interdecadal storm track preference. However, the physical mechanisms that link NAO variability to AMO variability via sea surface temperature influences on sea level pressures (and vice versa) in the Atlantic Basin, and the separate evidence that the AMO is associated with variability in the mean location of the Bermuda high (Ortegren et al. 2011), indicate that North Atlantic climate variability may contribute to further improvements in low-frequency forecasts of TC landfall probabilities throughout the southeastern United States.

b. Interdecadal drought variability

The influence of AMO variability on regional drought in the United States is well established (Enfield et al. 2001; McCabe et al. 2004; McCabe and Palecki 2006; Ortegren et al. 2011). The summer mean location of the Bermuda high also is significantly related to warm-season drought variability in the Southeast via its influence on moisture advection into the region (Stahle and Cleaveland 1993; Katz et al. 2003; Diem 2006; Ortegren et al. 2011). AMO+ is associated with increased drought frequency in the Atlantic coastal Southeast (Enfield et al. 2001; McCabe et al. 2004). Conversely, AMO+ is associated with multidecadal regimes of increased summer wetness in the Gulf of Mexico coastal states, including Mississippi, Louisiana, and eastern Texas (Ortegren et al. 2011). During multidecadal AMO+ phases, the NAO is generally relaxed (NAO−), and the Bermuda high shifts farther west and south toward the Caribbean Sea, with an anomalous ridge of high pressure as well as increased drought frequency over the Southeast (Stahle and Cleaveland 1993; Elsner et al. 2000; Ortegren et al. 2011). Under these conditions, water vapor advection on the west flank of the Bermuda high is diverted west of the southeastern ACS into the GCS. During AMO− phases, the NAO is typically excited (NAO+) and the Bermuda high shifts farther north and east. This provides increased water vapor advection and unstable southerly airflow into the Southeast along the Atlantic coast, as well as increased likelihood of northward TC recurvature in the western Atlantic, toward the U.S. East Coast. The multidecadal oscillatory behavior of regional drought in response to these components of North Atlantic climate is reflected in the negative relationship between interdecadal drought variability in the Southeast and Gulf South drought regions (Ortegren et al. 2011).

In summary, droughts and TC landfalls in the coastal states of the U.S. Southeast are more likely during AMO+ and/or NAO− phases. The subregional variability in TC landfall probability is apparently linked to the AMO and NAO variability via the location of the Bermuda high, such that U.S. East Coast (Gulf Coast) TC landfalls are more likely when the western ridge of the Bermuda high is centered farther north and east (south and west). Similarly, subregional drought variability also is linked to fluctuations in the AMO and NAO via the location of the Bermuda high, with prolonged moisture deficits (surpluses) in the ACS (GCS) when the Bermuda high shifts west and south (Ortegren et al. 2013).

c. Objectives

Enhanced understanding of the spatiotemporal patterns of the possible interactions between TCs and droughts may help improve drought preparedness and mitigation plans in the region. Because drought (e.g., Ortegren et al. 2011) and TC variability (Elsner et al. 2000) exhibit multidecadal oscillations in this region, it is likely that TCDB probabilities are different between the Gulf and Atlantic coasts at interdecadal time scales. Thus, our specific objectives in this study are to 1) document the occurrence of TCDBs during the period AD 1895–2011 in the Southeast, from Texas to North Carolina, and

2) examine spatiotemporal patterns of TCDBs in the context of known larger-scale oceanic–atmospheric influences on TC landfall location probabilities and drought variability.

2. Data and methods

a. *Quantifying drought*

We used the Palmer drought severity index (PDSI; Palmer 1965) to classify drought. The PDSI is water-balance based and provides a measurement centered on zero characterizing the cumulative departure of surface moisture supply and demand based on local mean conditions (Palmer 1965). The PDSI measures meteorological drought (i.e., drought lasting several months) by considering the moisture climate of the current and preceding months, making the index moderate in response to changing moisture conditions and not easily shifted by short-term variations in soil moisture in the way that the Palmer *Z* index is. Conversely, PDSI is more responsive to short-term changes in the moisture balance than the Palmer hydrological drought index, which measures long-term hydrologic drought (Heim 2002). Because PDSI has an intermediate response time to large changes in soil moisture, it provides a reasonable measure of drought to examine changes in soil moisture after TC passage.

We gathered hurricane season (June–November) monthly PDSI values during 1895–2011 for the climate divisions in the GCS and southeastern ACS (Fig. 1) from the National Oceanic and Atmospheric Administration (NOAA) Earth Systems Research Laboratory. Climate division data consist of aggregated weather station data within a given climate division and are well suited for regional analysis (Soulé 1990; Ortegren et al. 2011). The number of weather stations in a given climate division varied through time. There are two different methods employed by the National Climatic Data Center to account for this variation: 1) for the period 1931–2011, weather station values were averaged directly, and 2) for the period 1895–1930, a regression technique was used to estimate the divisional values based on statewide values recorded by the U.S. Department of Agriculture (Guttman and Quayle 1996). The change in methodology creates issues for both periods. For example, the direct averaging of values for the 1931–2011 period can lead to biases when a division is undersampled or varies greatly in topography (Keim et al. 2003, 2005; Allard et al. 2009). Our study area has relatively minimal elevation change to cause an extreme bias in our data with the exception of western North Carolina. To account for undersampling for a given division, we examined the record of all recording stations to ensure that a substantial proportion (>90%) of stations was reporting. During 1895–1930 the regression models used to estimate climate division conditions were shown to have less variance than the post-1931 period (Guttman and Quayle 1996). To help account for this, we use precipitation data from the actual weather stations in the U.S. Historical Climatology Network to verify the climate division data (Menne et al. 2009), which included bias adjustments. However, for some of the small climate divisions (e.g., Florida division 7) there was only one station recording data during the early portion of the record, which could potentially lead to biases in the classification of drought conditions for that division. To minimize the effect of this bias, we primarily examine the role of TCDBs at the regional level.

We used a monthly PDSI classification of at least a "moderate" drought (PDSI < -1.99) as the initial month of a drought. A monthly PDSI classification of "near normal" or wetter (PDSI > -0.49) determined the end of a drought. We analyzed only droughts that were present during the hurricane season. The length of existing droughts prior to TCDB occurrence ranged from multiple months to multiple years. Because the classifications of the PDSI categories of drought are somewhat arbitrary (Alley 1984), we were conservative in our definitions of the beginning and ending of a drought. Thus, the selection of a moderate drought (near-normal conditions) based on the PDSI should ensure that a surface moisture deficit had developed (ended) for a given region.

b. *Identifying drought cessation*

We labeled an event as a drought-busting event (DBE) when a month or a series of months with a moderate or worse drought classification was followed by a month of near normal or wetter conditions based on monthly PDSI values. To examine the storm type (i.e., frontal, air mass, or tropical; Faiers et al. 1994; Keim and Faiers 1996) that produced the DBE precipitation, and to confirm that a TC passed within the region, we used NOAA's Hydrometeorological Prediction Center daily weather maps. Once we determined that a TC was in close proximity during a DBE, we used the North Atlantic Hurricane Database (HURDAT; Jarvinen et al. 1984; Neumann et al. 1999) in combination with daily values from the Global Historical Climatology Network (available at http://www.ncdc.noaa.gov/oa/climate/ghcn-daily/) and the U.S. Historical Climatology Network (Menne et al. 2009) weather stations to confirm if the DBE was a TCDB. We examined if the timing of a TC tracking over a climate division corresponded to the daily weather station reports of precipitation within that climate division. We included those stations that were within 500 km from the center of the storm following criteria identified by Nogueira and Keim (2010). When a TC interacted with a frontal system or transitioned to an extratropical system, we still classified precipitation within a 500-km radius (Nogueira and Keim 2010) of the storm center as TC-related precipitation. While this methodology may include some non-TC precipitation, the presence of the TC or the remnants of a deteriorating TC at least enhanced the precipitation received for a given location.

We collected precipitation for the month in question from each weather station in the climate division to determine what proportion of that month's precipitation originated from a TC or was TC-related. If that proportion was greater than 50%, we classified the DBE as a TCDB, which is a conservative approach as this ensures that a TC-related event produced the majority of monthly precipitation. The U.S. Historical Climatology Network weather stations have been corrected to address biases that were introduced with the changing of locations and number of weather stations reporting. Additionally, rain gauge measurements of precipitation during the passage of a TC typically underestimate actual rainfall amounts because of high winds and splash-out (Nogueira et al. 2013). There were instances where precipitation from a frontal or air mass storm type preceded a TC during the same month and most likely contributed to drought cessation and to a TC being classified as a TCDB. However, only classifying a TC that provided over 50% of that month's precipitation as a TCDB ensures that the TC played a dominant role in ending drought conditions.

For locations that had multiple TC landfalls within the same month, we classified the combined influence of the multiple TCs as a single TCDB. HURDAT dataset records begin in AD 1851, but daily weather station records become spatially sufficient beginning in AD 1895. Thus, we limited our analysis of TCDB occurrence to the period 1895–2011, which is common to the reliable Global Historical Climatology Network and U.S. Historical Climatology Network weather station datasets.

Using the above definition of droughts and DBEs by climate division, we calculated the percentage of droughts ended by DBEs, the percentage of droughts ended by TCDBs, and the percentage of all DBEs that were TCDBs for the common period of 1895–2011. We also calculated both the raw number of TCDBs and TCDBs weighted by the area of the climate division to better illustrate where TCDBs were most common. We divided the number of TCDBs experienced by a given climate division by its area (km^2) and made the resulting numbers interpretable by multiplying each quotient by 1000, thus represented as TCDB 1000 km^{-2}. We examined possible similarities or regional clusters in track characteristics of TCDBs by averaging the longitude of all TCDBs tracks for every degree of latitude in the study area using the HURDAT dataset to compute an average track of a TC that leads to a DB.

TABLE 1. Contingency tables for the entire region used to calculate the odds ratio statistics between the climate indices and TCDB occurrence.

		NAO		
		Negative (0)	Positive (1)	Total
Year *a* TCDB	Occurred (1)	29	9	38
	Did not occur (0)	8	16	24
Total		37	25	62
		AMO short		
		Negative (0)	Positive (1)	Total
Year *a* TCDB	Occurred (1)	14	24	38
	Did not occur (0)	15	9	24
Total		29	33	62
		AMO long		
		Negative (0)	Positive (1)	Total
Year *a* TCDB	Occurred (1)	25	43	68
	Did not occur (0)	31	18	49
Total		56	61	117

c. *Identifying larger-scale ocean–atmosphere influences on TCDB patterns*

To explain spatial patterns in TCDBs and to examine possible larger-scale oceanic–atmospheric influences on TCDBs, we created a binary variable for TCDBs based on occurrence for a given year using 1 for occurrence and 0 for absence of TCDB for each climate division in the entire Southeast, the GCS, and the ACS. We used Pearson's chi-squared (χ^2) analysis to compare a suite of climate indices that have been shown to influence characteristics in TCs against the binary TCDB variable. We retrieved monthly mean data for June–November for the following indices for 1950 through 2011—the common period of all selected indices—from NOAA's Climate Prediction Center: 1) the NAO index, 2) the Southern Oscillation index (SOI), and 3) the east central tropical Pacific SST (Niño-3.4; available at http://www.esrl.noaa.gov/psd/data/climateindices/list/). We collected the AMO index (Enfield et al. 2001) from NOAA's Earth System Research Laboratory for 1950–2011 (AMO short) and the extended version covering 1895–2011 (AMO long). The climate indices were converted to binary format based on positive and negative phase. We created separate models for the entire study region, the GCS, and the ACS. To ensure that the relationship between the indices and TCDBs was not an artifact of the binary conversion of the indices, we also used the recorded values from each index and conducted a logistic regression model and found similar results to the χ^2 analysis. For the climate indices significantly related to TCDBs, we calculated odds-ratio

TABLE 2. Drought, DBEs, and TCDBs statistics.

	Total region	ACS	GCS
Droughts	2014	898	1116
DBEs	1461	668	793
Percentage of Droughts Ended by DBEs	72.5%	74.4%	71.1%
TCDBs	254	144	110
Percentage of DBEs that were TCDBs	17.4%	21.6%	13.9%
Percentage of droughts ended by TCDBs	12.6%	16.0%	9.9%

statistics for the entire region, the GCS, and the ACS by creating a contingency table with two rows and two columns (Table 1). The rows represent years either with or without a TCDB and the columns represent years experiencing either positive or negative climate index conditions. We calculated the odds ratio using the following formula:

$$\text{Odds Ratio} = \frac{X_1/(1 - X_1)}{X_2/(1 - X_2)},$$

where X_{ith} represents the probability of the occurrence of an event (i.e., TCDB) during negative (X_1) or positive (X_2) climate index conditions.

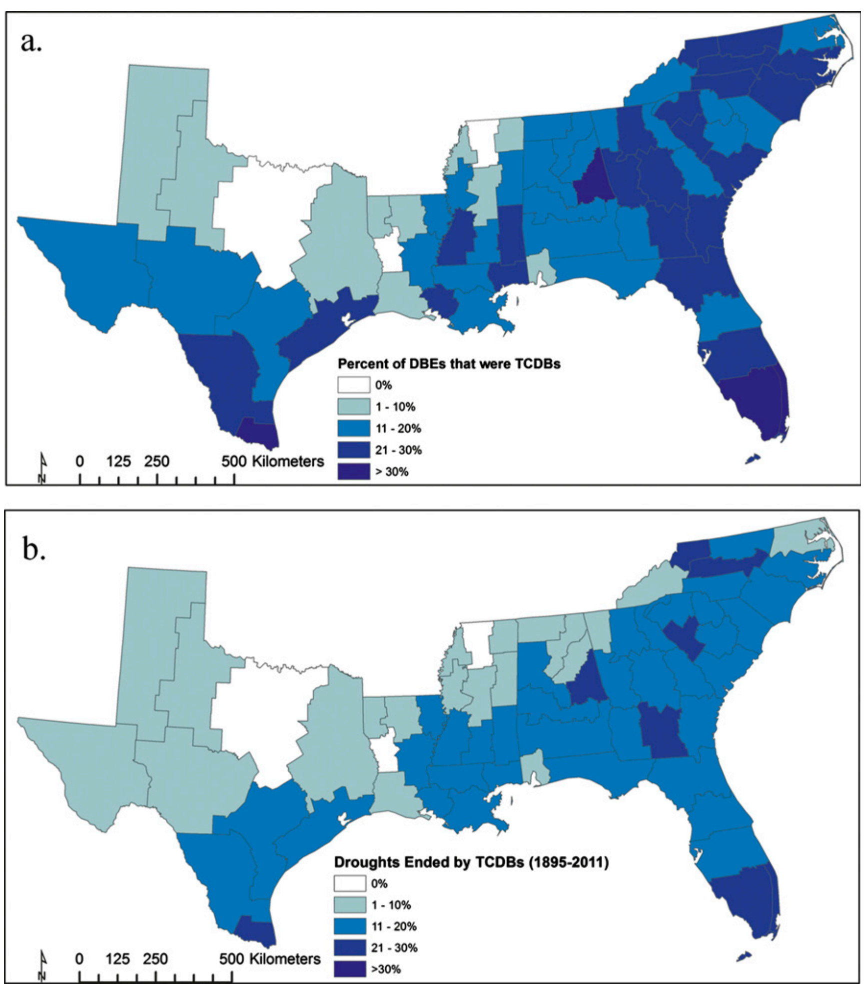

FIG. 2. (a) Percentage of DBEs that were TCDBs and (b) percentage of droughts ended by TCDBs by climate division during hurricane season (June–November) from 1895 to 2011.

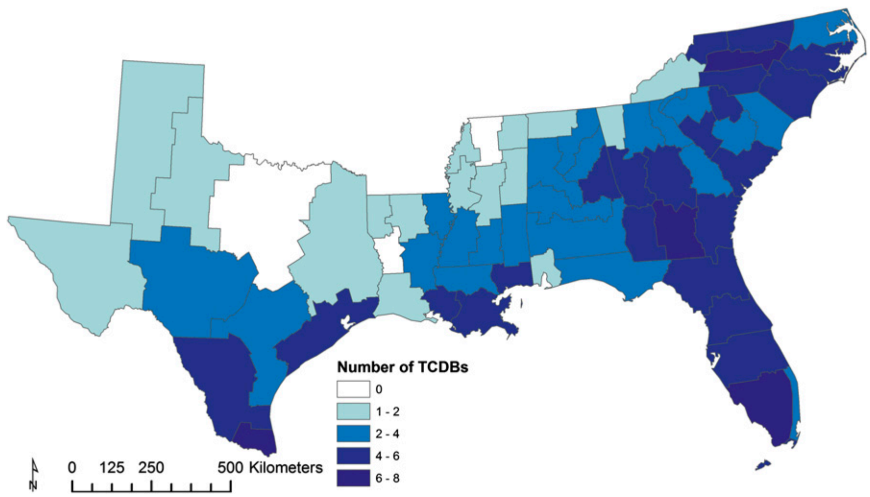

FIG. 3. Number of TCDBs recorded during hurricane season from 1895 to 2011.

3. Results

a. Spatiotemporal patterns of TCDBs

Based on our threshold of moderate drought or worse, 2014 droughts occurred as determined by the raw number of climate divisions experiencing a qualifying drought during hurricane season in any year of the study period. Hurricane season droughts were frequently (~72%) ended abruptly by DBEs (Table 2 and Fig. 2a), while TCs ended approximately 13% of droughts for the region (Table 2) and up to 33% of droughts for certain climate divisions (Fig. 2b). In the entire study area, there were 90 separate land-falling TCs that were TCDBs in at least one climate division, with 30 impacting only the ACS, 48 impacting only the GCS, and 12 affecting both regions. TCs ended both persistent (>2 yr) and short-term (<3 months) droughts. In the ACS, TCDBs occurred farther inland compared to the GCS (Fig. 3) and were more common both in terms of the absolute number of climate divisions experiencing TCDBs and as a percentage of total DBEs. Thus, TCDB influences were different between regions, with a greater impact in the ACS despite a greater total number in the GCS.

A marked spatial pattern exists for TCDB occurrence. When normalizing TCDB occurrence by climate division area, a more accurate representation of TCDBs appears (Fig. 4). Of the 68 state climate divisions in the study area, only three climate divisions did not experience a TCDB. TCs ended drought conditions throughout the majority of the study area, but six regions experienced TCDBs more

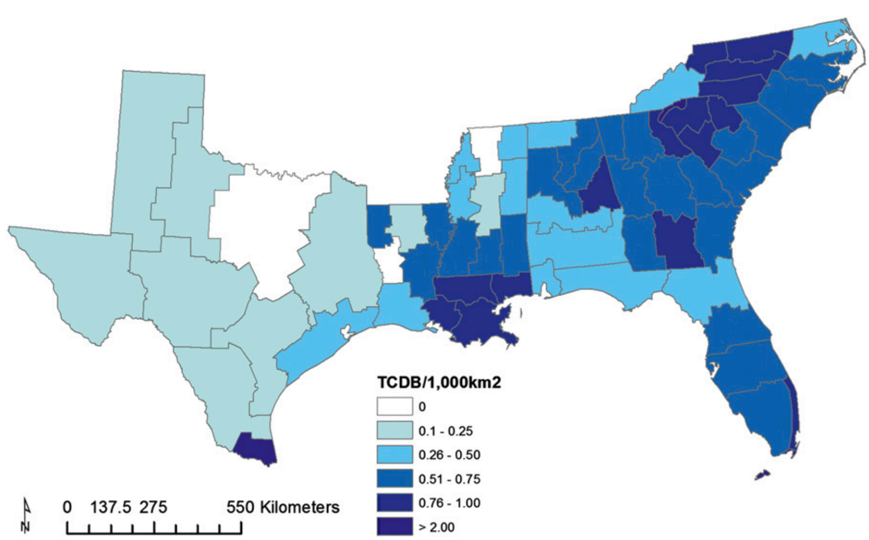

FIG. 4. Number of TCDBs 1000 km^{-2} to account for unequal climate division size.

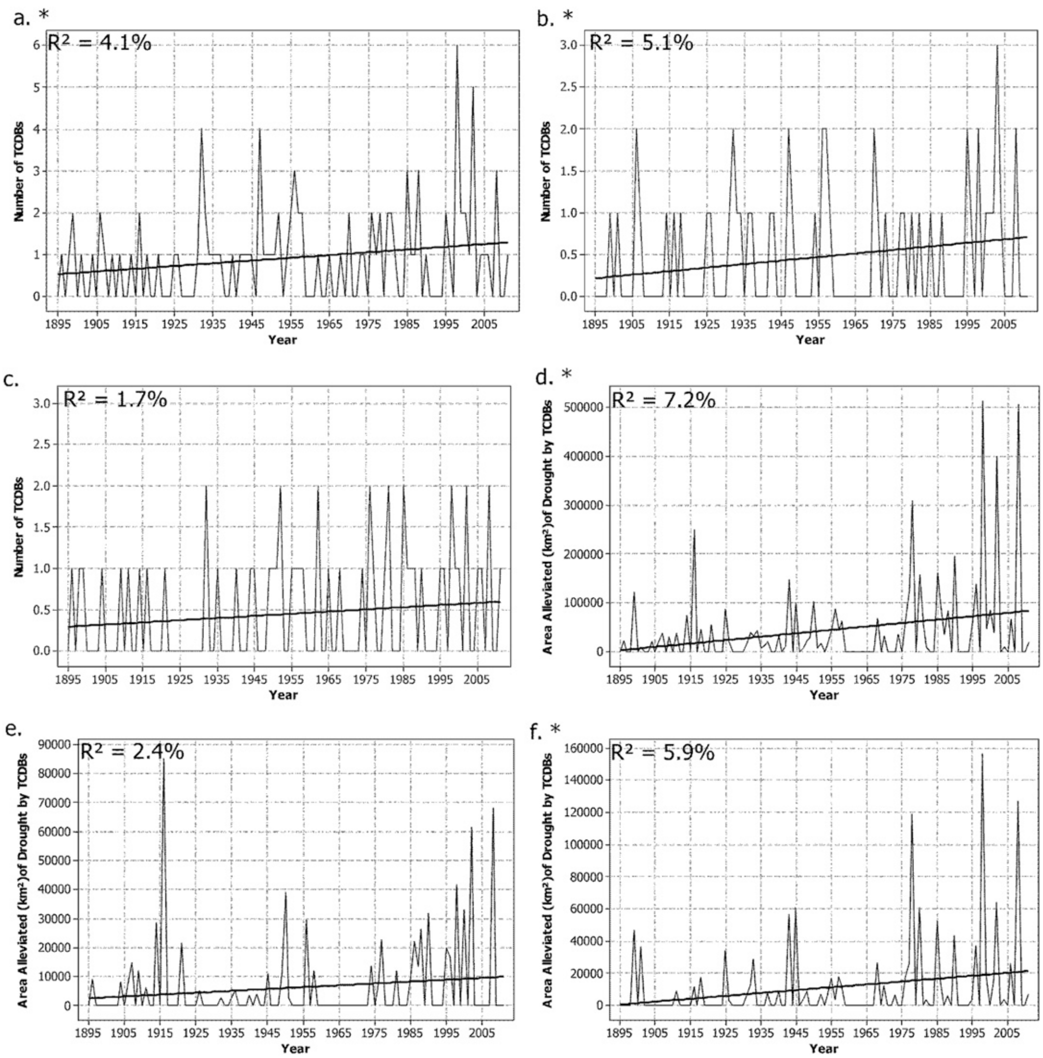

FIG. 5. Temporal trends in TCDB number for (a) the entire region, (b) ACS, and (c) GCS and for area of drought alleviated by a TC for (d) the entire region, (e) ACS, and (f) GCS. Significant trend at the $p < 0.05$ level is denoted by an asterisk.

frequently when climate division size was accounted for (i.e., greater number of TCDBs $1000\,\mathrm{km}^{-2}$): southern Texas, southern Louisiana, southern Florida, eastern Alabama, southern Georgia, and the Piedmont of north Georgia, South Carolina, and North Carolina.

The annual number of storms that act as TCDBs has significantly increased ($r = 0.202$; $p = 0.029$) during 1895–2011 for the entire region (Fig. 5a). The overall significant increase is principally associated with the ACS ($r = 0.225$; $p = 0.015$), as the GCS did not exhibit a significant trend ($r = 0.132$; $p = 0.157$; Figs. 5b,c). The area alleviated of drought conditions from TCs exhibits an increasing pattern temporally for the entire region ($r = 0.296$; $p = 0.003$; Fig. 5d). The significant increase ($r = 0.243$; $p = 0.008$) was more prevalent in the GCS compared to the ACS ($r = 0.154$; $p = 0.098$; Figs. 5e,f). The increase in TCDB frequency during the late twentieth to early twenty-first centuries is especially evident when examining the spatial patterns in approximately 30-yr segments (Fig. 6).

The average storm tracks of TCDBs for each state show three general routes TCs follow when making landfall in the southeastern United States and ending drought conditions (Fig. 7). Florida, South Carolina, and North Carolina TCDBs typically make landfall on the Atlantic Coast and recurve northeastward to the Atlantic Ocean. TCDBs impacting Georgia, Alabama, Mississippi, and Louisiana often make landfall along the Gulf Coast and recurve through Tennessee and the mid-Atlantic. TCs resulting in TCDBs for Texas will often not experience

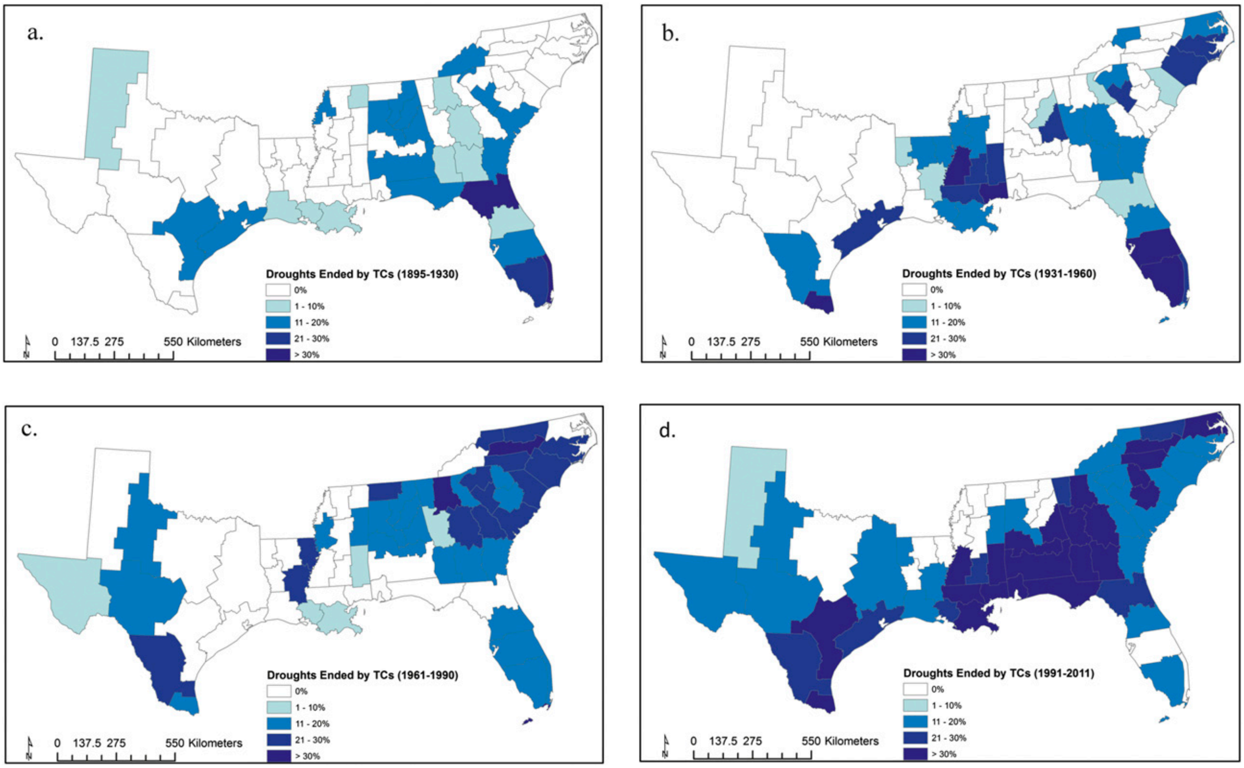

FIG. 6. Percent of droughts ended by TCDBs for periods of approximately 30 yr: (a) 1895–1930, (b) 1931–60, (c) 1961–90, and (d) 1991–2011.

much interaction with upper-level westerlies, allowing the TCDBs to make landfall in Texas and thus typically experience little to no recurvature.

b. Larger-scale ocean–atmosphere influences on TCDB probability

Of the suite of climate indices we tested only the NAO and AMO had a significant relationship with the probability of TCDB occurrence (Table 1). The NAO was significantly related to TCDB occurrence for the ACS, GCS, and the entire region, but had a stronger influence on the frequency of ACS TCDBs compared to the GCS from 1950 to 2011 (Table 3). Likewise, during 1950–2011, the AMO influenced TCDBs for the ACS, but not for the GCS (Table 3). Because the AMO exhibits multidecadal oscillatory behavior, we used the expanded version (Enfield et al. 2001) and conducted an additional chi-squared analysis of the common period 1895–2011. The expanded AMO record has a significant relationship with TCDBs for the entire region and the ACS, while the association with TCDBs in the GCS is stronger than was indicated using the 1950–2011 AMO record (Table 3). The odds for TCDB occurrence during NAO− conditions were 6.4 (entire region), 5.9 (ACS), and 3.4 (GCS) times greater than during NAO+ conditions (Table 3). Similarly, the odds for a TCDB occurring during AMO+ were 3.0 (entire region), 2.3 (ACS), and 1.7 (GCS) times greater than the odds of a TCDB event during AMO− conditions (Table 3).

4. Discussion and conclusions

a. Differences in TCDB characteristics between the ACS and GCS

TCDBs occurred throughout the coastal states of the southeastern United States during 1895–2011, although distinct geographic differences in the distribution of TCDBs emerged. The total number of TCs that became TCDBs was greater in the GCS than in the ACS, but the number of climate divisions experiencing a TCDB was greater in the ACS. TCDBs that occurred in the ACS typically influenced a larger region and ended a larger percentage of droughts compared to the GCS. One apparent explanation is the recurving of the TCs that typically end drought conditions. The GCS region covers more longitude while the ACS covers greater latitude. The average tracks that influenced the ACS typically affected most, if not all, of the states in the region because of northward recurvature (Fig. 7). Preferred TCDB tracks

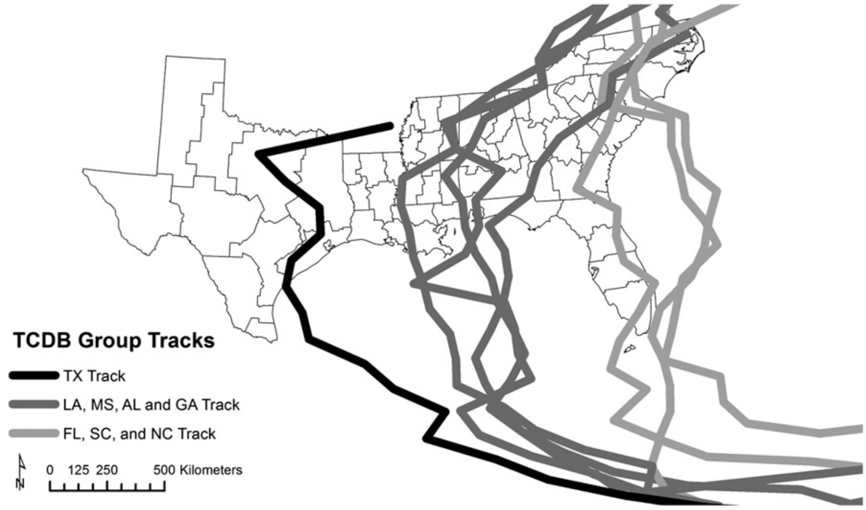

FIG. 7. Average tracks of TCDBs by state during 1895–2011.

in the GCS were separated into two groups, with many (~30%) of the TCDBs impacting the GCS found only in Texas climate divisions. The individual TCDBs that impacted Louisiana, Mississippi, and Alabama rarely influenced all three states because of northward recurvature (Fig. 7). While TCDBs have a larger role in the hydroclimate of the ACS, throughout the entire study region drought conditions never returned to a climate division the same calendar year after a TCDB had impacted that climate division.

The late twentieth and early twenty-first centuries' trend toward more frequent TCDBs is almost entirely confined to the ACS, while the increasing trend in total land area alleviated of drought by TCDBs is much stronger in the GCS. These results are in general support of findings that the driving forces behind TC landfall for the Gulf or Atlantic coasts are not uniform (Elsner et al. 2000; Elsner 2003; Keim et al. 2007; Dailey et al. 2009; Maxwell et al. 2012).

The spatiotemporal differences between the two regions are distinct, with core areas in each region that experience TCDBs more frequently (Fig. 4). Three of the six areas that have a high frequency of TCDBs are located along coastal regions that have been shown to experience a higher frequency of TC landfalls (i.e., southern Texas, southern Florida, and southern Louisiana/Mississippi; Keim et al. 2007). The remaining three regions (eastern Alabama, southern Georgia, and the Piedmont of north Georgia, South Carolina, and North Carolina) are more interior and not historically known as areas highly impacted by TC landfall. However, the average tracks for TCDBs for each state (Fig. 7) illustrate that the TCDBs that influence North Carolina, South Carolina, Florida, and Georgia often track over the Piedmont region where they experience orographic lifting approaching the Appalachian Mountains. The concentrations of TCDBs in eastern Alabama and southern Georgia may reflect that these climate divisions are near the boundary between the ACS and GCS and thus frequently receive rainfall from TCs that make landfall on either the Gulf or Atlantic coast. The interior regions also may experience greater numbers of TCDBs because of comparatively higher drought frequency, yet only the southern Georgia region ranked in the upper quartile of climate divisions in drought frequency, and no significant twentieth-century trends in drought frequency existed.

The increase in frequency of TCDBs is significant for the entire Southeast (Fig. 5a), reflecting a significant trend in the ACS (Fig. 5b) that is most pronounced since the late 1970s and concurrent with nonsignificant increases in the GCS (Fig. 5c). The general peaks in TCDBs appear to be associated with peaks in total land-falling

TABLE 3. Results from the χ^2 analysis from 1950 to 2011 (NAO and AMO short) and from 1895 to 2011 (AMO long).

Region	χ^2	*p* value	Odds ratio
NAO			
Whole region	11.293	0.001	6.4
ACS	9.976	0.002	5.9
GCS	4.387	0.036	3.4
AMO short			
Whole region	3.890	0.049	2.9
ACS	4.218	0.040	2.9
GCS	0.471	0.471	1.4
AMO long			
Whole region	8.015	0.005	3.0
ACS	4.439	0.035	2.3
GCS	1.976	0.160	1.7

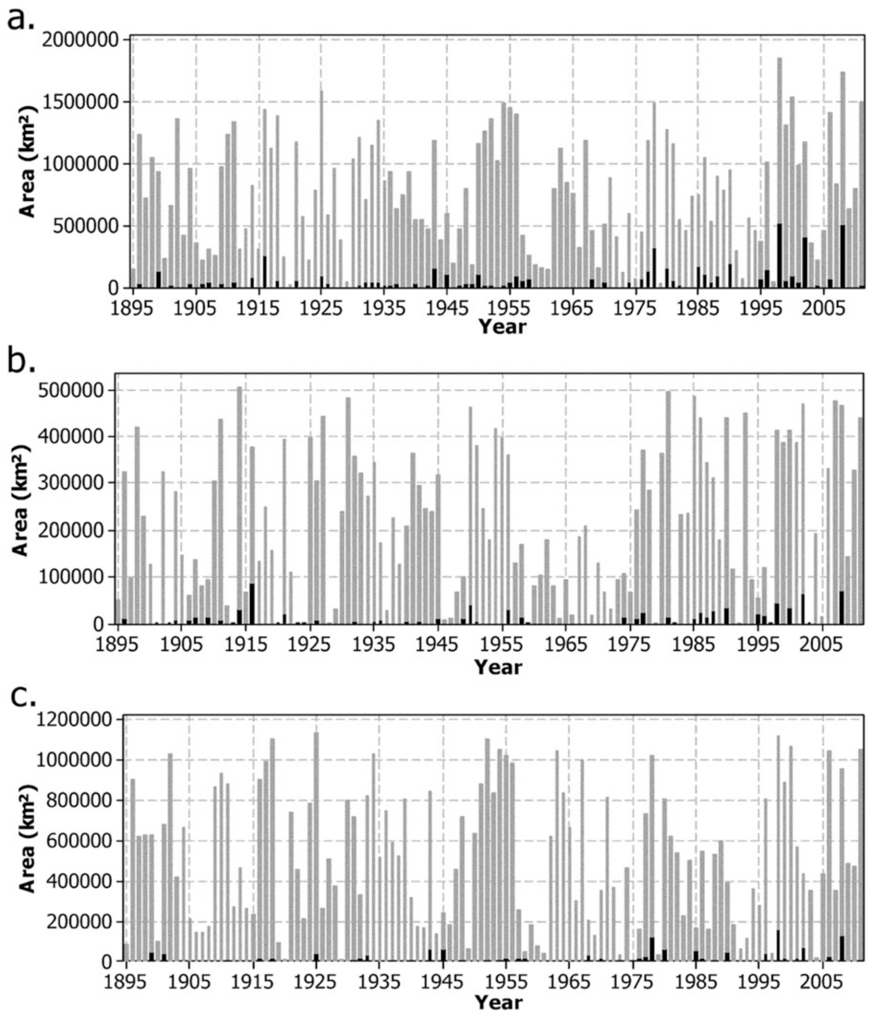

FIG. 8. Area alleviated of drought by a TCDB (black) compared to area experiencing drought conditions (gray) for (a) the entire region, (b) ACS, and (c) GCS during 1895–2011.

TCs for the Atlantic basin (Landsea 2007), with a higher number of TCDBs occurring in the mid-1900s and the late twentieth and early twenty-first centuries (Fig. 5a). The increase in TCDB occurrence is evident when examining changes in the area alleviated of drought conditions by TCs (Fig. 5d). However, the increase is only significant in the GCS (Fig. 5f). The weaker increase of area alleviated of drought conditions by TCs for the ACS (Fig. 5e) may partially be explained by a period of substantially less drought (1958–75) for the region, which coincides with an AMO− phase (Fig. 8). The area experiencing drought in the GCS or when the two regions are combined does not exhibit temporal patterns and is not an operative explanation for the increase in area alleviated of drought conditions by TCs (Fig. 8). The general increase in TCDB frequency through time in the entire Southeast is also evident from the examination of TCDBs by dividing the study period in approximately 30-yr segments (Fig. 6). The most recent period (1991–2011) contains the highest TCDB frequency in the entire Southeast even though it is the shortest period (Fig. 6).

b. General characteristics and larger-scale ocean–atmosphere influences on TCDBs

TCDBs were caused by TCs of all wind speed categories and no temporal patterns in the strength of the TCs that ended drought conditions occurred. The pattern of increasing drought area alleviated is associated with the total number of TCs ($r = 0.308$; $p < 0.001$) in the Atlantic basin and with the total number of hurricane landfalls ($r = 0.196$; $p = 0.033$) documented by Landsea (2007). The driving forces behind TC formation, in addition to steering mechanisms, are thus important to TCDB climatology, although the steering factors associated with the NAO have a greater impact on the odds of TCDB occurrence.

In spite of the documented out-of-phase relationship between TC landfall probabilities in the Gulf Coast and the higher latitudes of the U.S. East Coast that has been linked to variability in the NAO (Elsner et al. 2000), our chi-squared analysis revealed that the combination of NAO− and AMO+ conditions produces the greatest likelihood for TCDB occurrence in the entire southeastern United States. During 1950–2011, both the NAO and the AMO indices were significantly associated with TCDB probabilities. Using the extended AMO index (1895–2011), we identified a significant association between AMO phase and TCDB probability in the ACS and in the entire Southeast. The NAO is an indicator of the predominant steering mechanism for Atlantic basin TCs (Elsner et al. 2000; Elsner 2003; Keim et al. 2007). The AMO influences the number of Atlantic basin TCs that become major hurricanes (Knight et al. 2006; Miller et al. 2006) and is associated with multidecadal patterns of TC activity between coasts (Elsner et al. 2000; Keim et al. 2007). The combination of the favorable tracking conditions associated with NAO− and the general increase in total Atlantic basin TCs associated with AMO+ appears to produce the most likely larger-scale ocean–atmosphere conditions favoring the occurrence of TCDBs. While ENSO has been shown to influence TC activity (Gray et al. 1994), our analysis did not find ENSO to have a significant influence on TCDB occurrence. We suspect this is because the primary drought-related outcomes in the southeastern United States associated with eastern tropical Pacific SSTs are operative principally in the winter months (December–February), outside of the hurricane season (Seager et al. 2009; Ortegren et al. 2011).

In summary, TCDBs are common throughout the two study regions and provide a means either of ameliorating or terminating hurricane season droughts, thus making TC rainfall important to the hydroclimate of the Southeast. Differences in the increasing trends in the number of TCDBs and the area alleviated of drought conditions between ACS and GCS suggest that climatic oscillations do not equally impact these two regions. The significant trends associated with TCDBs can be partially explained by larger-scale ocean–atmosphere conditions conducive for TC formation and TC landfall. Understanding the larger-scale ocean–atmosphere influences behind TCDBs allows for enhanced predictability in the odds of a TCDB occurrence, a better understanding of how TCs influence the southeastern U.S. hydroclimate, and the potential to improve drought mitigation planning efforts.

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