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Key Points:
- The majority (73%) of droughts in the southeastern United States were ended rapidly over a month period
- Storm types had different spatial patterns of rapid drought with closed lows and atmospheric rivers ending drought over the largest areas
- The Frontal storm type ended drought rapidly the most frequently but is significantly decreasing in occurrence over the study period

Supporting Information:
- Supporting Information S1

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Changes in the Mechanisms Causing Rapid Drought Cessation in the Southeastern United States

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Abstract The synoptic processes that end droughts are poorly understood, yet have significant climatological implications. Here we examined the spatiotemporal patterns of rapid drought cessation (RDC) in the southeastern United States during the1979–2013 warm season (April–November) for three storm types: Frontal, Tropical, and Air mass. We defined RDC as a 1 month shift in soil moisture sufficient to alleviate an existing drought. We found that 73% of all warm-season droughts were ended by RDC events and the three storm-type groups ended droughts over similar spatial areas. Frontal storms were the most frequent mechanism for RDC events, yet their occurrences significantly decreased and were negatively related to increases in Northern Hemisphere air temperatures. Projected future warming in the Northern Hemisphere suggests a continued decline in the frequency and relative contribution of Frontal storms as RDC events, potentially influencing the timing and spatial scale of drought cessation in the southeastern U.S.

1. Introduction

Drought is a common part of the climate of the United States (U.S.) including the southeastern U.S. (SEUS), with substantial impacts on society and natural systems (Hayes, Wilhelmi, & Knutson, 2004; Mo, 2011). Many components of drought (e.g., intensity, frequency, and duration) in the U.S. have received substantial research attention (Cook et al., 2004; Herweijer, Seager, & Cook, 2006; Karl & Koscielny, 1982; Soulé, 1990), but less is known about the specific synoptic meteorological mechanisms that end droughts (Parry et al., 2016). Of particular interest to water managers and municipalities is rapid drought cessation (RDC), which we define as drought that is terminated within a 1 month period. The frequency of RDC events and the related storm types (Frontal, Tropical, and Air mass; Faiers, Keim, & Hirschboeck, 1994; Keim & Faiers, 1996) that cause these events are unknown. Summer-season precipitation in the SEUS may be largely driven by stochastic atmospheric variability rather than large-scale atmospheric-oceanic influences (Seager, Tzanova, & Nakamura, 2009). However, both the North Atlantic Subtropical High and the Atlantic Multidecadal Oscillation (AMO) appear to influence warm-season precipitation in the region (Li et al., 2011; Li, Li, & Kushnir, 2012; Li, Li, & Barros, 2013; Ortegren et al., 2011; Ortegren, Weatherall, & Maxwell, 2014). While previous studies have examined continental-scale patterns of drought termination in the U.S. (Namias, 1960; Karl, Quinlan, & Ezell, 1987), mechanisms responsible for RDC have received less attention (Verdon-Kidd et al., 2017), and a better understanding of such mechanisms is critical for predicting drought characteristics with anthropogenic climate change.

Few studies have focused on the spatiotemporal extent of RDC mechanisms in the SEUS. Land-falling tropical cyclones (tropical depressions, tropical storms, and hurricanes) have frequently caused RDC in the SEUS during the twentieth century (Brun & Barros, 2014; Kam et al., 2013; Maxwell et al., 2012, 2013), but the spatial coverage of tropical cyclone-induced RDC varies widely. For example, different RDC outcomes occur when treating the SEUS as one region where no RDC effect has been detected (Misra & Bastola, 2016) as opposed to climate division level or drainage basin scaling where RDC events have been documented (e.g., Brun & Barros, 2014; Maxwell et al., 2012, 2013). The RDC influence of Frontal and Air mass events in the SEUS also remains unclear. Air mass events associated with atmospheric rivers may result in extreme precipitation over large regions (e.g., Dettinger, 2013) and are a common component of hydroclimate in the SEUS (Debbage et al., 2017; Lavers & Villarini, 2015; Mahoney et al., 2016), yet no study has documented their relationship to RDC in the region. Additionally, frontal systems associated with midlatitude cyclones and Air mass events caused by convective storms are common sources of precipitation in the region, but their effects on RDC remain undocumented. Here we examine (1) the spatiotemporal patterns of different storm types that rapidly end drought in the SEUS, (2) whether any of the storm types exhibit a trend in drought cessation impacts, and (3) the large-scale influences on warm-season RDC.

2. Methods

2.1. Drought Metric

We used the Palmer Drought Severity Index (PDSI) (Palmer, 1965) to identify periods of drought and RDC events for the SEUS (24°N–37°N and 75–101°W). The PDSI is a water-balance index that uses departures from local temperature and precipitation climatological means in a surface-moisture supply-and-demand hydrologic model. The PDSI index represents "normal" conditions as a value of "0," with negative (positive) values indicating drought (wetness). Use of PDSI has limitations (cf. Alley, 1984; Karl, 1986; Werick et al., 1994), but the ease of computing PDSI and the availability of a century-long data record throughout the U.S. results in widespread use by U.S. Federal and State agencies and drought researchers. Recently, the accuracy of the PDSI has been questioned, because it uses the Thornthwaite temperature-based measure of potential evapotranspiration (PET), which may overestimate or underestimate trends in drought conditions (Sheffield, Wood, & Roderick, 2012). Specifically, Thornthwaite PET has been shown to exaggerate trends in global drought related to anthropogenic climate change (Hoerling et al., 2012; Vicente-Serrano, Beguería, & López-Moreno, 2010). Many studies suggest that the physically based Penman-Monteith method of estimating PET more accurately represents drought conditions with PDSI (Dai, 2013; Hoerling et al., 2012; Sheffield et al., 2012). Therefore, we used a MATLAB PDSI tool (Jacobi et al., 2013) with a Penman-Monteith PET addition (Ficklin, Letsinger, et al., 2015). We used the PDSI tool to calculate a high spatial-resolution (12 km × 12 km) grid of Penman Monteith-based PDSI from 1979 to 2013 using climate input data from METDATA (Abatzoglou, 2013). METDATA is a hybrid of two meteorological data sets: the Parameter-Elevation Regression on Independent Slopes (Daly et al., 2008) and the North American Land Data Assimilation System Phase 2 (Mitchell et al., 2004). The final METDATA product yields daily data at an ~4 km spatial resolution. METDATA has been validated in Abatzoglou (2013) for the continental United States. For ease in computation, the METDATA was aggregated to a 12 km by 12 km resolution for the PDSI MATLAB tool.

2.2. Defining Rapid Drought Cessation

To ensure that RDC events occurred at sufficient spatial scale to have water-management implications, we used PDSI at the climate division level to initially define subregional or regional drought (Maxwell et al., 2012, 2013). Climate divisions represent spatial units within U.S. states (approximately 7–10 divisions per state) delineated with consideration of climatic similarity (Guttmann & Quayle, 1996). Climate division data are derived from the unweighted arithmetic average of daily observations at weather stations within the division, and averaged for each month (Guttmann & Quayle, 1996; Karl, 1986). Climate division data are thus less suited for local climatic variability analyses but are useful for regional drought analyses (e.g., McCabe, Palecki, & Betancourt, 2004; Soulé, 1990). We gathered monthly PDSI data from climate divisions in the SEUS available from the National Oceanic and Atmospheric Administration for the same period of availability as the high spatial-resolution PDSI tool (1979–2013).

We defined a drought event as at least one climate division having a monthly PDSI value of ≤ -2.0 ("moderate drought"). Then, we defined an RDC event as one or more consecutive months of moderate drought followed immediately by a month with a PDSI value classified as "near-normal" or wetter (PDSI ≥ -0.50). Because PDSI values are calculated to take into account previous conditions, the index has a memory of 12–18 months (Guttman, 1998), and thus, a large month-to-month change represents a substantial shift in soil moisture. We wanted to ensure that an RDC event was not a result of a short ($<$1 month) dry period or mild drought and was from a large shift in soil moisture (Karl, 1986). The use of PDSI provides a conservative measure of moisture balance to ensure a substantial drought was in place for a RDC event to occur.

Here we examined droughts and RDC events for the warm season (April–November), when both municipal and ecological water shortages are typically exacerbated due to increased water demand. Cool-season droughts (and presumably RDC events) occur in the SEUS, impacting agricultural and other water-intensive industries. However, because of the increased drought impacts associated with higher air temperatures (e.g., Hayes et al., 2004) and climatological differences in the large-scale forcing of drought between the warm and cool seasons (cf. Ortegren et al., 2011; Seager et al., 2009), we focused on the warm season.

We used the PDSI tool to examine the spatial scale of RDC events. For every RDC event identified at the climate division level, we calculated PDSI at a 12 km × 12 km grid for the SEUS for the month before and the month of the RDC event. For example, if moderate drought was present at the climate division level in June of 1988 and then July 1988 had near normal (or wetter) PDSI values, we examined both months in the PDSI tool and calculated the percentage of 12 km × 12 km grid cells in the entire region that experienced an RDC event. An RDC event could occur multiple times for a given drought depending on the size of the drought. Thus, a single (spatially contiguous) drought covering much of the study area could be ended in different subregions by separate RDC events of either different or the same storm types and at either different or the same times within a given month. In this example, each (spatially noncontiguous) instance of subregional RDC would be classified as a distinct RDC event.

2.3. Storm-Type Classification

We used Daily Weather Maps (NOAA Central Library Data Imagining Project) and a global atmospheric river data set (Mahoney et al., 2016) to determine the storm type responsible for RDC events. The Daily Weather Maps databank contains daily surface weather, 500 hPa, and precipitation maps for the U.S. Using the daily weather maps, we classified storms as either Tropical (any tropical cyclone), Frontal (e.g., cold and warm fronts and upper level, closed-low systems), or Air mass (convective activity or atmospheric river) types (Faiers et al., 1994; Keim & Faiers, 1996) for the month that RDC occurred. We collected daily precipitation data from stations within the climate division where RDC occurred to see which storm for a given month contributed the most precipitation. To classify as a RDC event, a given storm type had to contribute at least 50% of the precipitation for the month in question. The 50% could be achieved by one individual storm event (e.g., a tropical cyclone) or multiple events of the same storm type for a given month (e.g., multiple cold fronts). We created two subcategories for Frontal systems to distinguish between (a) upper level lows (hereafter, Frontal-closed lows) and (b) standard midlatitude systems or open-wave cyclones with associated frontal systems (hereafter, Frontal-cold fronts). A frontal-closed low refers to a storm with cyclonic circulation and at least one pressure height contour that is enclosed at 500 hPa height. Frontal-closed lows often function as standard midlatitude wave cyclones. However, Frontal-closed lows can function partially independently of the westerly flow and thus may move more slowly than average midlatitude cyclones (Blackmon et al., 1977). Likewise, we separated Air mass events into (a) convective uplift-based thunderstorms (hereafter, Air mass -convective) and (b) atmospheric river-derived precipitation (hereafter, Air mass -atmospheric rivers).

2.4. Trend Analysis

For each broad storm-type category, we conducted a Mann-Kendall nonparametric trend analysis to determine significant trends during 1979–2013. The Mann-Kendall test is a commonly used trend analysis in climate studies (Ficklin, Maxwell, et al., 2015; Gocic & Trajkovic, 2013; Tabari, Somee, & Zadeh, 2011; Yue, Pilon, & Phinney, 2003), with an increasing/decreasing trend indicated by positive/negative Z values. We determined significance at the 0.05 α-level by comparing the Z to the $Z_{1-\alpha/2}$ value from a standard normal cumulative distribution table (Trenberth & Shea, 2006).

2.5. Large-Scale Oceanic-Atmosphere Influences

We gathered mean monthly large-scale oceanic-atmospheric index data for the 1979–2013 period to compare to RDC events for each of the three broad storm types. We chose the climate indices based on known influence on either drought or rainfall in the SEUS. Specifically, we examined the North Atlantic Oscillation from NOAA's Climate Prediction Center, the east-central tropical Pacific SST-Nino 3.4 (El Niño–Southern Oscillation) from NOAA's National Centers for Environmental Information, the Atlantic Multidecadal Oscillation (AMO) (Enfield, Mestas-Nuñez, & Trimble, 2001), and the Northern Hemisphere sea-ice extent from the National Snow and Ice Data Center. Because the count data of RDC events were not normally distributed, we used the percent of the total study area alleviated of drought to correlate with the climate indices instead of counts of RDC per storm type. Using the percent of the total study area that was alleviated by drought allows for a time series of the absolute proportion of the study area that experienced an RDC event.

Table 1
Summary Statistics of Rapid Drought Cessation Events for Each Storm Type From 1979–2013

Storm type	Number	Percentage of RDC events	Average percent area[a]	Median percent area[a]	Minimum percent area[a]	Maximum percent area[a]
Tropical	29	28%	5%	3%	0.03%	19%
Frontal	54	51%	6%	4%	0.77%	30%
Subcategories						
Frontal-closed low	8	8%	13%	13%	0.84%	30%
Front	44	42%	5%	4%	0.77%	25%
Air mass	22	21%	3%	1%	0.27%	13%
Subcategories						
Air mass-convective	18	17%	2%	1%	0.27%	5%
Atmospheric river	4	4%	8%	8%	4%	13%

[a]Percent area of the entire region considered the southeastern U.S. (24°N to 37°N and −101°W to −75°W).

3. Results and Discussion

During 1979–2013, there were 105 RDC events from 15 droughts. Drought was present in at least one portion of the region (24°N to 37°N and −101°W to 75°W) during 25% of the years. Impressively, 73% of all warm-season droughts were ended by RDC events, indicating that gradual alleviation of drought in the SEUS is less common. Frontal events (cold fronts and closed-low systems) were most frequently associated with RDC, followed by Tropical (tropical cyclones) and then Air mass (convective uplift and atmospheric rivers) events (Table 1). In the 34 year study period, Frontal events ended 38% of all droughts, while Tropical and Air mass events ended 20% and 15% of all droughts, respectively. While this is the first study to examine the RDC-related properties of Frontal and Air mass storm types, the percentage of droughts ended by tropical cyclones is comparable to previous studies (Brun & Barros, 2014; Maxwell et al., 2012, 2013).

The three storm types on average rapidly ended droughts over a comparable percentage of the study area (Figure 1 and Table 1). The smallest spatial impact of an individual event from each storm group also was

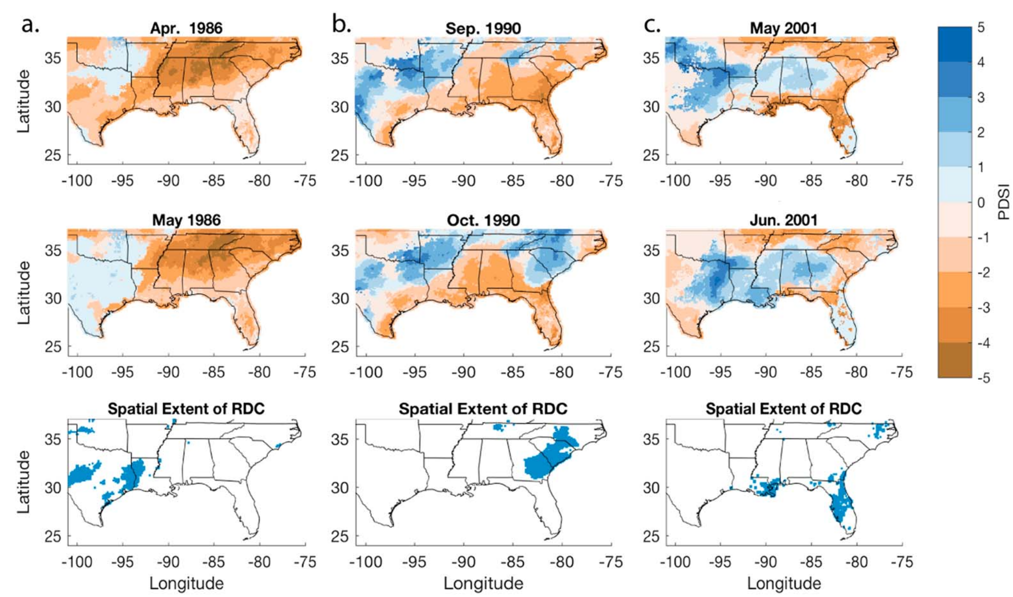

Figure 1. An example of an average rapid drought cessation (RDC) storm for (a) Frontal, (b) Tropical, and (c) Air mass storm types. PDSI for the 12 km × 12 km grid for (top row) the month before and (middle row) the month of RDC. The blue grids in the bottom row represent the cells that experienced rapid drought cessation.

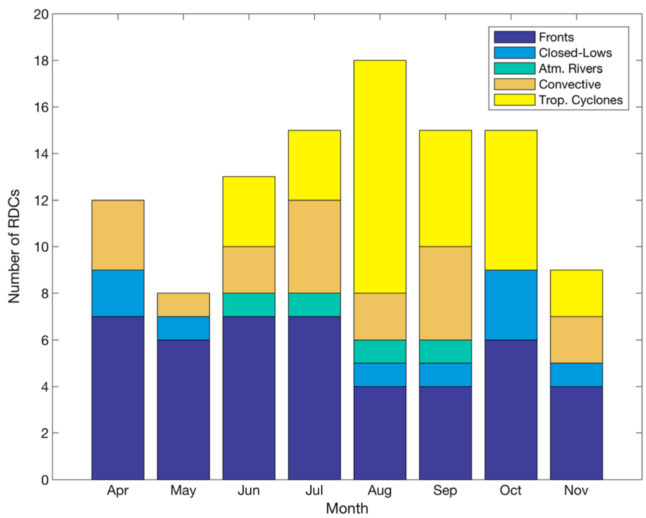

Figure 2. The proportion of rapid drought cessation (RDC) events for each subcategory of storm types for the warm season months from 1979 to 2013. Fronts and Frontal-closed lows are subcategories of the Frontal storm-type group. Similarly, Air mass-atmospheric rivers and Air mass-convective are subcategories of the Air mass storm-type group.

similar (Figure S1 in the supporting information). However, the largest spatial impact of individual events from the Frontal storm type rapidly ended drought conditions over a greater area (30% of study region) compared to Tropical (19%) and Air mass (13%) events (Table 1 and Figure S2 in the supporting information). Thus, frequency changes in RDC mechanism *types* may have an impact on the overall area affected by drought despite no changes in the total number of RDC events. In all cases in which a midlatitude cyclone caused a RDC event, it was the Frontal-cold front type that provided the precipitation to end the drought. Warm or occluded fronts never produced sufficient precipitation to cause RDC events. Importantly, in 87% of the cases where Frontal-cold fronts were responsible for RDC, multiple storms passed through the drought area during a given month, rather than a single storm.

Frontal-closed low events caused RDC less frequently than Frontal-cold fronts, but over the largest area (on average) compared to any other storm type (Figure S3 in the supporting information and Table 1). RDC caused by Frontal-closed low events was the result of a single storm in all but one case, where two Frontal-closed low systems occurred during the same month. Because Frontal-closed lows are partially separated from the prevailing westerly winds, their slower average migration compared to frontal midlatitude systems helps explain their larger spatial footprint of drought alleviation (Figure S3 in the supporting information) as they reside over an area comparatively longer. In two cases, Frontal-cold fronts and Frontal-closed-low storms combined during 1 month to alleviate drought, making it difficult to distinguish between the two synoptic subtypes; thus, these RDC events were not counted in either subcategory but were included in the broader Frontal category.

Air mass events were associated with the fewest RDC events, yet the Air mass-atmospheric river subcategory had the second-largest spatial influence (Table 1 and Figure S4 in the supporting information). Air mass-atmospheric rivers can advect large amounts of moisture (Lavers & Villarini, 2015) and account for up to 25% of annual rainfall in the SEUS (Mahoney et al., 2016). Air mass-convective events were associated with considerably more RDC events (n = 18) than were Air mass-atmospheric rivers (n = 4), yet ended drought for the smallest average area of all storm types (Table 1 and Figure S5 in the supporting information). Air mass -convective events most frequently occurred along the Atlantic and Gulf coasts, where humid, unstable air is the warm-season climatological norm (Figure S5 in the supporting information).

Tropical cyclones were associated with approximately one third of RDC events (Table 1). Tropical cyclones ended droughts ranging from subregional (e.g., 19% of the area) to local levels (0.3%) (Figures S1 and S2 in the supporting information). The Tropical-type produced RDC events with the smallest minimum spatial extent and in this case drought alleviation was localized along the coast (Figure S1 in the supporting information). However, the maximum spatial extent of a Tropical-type RDC event was comparable to Frontal-cold front and Air mass-convective subcategories. During 1979–2013 the only storm types that ended drought conditions for large portions of the SEUS were Frontal-closed lows and Air mass-atmospheric rivers. However, because these storm subtypes are infrequent (associated with 12% of all RDC events), they have a smaller cumulative spatial impact on RDC than Frontal-cold fronts or tropical cyclones (Table 1).

These findings help reconcile inconsistent results in the literature regarding the relative importance of tropical cyclones to drought amelioration throughout the SEUS. Insofar as studies of tropical cyclone-related drought amelioration at higher spatial resolution (e.g., Brun & Barros, 2014; Maxwell et al., 2012, 2013) indicated that tropical cyclones frequently ended droughts at local and subregional scales, our results are in agreement. The alternate conclusion that tropical cyclones had no significant influence on soil moisture or drought cessation (Misra & Bastola, 2016) was based on analyses of regional drought recovery (i.e., the entire SEUS as one unit). While we find no evidence that Tropical events can rapidly end drought across the *entire* SEUS, the Tropical contribution to RDC in the study area is important at smaller spatial scales.

The relative importance of different storm types to RDC varied both intra-annually and inter-annually. Frontal events were the dominant cause of RDC from April–July and November (Figure 2). Frontal-cold fronts were

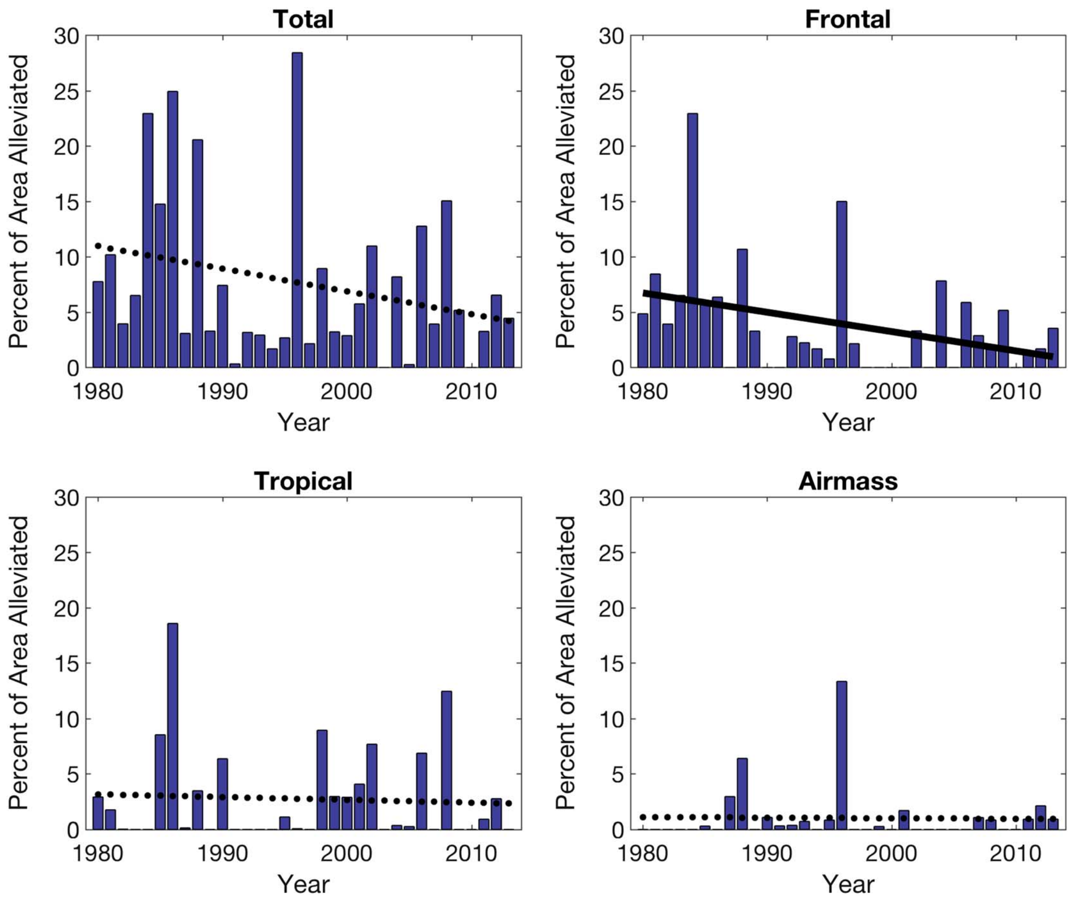

Figure 3. Time series of the percent of the total study area alleviated of drought by all storm types for RDC events (total); Frontal, Tropical, and Air mass storm types. The *y* axis represents the percent of the total region (24°N to 37°N and 75°W to 101°W) where drought was rapidly alleviated. The trend lines are dotted (insignificant) or solid ($p < 0.05$).

frequent throughout the warm season while Frontal-closed low events occurred more frequently August–November (Figure 2). Air mass-convective type RDC was more common during July–September, while Air mass-atmospheric rivers occurred during June–September. Tropical events caused RDC throughout June–November and were the leading cause of RDC during August and September. Thus, during the peak Atlantic Basin hurricane season, tropical cyclones are the most common RDC events in the region. While all storm types caused RDC events, the Air mass group was the least frequent during our 35 year study period, occurring in 14 (40%) years, compared to Tropical (18 years; 51%) and Frontal (23 years; 66%) storm types (Figure 3). The median return period of RDC was 1 year for Frontal and Tropical events and 2 years for Air mass events. The Air mass group had the longest sequence of consecutive years (7) without a RDC compared to Tropical (4) and Frontal (3) (Figure 3).

The frequency of RDC events has decreased, although not significantly ($p > 0.05$) during the study period (Figure 3). However, the Frontal storm type exhibited a significant ($p < 0.05$) negative trend in both the spatial extent of drought alleviation and the frequency of RDC events (Figures 3 and S6 in the supporting information). This decrease in RDC events from the Frontal storm type also is significant when examining the peak warm season (Figures S7 and S8 in the supporting information). Conversely neither Tropical nor Air mass activity significantly changed during peak warm season.

The significant decrease in Frontal RDC has a negative correlation with average warm-season Northern Hemisphere temperature anomalies ($r = -0.495$; $p = 0.003$).

Frontal-caused RDC events were significantly related to the AMO averaged over the warm season ($r = -0.554$; $p < 0.001$) and to average June and July sea-ice extent ($r = 0.342$; $p = 0.04$) although we interpret these associations with caution because of limitations of trend and correlation analyses using short records. The connection between Frontal RDC and Northern Hemisphere sea-ice extent supports the recent finding of a downward trend in midlatitude (frontal) storm activity over much of the midlatitudes in the Northern Hemisphere, including the SEUS, attributed to the possible effects of reduced sea ice (Lehmann & Coumou, 2015). Warm Atlantic sea-surface temperatures (AMO+) have been linked to aridity in the SEUS (Enfield et al., 2001; McCabe et al., 2004), suggesting decreased frontal activity. Global temperatures are projected to increase (Rahmstorf & Coumou, 2011) indicating that sea-ice extent will likely continue to decrease. Thus, Frontal-type RDC events are likely to continue to decrease with increasing Northern Hemisphere temperatures, especially during positive AMO phases, with implications for SEUS hydroclimate.

4. Conclusions

We found that multiple storm types rapidly end drought conditions in the SEUS and the spatiotemporal scales at which they operate vary substantially. Differences in spatial scale are important when considering how a given drought may end as our study found that only Frontal-closed-low systems and occasionally Air mass-atmospheric river events appear to end drought at the broad regional scale. RDC from Frontal events decreased significantly during the study period. The decreasing proportion of RDC from Frontal events and the seasonal timing of Frontal events could indicate that future droughts will more likely be ended by other storm types, changing the spatiotemporal aspects of drought termination and leading to potentially longer droughts. Further, the spatial scale at which drought is rapidly terminated may become smaller with fewer Frontal-closed low events, which on average ended drought over the largest proportion of the region. Our finding of a trend toward fewer Frontal RDC events, associated with warmer Northern Hemisphere temperatures and the positive phase of the Atlantic Multidecadal Oscillation, suggests that the timing of RDC events may shift from the early to late warm season—when tropical activity is highest—and become less common during the early and late warm season periods. Thus, our results suggest that if a trend toward warmer conditions continues, additional changes in the frequency and geographic extent RDCs should be expected in the SEUS.

Acknowledgments

Climate data from this study are from publicly available (https://climate.northwestknowledge.net/METDATA/ for METDATA) or published articles. The code used for the calculations of the high-resolution PDSI output used for comparisons can be acquired on GitHub (https://github.com/dficklin/CAGEO-paper). The resulting data for rapid drought cessation events are provided in the supporting information.

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