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Spatiotemporal variability of meteorological droughts in southeastern USA

Subhasis Mitra[1] · Puneet Srivastava[1]

Abstract Droughts in the southeast USA have been linked to economic losses and intractable water conflicts. The region has witnessed several severe droughts events during the period from 1901 to 2005. In this study, spatiotemporal variability in meteorological drought characteristics in the southeast were analyzed using two different datasets by the means of standard precipitation index and standard precipitation evapotranspiration index for the period 1901–2005 for agricultural and non-agricultural seasons. The study periods were divided into three epochs 1901–1935, 1936–1970, and 1971–2005 and drought characteristics, in terms of severity, frequency, number, and trends were analyzed. Additionally, areal extent, drought severities and return periods associated with three severe drought years 1904, 1954, and 2000 were analyzed. Except for the state of Florida, results indicate decrease in drought severity during the recent epoch of 1970–2005 in the study domain. Trend analysis confirms that the study domain has become wetter over the last 105 years. Wetting trends were more prominent in the agricultural season. Additionally, droughts seem to have migrated from the western part of the study area encompassing the states of Alabama, Tennessee, Louisiana, and Mississippi to the Florida panhandle region during the recent epoch. Droughts exhibited higher spatiotemporal variability during the agricultural season compared to the non-agricultural seasons. Results also showed that early to mid-1950s experienced some of the most severe droughts in the study domain. Some of the drought events, such as the drought of 1954 and 2000, have been equivalent to a 100-year drought event in the southeast. The results from this study form the benchmark for studying the impacts of future climate change projections on meteorological droughts in the southeast.

Keywords Droughts · SPI · SPEI · SAF curves · Southeast USA

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1 Introduction

Drought is a recurrent phenomenon in the USA. Past droughts have led to significant economic and social losses. As an example, in the last three decades, droughts and heat waves have caused economic losses totaling about $145 billion across the USA (Lott and Ross 2006). The southeast USA (Fig. 1) is one of the major agricultural areas in the nation. The region exhibits high heterogeneity of crop production and, with an annual output of about $55 billion in agricultural production (about 17% of total annual agricultural production of the USA), is a major economic contributor (Ingram et al. 2013). Despite abundance of moisture, the region is prone to droughts as deficit in precipitation leads to acute water shortages and freshwater supplies to the Gulf Coast. In addition to acute water shortages, droughts have also led to regional water conflicts (Southern Environmental Law Center 2013; Singh et al. 2015, 2016; Sun et al. 2008). Since 1980s, the southeast USA has experienced more billion-dollar disasters than any other region in the country (NCADAC 2013). In the southeast, La Niña phase of El Niño Southern Oscillation (ENSO) has been widely accepted as the main reason for inducing droughts (Ropelewski and Halpert 1986; Dai and Wigley 2000). According to Manuel (2008), agricultural losses in the 2007 La Niña-induced drought totaled more than $1 billion in the state of Georgia alone. The drought of 2007 provides an example of the economic losses in the agricultural, energy,
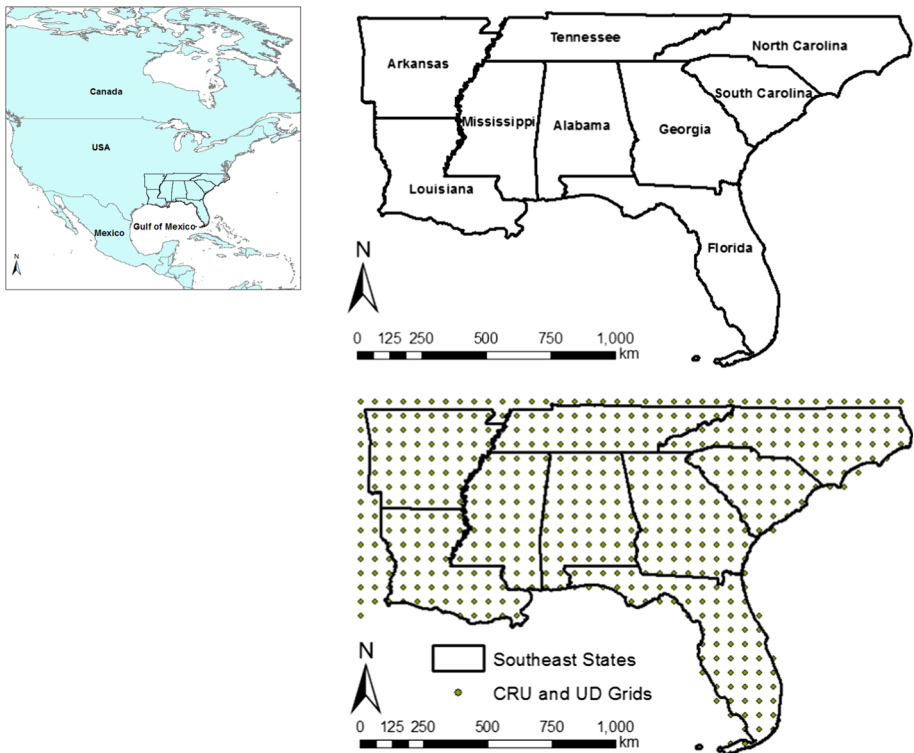

Fig. 1 Study domain showing 0.5° grid locations from the CRU and UD precipitation and temperature datasets and associated states within the study domain

and natural resources sectors that can result from severe drought events in the southeast (Manuel 2008; Maxwell and Soulé 2009; Seager et al. 2009).

Previous studies have reported conflicting conclusions regarding droughts in the southeast. Study by Portmann et al. (2009) found that the southeastern USA is one of the very few places in the world displaying a cooling temperature trend, while Andreadis and Lettenmaier (2006) showed high spatial variability of soil moisture drought trends. Soule and Yin (1995) reported an increase in short-term drought trends, while Edwards and Mckee (1997) and Yin (1993) reported wetter trends in the region. Ganguli and Ganguly (2016) and Wang et al. (2010) found decreasing precipitation trends over the southeast USA, while Rose (2009) did not find any trends in precipitation in the region. Martino et al. (2013) reported few decreasing precipitation trends in the southern part of the southeast. Winter precipitation variability in the region has been strongly linked to ENSO (Douglas and Englehart 1981; Ropelewski and Halpert 1986; Kiladis and Diaz 1989); however, there is a lack of consensus on the drivers of summer precipitation variability (Enfield et al. 2001; McCabe et al. 2004; Diem 2006; Seager et al. 2009; Li et al. 2012; Maxwell et al. 2012). The studies cited above show contrasting trends in precipitation and droughts which greatly depends on the differences in study domain and study periods. Almost no studies have been reported toward drought indices related to moisture deficit in the region. Additionally, studies conducted previously do not present any information related to droughts in the agricultural and non-agricultural seasons. *Southeast being one of the major agricultural regions in the USA, greater stress is laid on regional scale droughts property analysis corresponding to agricultural and non-agricultural seasons in this study.*

Recently, contrasting conclusions were drawn about global drought climatology (Sheffield et al. 2012; Dai 2013). Dai (2013) concluded that droughts have intensified as a result of global warming, while Sheffield et al. (2012) showed little change in drought conditions in recent years. Trenberth et al. (2014) indicated that model parameterizations used in deriving drought indices and the choice of precipitation and forcing datasets can influence drought analysis. These studies, therefore, highlight the need for using more than one dataset and drought index when assessing drought climatology, and combined with contrasting drought analysis in the region, form the basis for reassessing droughts in the southeastern USA. A comprehensive assessment of how meteorological droughts are changing across the southeast for agricultural and non-agricultural seasons and a more robust drought analysis of the entire southeast is needed. Also, all the studies conducted in the past for the southeast used sparse station data from which analyzing spatial drought characteristics such as areal extent is impossible. The use of gridded data in this study makes it possible for *analyzing the severity–area–frequency characteristics of retrospective droughts*. Additionally, previous studies have not quantified the drought characteristics such as severity, frequency and number over the study domain. Therefore, in this study, special focus is directed toward quantifying the drought characteristics. Since the past research has been at different spatial domains, not much detail was available regarding droughts at the state level. Even within a region, different areas can exhibit different drought characteristics. Therefore, in this study, spatiotemporal characteristics of droughts in individual states have been analyzed in detail.

Evaluating the spatial and temporal variability associated with retrospective drought events provides a basis for understanding the severity, frequency and areal extent of droughts, and enables the understanding of potential future drought vulnerabilities due to climate change. Building on the previous findings of drought assessment in the southeastern USA and recommendations cited in Trenberth et al. (2014), the objectives of this study were to (1) analyze the severity, frequency, and trends in retrospective

meteorological droughts in the southeast using different datasets and drought indices and (2) analyze drought severity, spatial extent, and return period of the selected severe historic drought events.

2 Data and methodology

For this study, gridded monthly precipitation and temperature data from the Climate Research Unit (CRU), University of East Anglia (Harris et al. 2014; Mitchell and Jones (2005)) available for 1901–2005 at 0.5° spatial resolution was used (Fig. 1). The second dataset used in the study was the monthly gridded precipitation and temperature dataset from the University of Delaware (UD) (climate.geog.udel.edu/~climate/) available for 1901–2005 at 0.5° spatial resolution (Fig. 1). The spatial extent of the study domain and grids considered for the study are shown in Fig. 1. These datasets were used as long-term gridded data for precipitation and temperature were available for the study domain. The CRU dataset is one of the most widely used interpolated dataset as many consider it to be the best available precipitation dataset for larger scales (Tanarhte et al. 2012; Koutsouris et al. 2016). The data sources for the CRU dataset include data from Jones and Moberg (2003), the Global Historical Climatology Network (GHCN-v2) (Peterson and Vose 1997), and monthly climate bulletins (CLIMAT). Data sources for the UD dataset include station data from GHCN-v2, the Global Synoptic Climatology Network via the National Climatic Data Center (NCDC), the Global Summary of the Day (GSOD) from NCDC, and the archive of Legates and Willmott (1990). Both the CRU and UD datasets use different interpolation techniques, and based on the recommendations of Trenberth et al. (2014), comparison of results from both the datasets would help derive conclusive results regarding the characteristics of retrospective droughts in the southeast.

The precipitation datasets of both the CRU and UD exhibit similar seasonal patterns over the study domain. During the months of winter (November–January) and spring (February–April) months, the states of Alabama (AL), Georgia (GA), Mississippi (MI), Tennessee (TN), Arkansas (AR) and Louisiana (LN) received more rainfall than North Carolina (NC), South Carolina (SC) and Florida (FL) (Fig. 2). However, during the summer (May–July) and fall (Aug–Oct) months, Florida received more rainfall than the rest of the southeast (Fig. 2).

The standardized precipitation index (SPI; Mckee et al. 1993) and the standardized precipitation evapotranspiration index (SPEI; Vicente-Serrano et al. 2010) were calculated for drought assessment at 6- and 12-month timescales. Two seasonal 6-month timescales were derived namely 6-month SPI/SPEI ending in April (winter–spring/non-agricultural season) and 6-month SPI/SPEI ending in October (summer–fall/agricultural season) for seasonal analysis of drought. The seasons of winter–spring and summer–fall were combined together due to similar spatial pattern of precipitation exhibited in the study domain (Fig. 2). The seasons also correspond to the agricultural (summer–fall) and non-agricultural (winter–spring) seasons in the southeast. The droughts of summer–fall seasons gain particular importance in the southeast as the season is associated with the peak growing seasons, and drought impact during the growing seasons can affect agricultural output in one of the major agricultural hubs in the nation. The 12-month SPI/SPEI ending in September was also calculated to study the variation of droughts within a water year in the study domain.
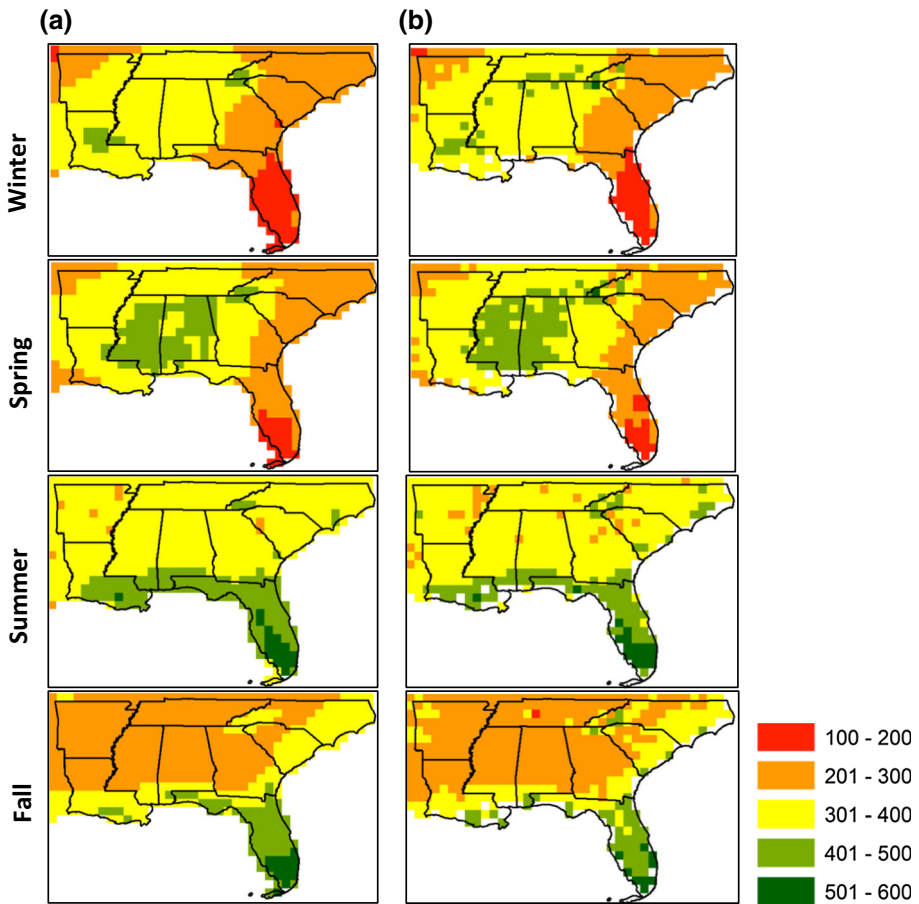
Fig. 2 Average precipitation (mm) over the study domain for the winter, spring, summer and fall seasons for **a** CRU dataset, **b** UD datasets

SPI and SPEI have been widely used for meteorological drought analysis (Mo 2008; Shukla and Wood 2008; Mishra and Singh 2010; Mishra and Cherkauer 2010; Vicente-Serrano et al. 2010; Mallya et al. 2016). The SPI is a measure of deficit in precipitation and is based on the probability of precipitation at different time scales. SPI has been found to be superior to other drought indices (Guttman 1998; Steinemann 2003; Keyantash and Dracup 2002; Paulo and Pereira 2007), not just because it is computationally easy to calculate, but also because of its ability to detect droughts early (Wu et al. 2001). SPEI is similar to SPI computationally, but was developed to add another dimension to the water cycle (evapotranspiration) while keeping the calculation relatively simple.

SPI was calculated by fitting the precipitation time series for each grid cell at any time scale to the gamma distribution function and calculating the standard inverse (Mckee et al. 1993). SPI is usually a continuous time series and is based on historic precipitation data. For example, SPI-3 is based on 3-month continuous cumulative historic precipitation datasets and fitting it into a gamma distribution function. However, in this study SPI for agricultural and non-agricultural seasons have been calculated. SPI for agricultural season (May–Oct) was based on the May–Oct cumulative rainfalls of the previous years which

then are fitted into gamma distribution function. Similarly, SPI for non-agricultural season and water year (annual) is based on cumulative historic precipitations of the non-agricultural season and water years. Similar logic was applied for calculation of seasonal and annual SPEI indices. Therefore, for each individual year (1901–2005), drought indices were calculated for annual, agricultural and non-agricultural season. These SPI/SPEI series based on yearly datasets have been used extensively in the past studies (Mishra et al. 2009, 2014; Mishra and Cherkauer 2010; Mallya et al. 2016).

The gamma cumulative distribution function ($G(x)$) for the calculation of SPI is expressed as:

$$G(x) = \frac{\int_0^x x^{\alpha-1} e^{\frac{-x}{\beta}} dx}{\beta^\alpha \Gamma(\alpha)} \tag{1}$$

where the precipitation is converted into log-normal values to compute the statistic U, shape parameter β, and scale parameter α.

For the calculation of SPEI, potential evapotranspiration (PET) was calculated using the Thornthwaite's equation (Thornthwaite 1948) at each grid cell. Various other methods such as Penman–Monteith and Hargreaves are available for the computation of potential evapotranspiration. Vicente-Serrano et al. (2010) suggested that the selection of PET computation method for the computation of SPEI in not important as the main objective is to make a relative temporal estimation of PET. Similar conclusions were drawn by Mavromatis (2007) as well. Owing to the simplicity of calculation and limited data requirement, the Thornthwaite method was used for the calculation of PET in this study. PET was subtracted from the precipitation data to calculate water deficit, and then an approach similar to the one used for SPI (Mckee et al. 1993) was used to calculate SPEI. Drought categories were derived based on Charusombat and Niyogi (2011) and are listed in Table 1. The probability density function $f(x)$ of a three parameter log-logistic distributed variable used to calculate SPEI is expressed as:

$$f(x) = \frac{\beta}{\alpha} \left(\frac{x-\gamma}{\alpha}\right)^{\beta-1} \left(1 + \left(\frac{x-\gamma}{\alpha}\right)^\beta\right)^{-2} \tag{2}$$

where α, β and γ are scale, shape, and origin parameters, respectively.

After derivation of drought indices values at difference time scales at each grid location within the study domain, various drought characteristics such as drought severity, frequency, and extent were extracted for analysis. Then, yearly drought impact index (DII) was computed by normalizing the product of areal extent and mean severity of droughts. DII identifies the years in the time series during which the drought impact was the highest within the study domain. Subsequently, the study period was divided into three consecutive 35-year epochs (early: 1901–1935, mid: 1936–1970 and late: 1971–2005). This was done to understand the temporal and spatial variability and trends of retrospective droughts in the early, mid-, and late periods of the twentieth century. This was also done as droughts exhibit multiyear

Table 1 Ranges of drought indices (SPI, SPEI) for various drought categories

Drought severity	SPI/SPEI	Category
Mild drought	−0.50 to −0.99	D0
Moderate drought	−1.00 to 1.49	D1
Severe drought	−1.50 to −1.99	D2
Extreme drought	−2.00 or less	D3

influences and the three periods chosen approximately correspond to significant drought events in the region (1904, 1930, early to mid-1950s, 1980 and 2000). Additionally, dividing the dataset into 35-year period provided a sufficient length of time series for estimating trends and conducting other statistical analyses. This kind of segmentation of time series analysis have been used previously in various studies including Ganguli and Ganguly (2016), Mallya et al. (2016), and Kam and Sheffield (2016). The choice of the period was also based on prior literature that suggested that most of the anthropogenic warming has occurred since 1970s (IPCC 2013; Dai et al. 2004; Peterson et al. 2008).

Total drought severity for an epoch at each grid point for an epoch was defined as the cumulative values of drought index (SPI or SPEI) of individual drought events (SPI or SPEI less than or equal to −0.99) within an epoch (Table 1). Drought severities have units of SPI/SPEI equivalent units (McKee et al. 1993). Subsequently, drought frequency and the number of drought events were also calculated based on moderate drought category. Trend analysis was done using the modified Mann–Kendall trend approach that accounts for autocorrelation in the time series (Kulkarni and von Storch 1995; Hamed and Rao 1998) at 5% significance level. Trends were analyzed for the seasonal (agricultural and non-agricultural) and annual SPI and SPEI values for the periods of 1901–2005 and 1936–2005 over the study domain. Further t test was used to study whether the frequency of drought years has changed significantly during the recent epoch 1971–2005 compared to 1936–1970 epoch. Further, collective significance tests (or field significance) using false discovery rate (FDR) were conducted to account for the spatial correlation of gridded data (Benjamini and Hochberg 1995; Benjamini and Yekutieli 2001). The FDR field significance test has been found to be a powerful test and relatively insensitive for spatially correlated datasets such as the gridded dataset used in this study (Khaliq et al. 2009; Ventura et al. 2004). Field significance tests have been performed at the same significance levels as their locally identified trends (5%). Also, severity–area maps were developed and analyzed for the three epochs. In addition, based on the DII, three individual extreme drought years (1904, 1954, and 2000) and associated temperature and precipitation variability were analyzed. Each of these years lied within the early, mid-, and late study periods. The years also represented some of the severe drought events in the study domain (Tables 2, 4, 5, 6).

Table 2 Top five drought years based on areal extent and DII for the annual 12SPI and 12SPEI based on SPI/SPEI < −0.99 using CRU dataset

12SPI		12SPEI	
Year	Areal extent (%)	Year	Areal extent (%)
1954	77.82	1954	85.28
1904	68.55	1925	63.51
1963	52.82	1904	58.87
1943	51.61	1943	52.62
1981	51.41	1931	52.00
Year	DII	Year	DII
1954	1.00	1954	1.00
1904	0.75	1925	0.60
1963	0.62	1904	0.57
1943	0.56	1963	0.54
1917	0.53	1943	0.54

Severity–area–frequency curves (SAF curves) (Henriques and Santos 1999; Mishra and Singh 2009) were constructed for the annual, agricultural, and non-agricultural seasons. SAF curve analysis is a useful technique for drought assessment and has been used by many others (Mishra and Singh 2009; Mishra and Cherkauer 2010). Drought properties such as severity and frequency were estimated for different areal thresholds. Frequency analysis was performed using the Extreme Value I distribution (Mishra and Singh 2009; Mishra and Cherkauer 2010) for different drought severities and areal extents to estimate return periods. Some of the results regarding the UD datasets are presented in the appendix section.

3 Results

3.1 Drought characteristics in the southeast

The drought indices calculated from the CRU and UD datasets were consistently able to capture the meteorological droughts over the study domain. Both the datasets were able to capture some of the notable droughts in the region [based on the annual 12-month SPI (12-SPI) and 12-SPEI]. Some of the notable droughts that occurred during the early 1930s, early to mid-1950s, late 1980s, and 2000 are shown in Figs. 3 and 4. Both the datasets showed similar results regarding the areal extent and DII (Figs. 3, 4). Analysis of the CRU
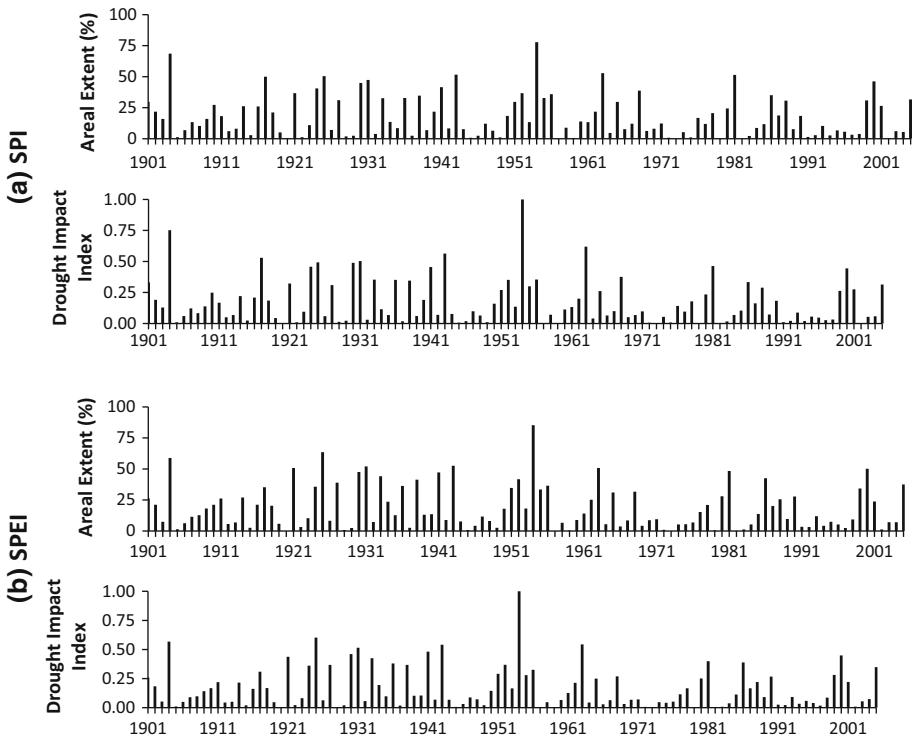

Fig. 3 Temporal variation of areal extent and drought impact index for the study domain for the study period (1901–2005) using CRU datasets based on **a** SPI < −0.99, **b** SPEI < −0.99
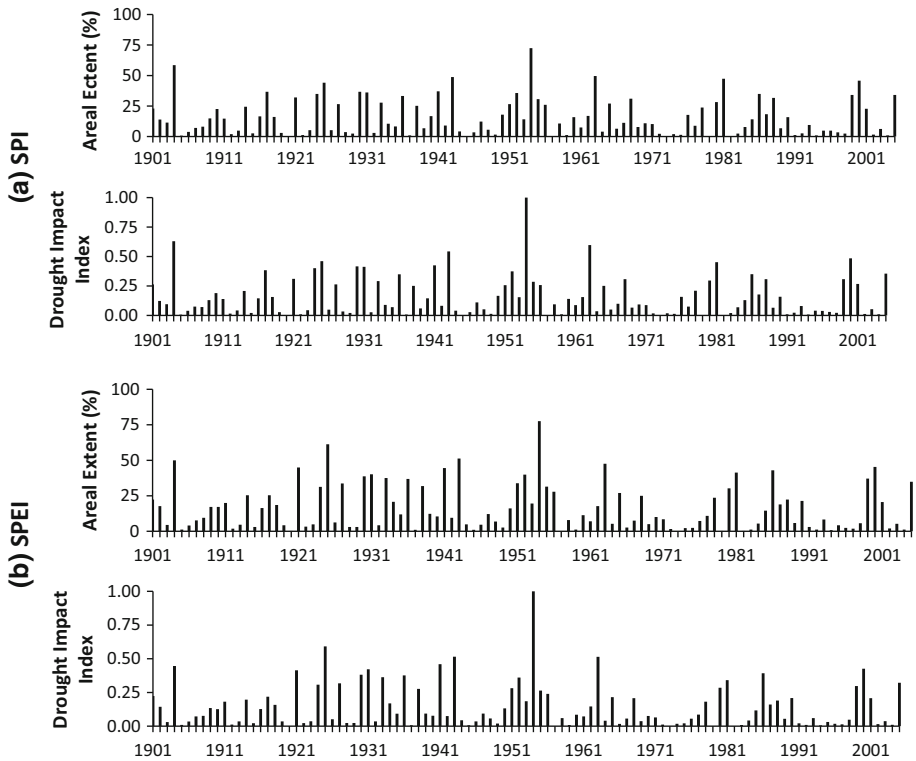
Fig. 4 Same as Fig. 3, but using UD dataset

dataset based on the annual 12-month SPI (12-SPI) shows that the year 1954 was the most severe drought year based on both areal extent (approximately 70%) and DII (Tables 2, 5). Other notable severe meteorological drought years were 2007, 1943, 1904 and 1963. Similar results were seen with 12-month SPEI (12-SPEI) (Table 2). Both indices consistently agreed on the extreme drought years in the region; however, the areal extent of the droughts varied.

Agricultural season droughts [6-month SPI ending in October (6-SPI-AG) and 6-month SPEI ending in October (6-SPEI-AG)] showed similar results related to areal extent and DII when compared to the results based on the 12-month indices (12-SPI and 12-SPEI). In addition to the historic drought years identified by the 12-SPI and 12-SPEI (Table 2), years 1931 and 2000 also figured prominently within the top five agricultural season drought years based on areal extent and DII (Table 3). Areal extents of droughts calculated with SPEI during the agricultural season were consistently higher than those calculated using SPI, as during those months' higher temperatures lead to larger evapotranspiration and greater water deficit, and consequently more grids are identified as under drought based on SPEI than SPI.

The most notable drought years based on non-agricultural season droughts [6-month SPI ending in April (6-SPI-NAG) and 6-month SPEI ending in October (6-SPEI-NAG)] were different than those identified based on 12-month drought indices suggesting that severity of droughts have a strong seasonal component. The most severe droughts for non-agricultural seasons occurred in the years 1981 and 1967 (depending on drought indices; Table 4).

Table 3 Top five drought years based on areal extent and DII for the agricultural season 6-SPI-AG and 6-SPEI-AG based on SPI/SPEI < −0.99 using CRU dataset

6-SPI-AG		6-SPEI-AG	
Year	Areal extent (%)	Year	Areal extent (%)
1954	69.15	1954	79.64
1952	60.69	1931	64.31
1931	60.69	1952	60.69
2000	53.43	1936	59.88
1904	50.40	2000	59.07
Year	DII	Year	DII
1954	1.00	1954	1.00
1952	0.83	1931	0.74
1931	0.79	1952	0.69
2000	0.69	2000	0.67
1924	0.66	1936	0.62

Table 4 Top five drought years based on areal extent and DII for the non-agricultural season 6-SPI-NAG and 6-SPEI-NAG based on SPI/SPEI < −0.99 using CRU dataset

6-SPI-NAG		6-SPEI-NAG	
Year	Areal extent (%)	Year	Areal extent (%)
1981	85.28	1967	85.28
1910	75.00	1981	83.06
1904	72.58	1910	80.85
1918	70.97	1918	68.75
1967	69.96	1907	68.35
Year	DII	Year	DII
1981	1.00	1967	85.28
1986	0.86	1981	83.06
1904	0.82	1910	80.85
1910	0.78	1918	68.75
1918	0.72	1907	68.35

Similar results were derived from the UD dataset. The major drought years identified by the UD dataset agree well with the CRU datasets for the annual and seasonal droughts (Tables 5, 6, 7). There were broad similarities within the dataset. However, there were specific differences based on the criteria (areal extent or DII) and choice of index and dataset. For example, the areal extents calculated using the CRU dataset were consistently larger than those calculated using the UD dataset, and the areal extents calculated through SPI were lower than the areal extent calculated through SPEI for the agricultural season.

3.2 Spatiotemporal variability of retrospective droughts

The spatiotemporal variability of droughts in the southeast was studied based on the average drought characteristics calculated over the epochs (1901–1935, 1936–1970,

1970–2005). The average droughts characteristics such as severity, frequency, and the number of drought events were calculated and studied for the three epochs.

3.3 Drought severity

Drought severity is defined as the cumulative values of SPI or SPEI within a droughts event (Mckee et al. 1993). For this study, drought severity for an epoch at each grid cell was defined as the cumulative value of SPI/SPEI values for the months that are under moderate, severe and extreme droughts (SPI/SPEI < −0.99). The results from the CRU dataset based on 12-SPI and 12-SPEI show that droughts were more severe during the early (1901–1935) and mid- (1936–1970) epochs than during the late (1970–2005) epoch. During 1901–1935, almost the entire study domain experienced greater drought severities, especially in the coastal regions of coastal North Carolina and South Carolina based on 12-SPEI (Fig. 5a). Droughts tended to shift westward during the epoch of 1936–1970 in
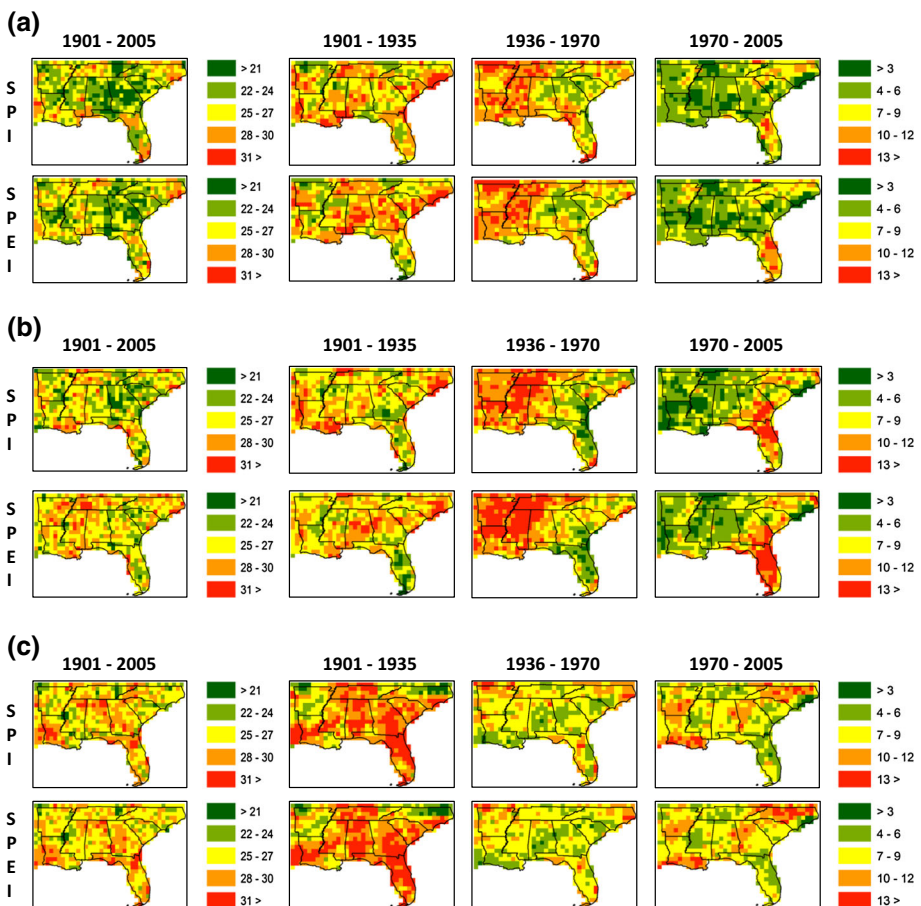
Fig. 5 Epochal variation in drought severities over the study domain using CRU dataset based on **a** annual 12-SPI and 12-SPEI, **b** agricultural season 6-SPI-AG and 6-SPEI-AG and **c** non-agricultural season 6-SPI-NAG and 6-SPEI-NAG

which the states of Mississippi, Arkansas, Louisiana, Tennessee and coastal Florida experienced greater drought severities while the states of Alabama and Georgia experiences lower droughts. During 1971–2005, very few areas showed high drought severity. In this epoch, almost the entire study domain experienced exceptionally low drought severity not observed during the previous two epochs (Fig. 5a). All the states except the Florida panhandle showed signs of greater wetness than the previous epochs.

The CRU dataset for the agricultural season based on 6-SPI-AG and 6-SPEI-AG also showed similar results as the 12-month indices (Fig. 5b). During the agricultural (Ag) season, the epoch of 1936–1970 was the driest and the states west of Georgia experienced greater drought severities. The results also suggest that the Ag seasons of the recent epoch were the wettest in the southeast except for the Florida Panhandle region. The state of Florida experienced more severe droughts during the recent epoch than the two earlier epochs. Drought severities in the study domain during the non-agricultural (N–Ag) season experienced different spatiotemporal pattern than the droughts of Ag season or annual droughts. The annual and Ag season drought patterns showed wetting pattern in the recent epoch in the study domain, which was not observed during the N–Ag season. During the N–Ag months, the epoch of 1901–1935 experienced greater drought severities than the recent two epochs. During the 1901–1935 epoch, the states of Florida, Alabama, Tennessee, Mississippi, and Louisiana experienced more severe droughts (Fig. 5c), while during the recent 1970–2005 epoch, North Carolina and coastal Louisiana were observed to have greater drought severity than rest of the study domain. Both the drought indices were consistently able to capture the temporal and spatial evolution of the droughts within the study domain.

Similar results were derived from the UD dataset in which the epoch of 1936–1970 was observed to be the driest epoch and a strong wetting tendency was seen during the recent epoch (1971–2005) for the annual and agricultural season (Fig. 15a, b). Results from the UD datasets for the N–Ag season were also in agreement with the CRU dataset (Fig. 15c).

3.4 Drought frequency

Drought frequency was defined as the total number of years a particular grid was under drought based on annual or seasonal indices. Analysis of drought frequency with the CRU dataset showed that over the entire period 1901–2005, the study domain received between 10 and 18 years (Fig. 6a) of droughts based on 12-SPI/SPEI. These numbers varied considerably within the three epochs. During 1901–1935, large areas within the study domain encompassing Alabama, Georgia, Tennessee, and coastal North and South Carolina observed total drought frequencies where >6 years or 17% of the period. Droughts shifted westward during 1936–1970 toward the states of Mississippi, Tennessee, and Louisiana. The 1970–2005 epoch showed considerably lower drought frequencies (Fig. 6a). In this epoch, most of the areas within the study domain showed drought frequency <4 years or 11% of the period except Florida where drought frequencies were >6 years. Similarly, based on the Ag season drought indices (6-SPI-AG and 6-SPEI-AG), the epoch 1936–1970 experienced the highest drought frequency for most of the study domain except for the state of Florida, while the epoch of 1970–2005 experienced the lowest drought frequency. Comparison of 1936–1970 and 1971–2005 showed that the areas that were exhibiting higher drought frequency in the previous epoch (all areas in the study domain except Florida) showed considerable lower drought frequency in the recent epoch and vice versa (Fig. 6b). Analysis of N–Ag season drought indices (6-SPI-NAG and 6-SPEI-NAG) showed that higher drought frequency was observed in 1901–1936 in the states of
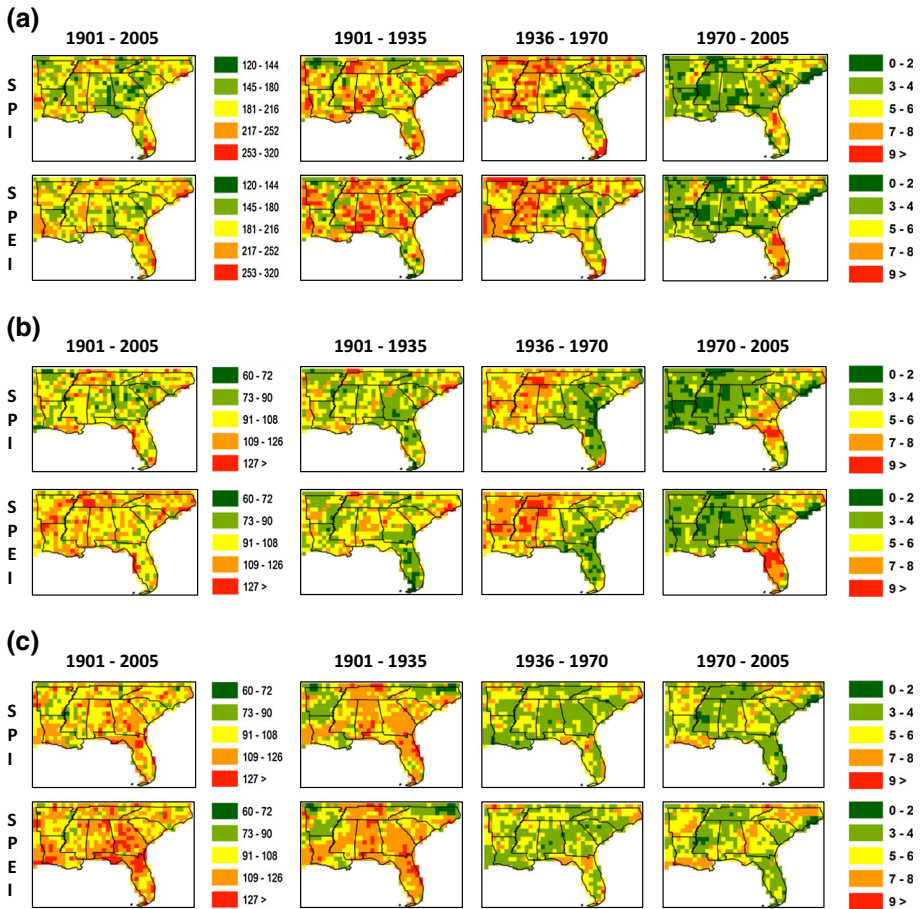
Fig. 6 Epochal variation in drought durations (in months) over the study domain using CRU dataset based on **a** annual 12-SPI and 12-SPEI, **b** agricultural season 6-SPI-AG and 6-SPEI-AG and **c** non-agricultural season 6-SPI-NAG and 6-SPEI-NAG

Alabama, Georgia, Florida, and Tennessee (Fig. 6c). Comparison of the UD dataset showed similar results. The Ag season of the 1936–1970 epoch exhibited higher drought frequencies, while in 1971–2005 epoch lower drought frequencies were observed within the study domain (Fig. 16a, b). N–Ag season for the UD dataset showed smaller areas experiencing higher drought frequencies during 1901–1936 compared to the CRU datasets. Comparison of SPI and SPEI indices indicated that larger areas exhibited higher drought frequency for the SPEI compared to SPI for all the epochs (Fig. 6b) suggesting that greater areas exhibited moisture deficit due to higher temperatures (Fig. 7).

Figure 8a–c shows the total number of years under droughts when at least 50% of the grid cells were under mild, moderate, severe, or extreme droughts (SPI < −0.49) for annual, Ag and N–Ag seasons. The results show that the 1971–2005 epoch was the wettest compared to the previous two. Based on the 12-SPI during 1971–2005, 4–5 years exhibited droughts of areal extent 50% or more (based on the CRU or UD datasets). However, 8–9 years matched the same criteria during the previous two epochs (Fig. 8a). The results

were similar for the Ag season based on 6-SPI-AG and 6-SPEI-AG (Fig. 8b). Hypothesis tests carried out to investigate whether the number of drought years have changed from 1936–1970 to 1971–2005 epochs did not show field significant results. Although some of the areas in the study domain showed locally significant decreases in the number of drought years for Ag season during the recent epoch, almost none of them were field significant.

3.5 Drought number

Drought number was defined as the total number of drought events occurring at a particular grid cell based on the 12-month drought indices. For example, if based on 12-SPI at a particular grid cell the years 1950, 1951, 1953, and 1954 were drought years (SPI < −0.99), then 1950–1951 and 1953–1954 would be considered separate drought events. Analysis of the CRU and UD datasets based on 12-SPI/12-SPEI showed that most number of grids within the study domain experienced fewer drought events (<4) during 1970–2005 and many grids received fewer than two drought events compared to the earlier epochs (Figs. 7a, 17a). Analysis of the early epochs show that many grids in Louisiana, Mississippi and Tennessee received 7–8 drought events during 1936–1970, while during the 1901–1935 epoch many grids in Alabama and Georgia showed more drought events (>7).

The results from the analysis of drought severity, frequency, and numbers show that the droughts in the southeast exhibit high spatial and temporal variability. The results from the study are consistent with the results from Edwards and Mckee (1997) and Yin (1993) who reported wetter trends in the region in recent years. However, apart from conclusively proving that the recent 1971–2005 was the wettest compared to the two earlier epochs this study showed that greater wetness corresponded to the Ag seasons compared to the N–Ag season and Ag season droughts severities and frequencies were lower during the recent epoch compared to the N–Ag season.

3.6 Trend analysis

Figure 9a–c shows trends in drought intensity (for the CRU dataset) computed using the modified Mann–Kendall trend test for both the drought indices for the annual, Ag and N–Ag seasons, respectively. Based on the 12-month indices, large areas within the study domain indicated wetting trends for 1901–2005 (Fig. 9a). Field significant wetting trends were observed in Alabama, Mississippi, Tennessee, and coastal North Carolina for
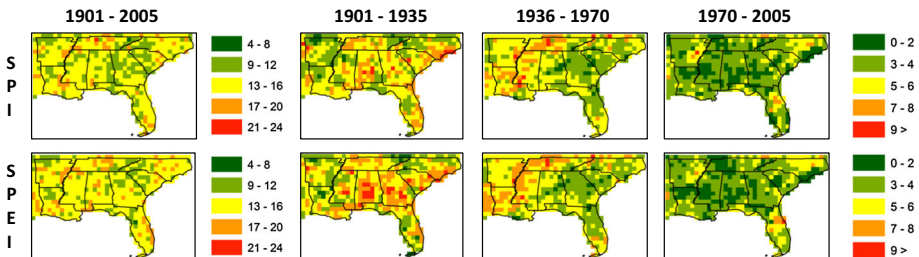
Fig. 7 Epochal variation in number of drought events over the study domain using CRU dataset based on 12-SPI and 12-SPEI

Fig. 8 Number of years with at least 50% of the study domain under mild, moderate, severe and extreme droughts (SPI < −0.49) using CRU and UD datasets for **a** annual 12-SPI, **b** agricultural season 6-SPI-AG and 6-SPEI-AG and **c** non-agricultural season 6-SPI-NAG and 6-SPEI-NAG
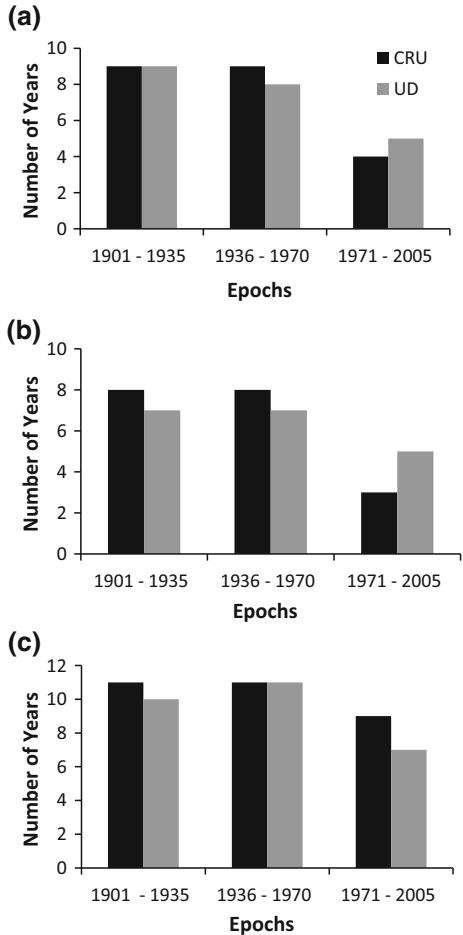
1901–2005. Stronger locally significant (not field significant) (0.01–0.05 per year) wetting trends were observed during 1935–2005, especially in Northern Alabama, Mississippi and Tennessee. Similar trends were observed in the UD dataset. However, almost none of the grids showed field significance either during the 1901–2005 or 1936–2005 (Fig. 18a). Increase in drought intensity trends were observed for Florida; however, the trends were not field significant for both the CRU and UD datasets.

The trend analysis results for the agricultural season showed strong decreasing field significant trends in drought intensity in the states of Tennessee, Northern Alabama, Mississippi, and coastal North Carolina in the CRU dataset for both the indices (Fig. 9b). More number of grids exhibited local trends. Locally significant strong increasing trends (−0.01 to −0.03 per year) in drought intensity were observed over Florida. Results from the UD dataset were similar to the results derived from the CRU dataset in that the areas showing greater decrease in drought intensity for the CRU dataset also showed greater decrease for the UD dataset for both the indices. However, far fewer grids exhibited field significance for the UD dataset compared to the CRU dataset (Figs. 9b, 18b). For the non-
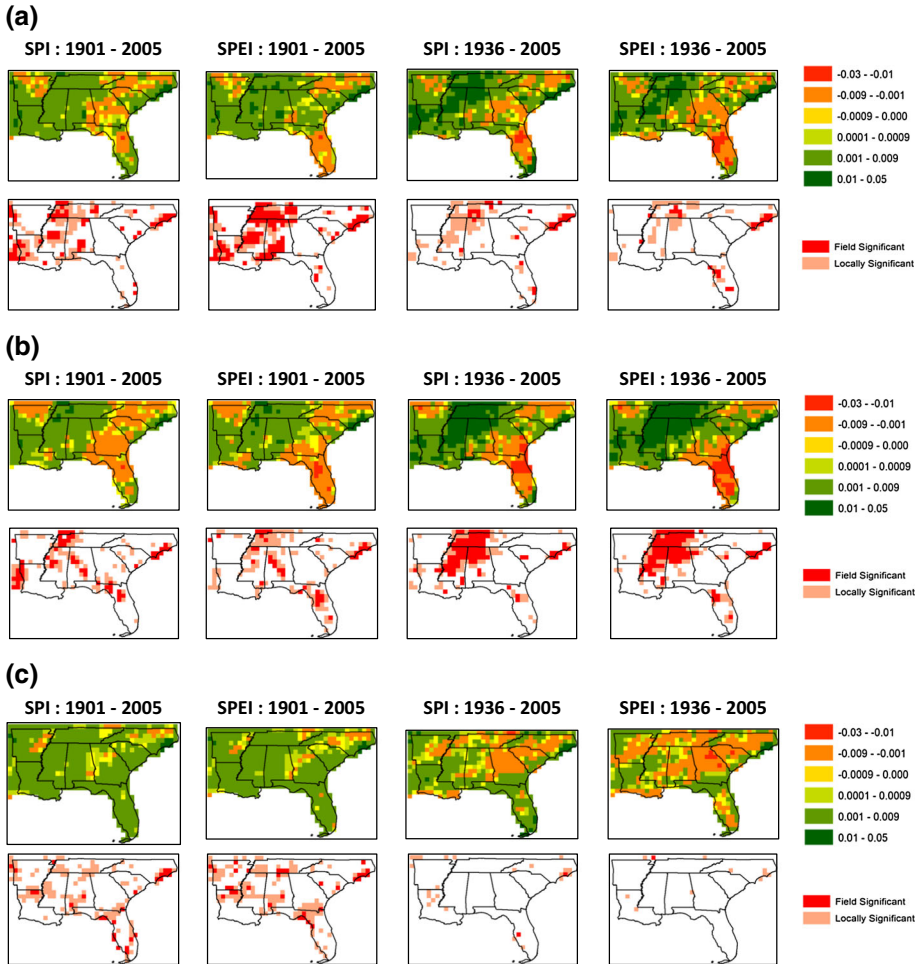
Fig. 9 Modified Mann–Kendall trend slope and associated field and locally significant grids for the study domain using CRU dataset for **a** annual 12-SPI, **b** agricultural season 6-SPI-AG and 6-SPEI-AG and **c** non-agricultural season 6-SPI-NAG and 6-SPEI-NAG

agricultural season, very few local and field significant trends were observed for both the datasets for both the indices (Figs. 9c, 18c).

Trend analysis results from both the datasets showed that there exist strong wetting trends in the southeast except for the state of Florida where increased drying is observed. These results validate the findings of the previous section. Similar results were reported by Edwards and Mckee (1997) and Yin (1993) suggesting the southeast is experiencing wetter conditions during the recent decades however, the most important trends analysis results showed that the decreasing trends were more prominent during the Ag season in the western part of the study domain. This can have wide consequences on the agricultural sector and future evolution of droughts due to climate change in the study domain. However, it is also important to note that many of the trends for the non-agricultural season are not field significant, especially in the states of Georgia and South Carolina. Analyses of
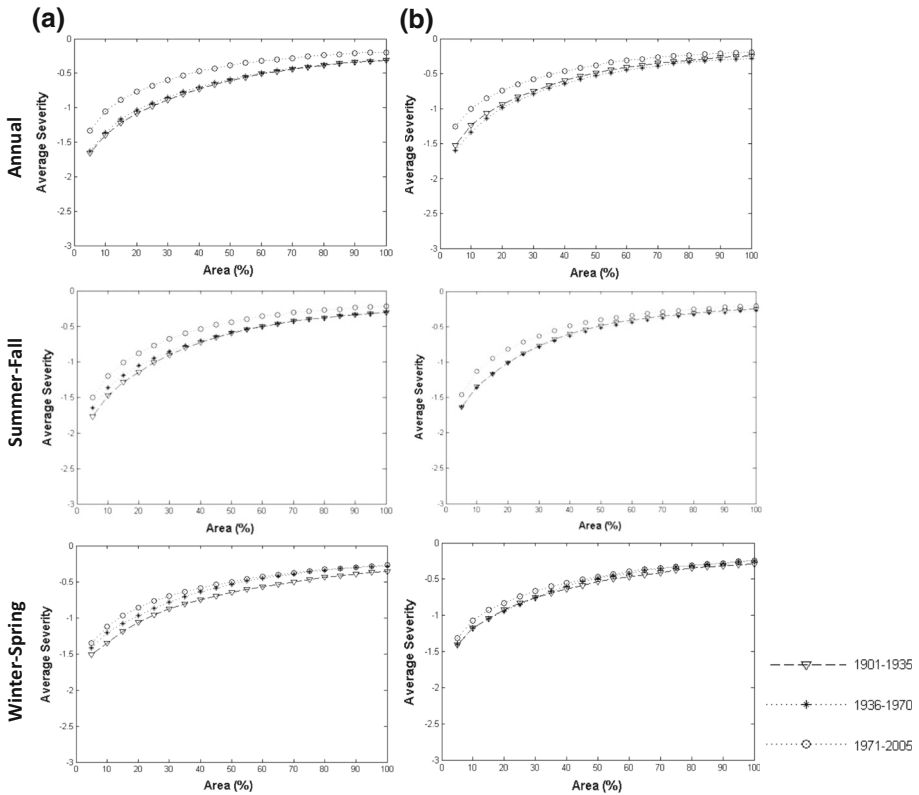
Fig. 10 Severity–area maps for the study domain with the three epochs for annual 12-SPI, summer–fall season 6-SPI-Oct and winter–spring season 6-SPI-Apr based on **a** CRU dataset, **b** UD dataset

the results regarding different states in the study domain exemplify high variability (spatial and temporal) of drought evolution in the study domain.

Analysis of severity–area (SA) maps also indicates a wetting trend in the study domain during the recent epoch as compared to the two earlier epochs (Fig. 10a, b). Based on annual 12-SPI, average drought severity in 20% of the study domain was equivalent to a D0 drought category for 1971–2005 as compared to a D1 drought category for 1936–1970. During the Ag season as well, 1971–2005 was the wettest epoch compared to the previous two. However, during the N–Ag season, the difference between the three epochs was very small. Similar results were found for the UD dataset (Fig. 10b). However, smaller differences in drought severity between 1971 and 2005 and the two earlier epochs were observed for the UD dataset as compared to the CRU dataset.

The results from previous sections, trend analysis, and SA maps show consistent results from both the CRU and UD datasets. The results strongly indicate a decreasing trend in drought intensity over the western portion of the study domain. Decreasing trends are more prominent during the Ag season which is an important result derived from the analysis. It is beyond the scope of this present study to investigate the causal mechanisms of the results presented and whether the observed wetting in the 1970–2005 epoch is related to climate change or climate variability cycles. There are a number of plausible reasons namely— land use change, sea surface temperature changes, aerosols, or global changes for this to

happen. Thus, the diagnosis of the results regarding the causal mechanisms needs to be part of a follow-up study.

3.7 Major historic droughts in the southeast

3.7.1 The drought year of 1904

The year 1904 exhibited one of the most severe precipitation deficits over the study domain. The mean precipitation over the study domain was 1042 mm as compared to the average annual precipitation of 1300 mm (80% of average precipitation). Average precipitation was much lower during the winter season (Fig. 11a). Precipitation deficit was maximum during the month of April followed by near normal precipitation levels during the summer and early fall months. Monthly temperatures during the summer months were below normal indicating lower evapotranspiration demands (Figs. 11b, 19b). Based on the annual 12-SPI/12-SPEI (annual in Fig. 11c), drought conditions persisted over the states of Alabama, Georgia, Tennessee, and Mississippi. During the Ag months, drought was not widespread. However, drought was more severe during the N–Ag season of 1903–1904. During the N–Ag season, almost the entire study domain was under at least D1 drought category except the state of Florida (Fig. 11c). Based on the 12-SPI 14% of the study domain was under D3 drought category (Table 1) and 21% of the area was under D2 drought category. Only 5% area exhibited D3 drought conditions during the Ag season (6-
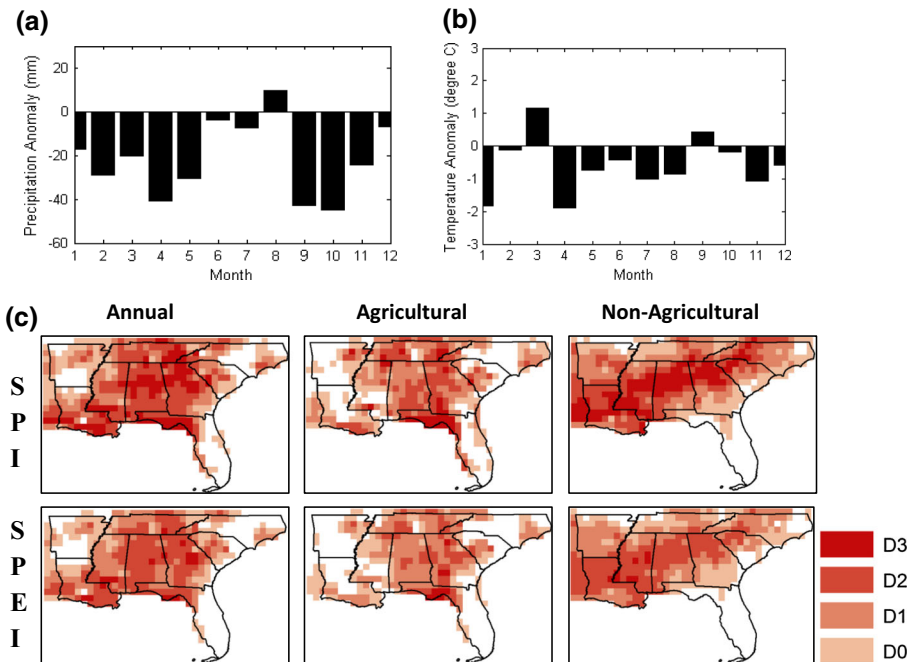

Fig. 11 Severity and areal extent of drought during the year 1904 based on CRU dataset: **a** precipitation anomaly in 1904 from the average of 1901–2005, **b** anomaly in average temperatures in 1904 from the average of 1901–2005, **c** severity and areal extent of droughts based on drought indices for annual, agricultural and non-agricultural seasons for year 1904

SPI-AG), while 17% of the area exhibited D3 drought conditions during the N–Ag season (6-SPI-NAG). Similar results were observed for the UD dataset (Fig. 19a). N–Ag months received greater precipitation deficit than the Ag months. Smaller areas showed drought under a particular category with the UD dataset as compared to the CRU dataset (Figs. 11c, 19c).

Analysis of SAF curves showed that droughts with lower return periods were less severe for the same areal coverage than those from higher return periods (Fig. 14a, b). Analysis of the CRU and UD dataset SAF curves showed broad similarities for the annual, N–Ag and Ag seasons. For all the categories analyzed (annual and seasonal), 25-year or higher return period droughts showed a severity index of about −1 and extended over 100% of the study domain.

Analysis of the year 1904 plotted on the SAF curves showed that based on 12-SPI index, the 1904 drought was equivalent to 30% of the study domain affected by a D3 drought category with a return period of 25 years. The entire study domain was affected with an equivalent of 100-year or higher return period D2 drought (Fig. 14a). During the Ag season the entire study domain received a D0 category drought equivalent to 25- and 50-year return period. Similar results were observed with the UD dataset (Fig. 14b).

3.7.2 The drought year of 1954

The drought of 1954 was the most severe drought year within the study period (1901–2005; Tables 2, 3). The domain averaged annual precipitation during the year 1954 was
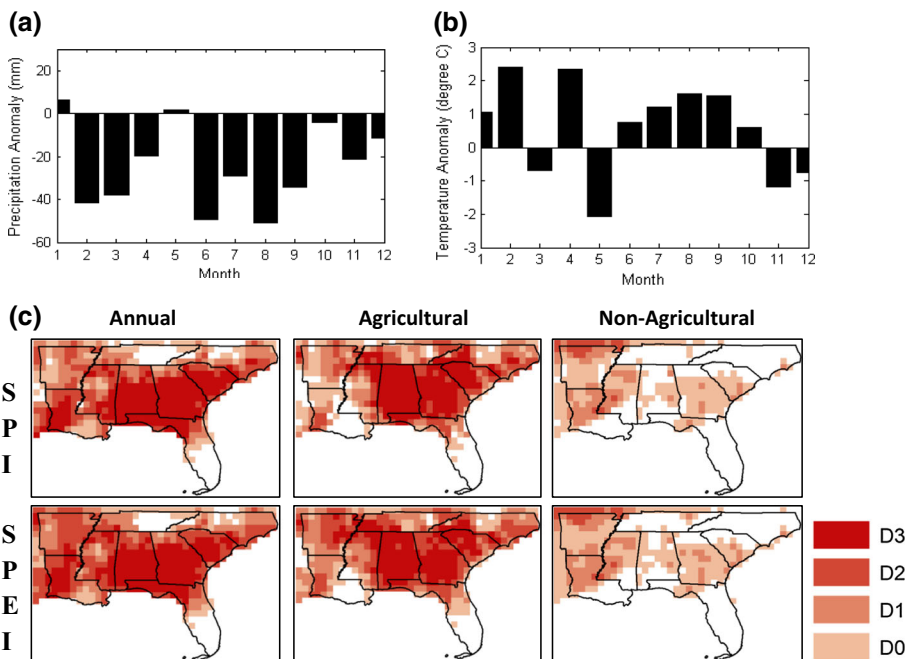

Fig. 12 Severity and areal extent of drought during the year 1954 based on CRU dataset: **a** precipitation anomaly in 1954 from the average of 1901–2005, **b** anomaly in average temperatures in 1954 from the average of 1901–2005, **c** severity and areal extent of droughts based on drought indices for annual, agricultural and non-agricultural seasons for year 1954

1008 mm (77% of annual average). Average precipitation for the entire study domain was lower for all the months during the year except May. High precipitation deficits were observed during the summer months corresponding to the agricultural season in the study domain (Figs. 12a, 20a). Higher than average temperatures were observed during all the months except March, May, and December, indicating higher evapotranspiration needs during the summer season (Figs. 12b, 20b). Analyses of annual SPI/SPEI indices indicate that many parts of the study domain were under D3 category drought. The states of Alabama and Georgia were the worst hit. Based on 12-SPI 30, 15 and 23% of the area was under D3, D2, and D1 category drought conditions respectively (CRU dataset) (Fig. 12c). Droughts were severe during the agricultural seasons as well when approximately 26% of the study domain was under D3 drought which mostly occurred over the states of Alabama, Georgia, Tennessee, South Carolina, and Northern Florida. Droughts were not widespread during the N–Ag season where just 3% of the study domain was under D2 drought conditions and no areas were under D3 drought category.

SAF curve analysis showed that based on 12-SPI, 33% of the study was affected by an equivalent of D3 category droughts of 100-year return period and the whole study domain was affected by an equivalent of D2 category drought with 100-year return period (Fig. 14a). Similar results were observed for the Ag seasons and with the UD datasets (Fig. 14a, b). SAF curve analysis for the N–Ag season showed that droughts were not that severe during that season.
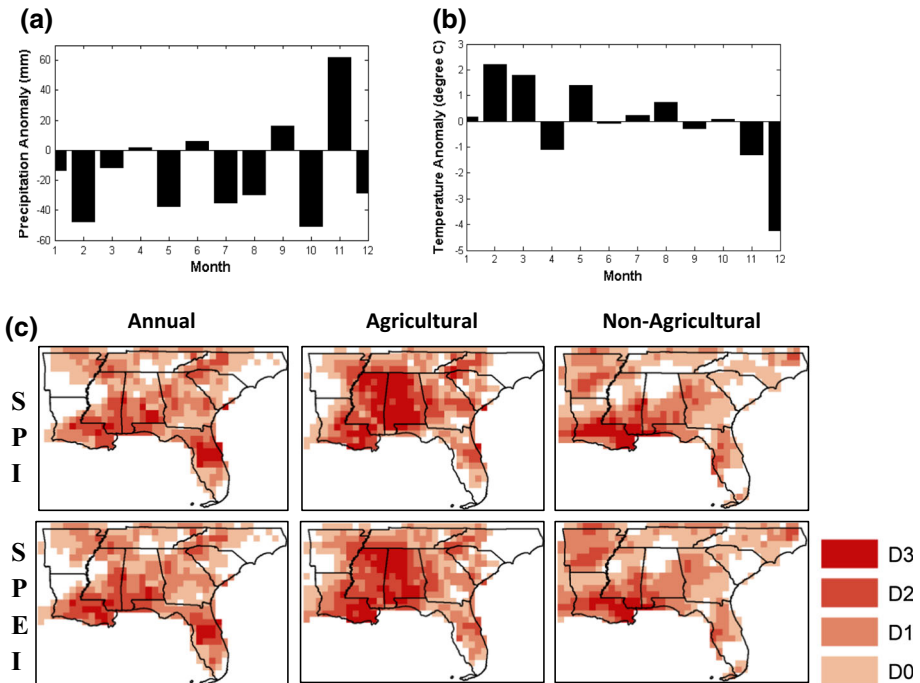

Fig. 13 Severity and areal extent of drought during the year 2000 based on CRU dataset: **a** precipitation anomaly in 2000 from the average of 1901–2005, **b** anomaly in average temperatures in 2000 from the average of 1901–2005, **c** severity and areal extent of droughts based on drought indices for annual, agricultural and non-agricultural seasons for year 2000

3.7.3 The drought year of 2000

The drought of 2000 was important since the drought was one of the severest droughts during the Ag months (Tables 3, 6). The drought of 2000 also reignited the Tri-State water wars between the states of Alabama, Florida and Georgia. Increased demands from urbanization and irrigated agricultural lowers freshwater availability of freshwater flows at the downstream end and creating intractable water conflicts in the region. The total domain averaged precipitation deficit for 2000 was approximately 170 mm which was 13% of the total period (1901–2005). Precipitation deficits were observed throughout the summer season except the month of June (Figs. 13a, 21a). Higher than normal temperatures were observed during the N–Ag months except April (Figs. 13b, 21b). During the Ag seasons droughts were more prominent. Based on 6-SPI-AG droughts approximately 14, 12, and 21% of the study domain were under D3, D2, and D1 drought categories, respectively. Drought during the N–Ag season was far less intense with only 6, 5, and 27% of the study domain were under D3, D2, and D1 drought categories, respectively. Drought mostly affected all the states in the study domain except North Carolina, with Alabama being the
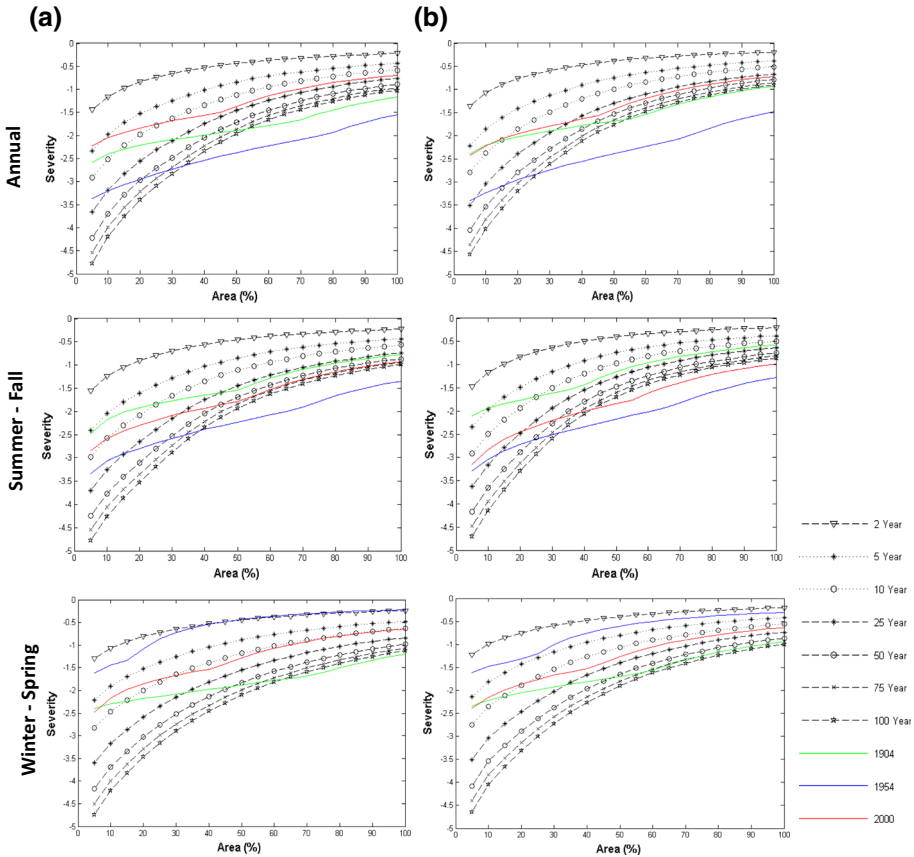

Fig. 14 Severity–area–frequency maps for the study domain for annual 12-SPI, agricultural season 6-SPI-AG and non-agricultural season 6-SPI-NAG with the selected major drought events using **a** CRU dataset, **b** UD dataset

most affected. During the N–Ag season droughts were active along the coastal regions of Alabama, Georgia and Louisiana (Figs. 13c, 21c). Analysis of SAF curves showed that based on 12-SPI, 30% of the study domain received an equivalent of D2 category drought with a return interval between 10 and 25 years. During the Ag season, the entire study domain received an equivalent of D1 category drought with a return interval of 75 years (Fig. 14a). Results were slightly different for the UD datasets where for the Ag season the entire study domain received an equivalent of D2 category drought with a return period of >100 years (Fig. 14b).

The results from analysis of three drought years (1904, 1954, and 2000) show that the study domain has been impacted by meteorological droughts in the past and appropriate management strategies should be implemented to mitigate their effects. Apart from that even having moisture rich environment, lack of water availability during droughts can lead to a lot of problems including water wars, loss in agricultural production, threaten aquatic biota, lack of water at downstream regions, groundwater depletion, and adverse effect on the fish industry along the gulf coast (Mitra et al. 2014, 2016; Singh et al. 2015).

4 Conclusions

Several studies have shown the high spatial and temporal variability of precipitation in the southeast and have also reported conflicting conclusion regarding droughts in the southeast. This was primarily due to differences in selection of study area and study period. Most of the studies have focused on trend analysis on precipitation, rainy days, soil moisture or runoff in the southeast region and not on droughts. Drought studies done by Ganguli and Ganguly (2016) and Edwards and Mckee (1997) have used continuous SPI values for analysis and have not done any analysis regarding seasonal variability of droughts in the study area. Almost no studies have been reported related to drought indices related to moisture deficit in the region. In this study, analysis regarding variability of droughts related to the agricultural and non-agricultural seasons has been performed for the first time using SPI and SPEI.

The study was conducted to analyze retrospective meteorological drought properties in the southeast using two different datasets and two drought indices (SPI and SPEI) for Ag and N–Ag seasons. The study period was divided into three epochs (1901–1935, 1936–1970, and 1971–2005) and drought characteristics such as severity, number, and frequency were studied. Trend analysis was performed to analyze the trends in both the seasonal and annual drought severity over the study period. Three most severe drought events were analyzed and associated severities, areal extent, and return period were also analyzed.

Both the CRU and UD datasets broadly agreed and were able to capture the drought events; however, there were slight differences between the two datasets in depicting drought characteristics and areal extent of droughts. The results indicated that droughts showed high spatial and temporal variability. Droughts were more severe and frequent during the early (1901–1935) and mid (1936–1970) of the twentieth century. Both frequency and severity of droughts have declined in the recent decades. Drier conditions were experienced during 1936–1970 in the western region of the study domain compared to the Florida. However, during 1970–2005 the entire study domain experienced less frequent droughts except in Florida. Droughts seem to show migration from the western part of the study area to Florida within the last two epochs. Trend analysis results indicated significant

lowering of drought intensity in study domain especially during the Ag seasons except Florida where increase in drought intensity was observed. Results from trend analysis regarding the seasonal SPI/SPEI values have been a novel contribution from this study. Trends were stronger during the agricultural season and for the period of 1936–2005. Even though earlier studies have conducted drought analysis within the study domain, in this study for the first time drought properties such as severity, frequency and number have been analyzed on agricultural season basis and results show decrease in drought severity and frequency during the Ag season. Results showed that droughts properties exhibited higher variability during the Ag season compared to the N–Ag seasons. Droughts during the agricultural season have been found to show greater field significance compared to the non-agricultural season. These results have wide ranging implications for the agricultural sector in the study domain. Analysis of different drought years indicated that drought can have significant impacts on the agricultural production in the study domain. Some of the drought events such as the drought of 2000 have been equivalent to a 100-year drought event over the entire study domain. Analysis of SA and SAF curves helped quantify drought evolution and individual drought events, respectively, and provides valuable information regarding the historic droughts in the study area.

The present study was conducted using 0.5° resolution from the CRU and University of Delaware. However, there could be concerns regarding the use of such coarse resolution data for regional scale studies. However, the CRU dataset is one of the most widely used interpolated dataset as many consider it to be the best available precipitation dataset (Tanarhte et al. 2012; Koutsouris et al. 2016). The data sources for the CRU dataset include data from Jones and Moberg (2003), the Global Historical Climatology Network (GHCN-v2) (Peterson and Vose 1997), and monthly climate bulletins (CLIMAT). The two datasets were used in the study to map any differences in results due to different datasets. The results were found to be similar for both the datasets with very minor differences. With an area of about 1.3 million km^2, the study domain would generally qualify to be regional in scale. The objectives of the study were to quantify the epochal changes in drought properties over the entire region and states (as a whole) and not at the watershed or sub-watershed scales. Various drought and precipitation studies (Ford and Labosier 2014; Doublin and Grundstein 2008; Keim et al. 2011) have used even coarser climate division level datasets for similar scale analysis in the southeast region.

The consequences of recent droughts events have led to increased water conflicts in the region, lowering flow levels to down streams regions, lowering of groundwater levels, threatening aquatic biota and affecting fish industry. Changes in severity and duration of short-term droughts (seasonal) can lead to changes in surface soil moisture that can affect agricultural productivity (Heim 2002). Changes in meteorological drought duration and severity impact water resources and environmental sectors such as groundwater levels, deep soil moisture, and reservoir. Some of these intractable issues in the study area make it extremely important to assign causal mechanisms to the trends observed in the study and also to study the impact of future climate change which would part of a follow-up study. The results from this study provide the baseline for future climate change studies in which general circulation model data from multiple models can be used to outline possible future course of drought trends in the study domain. This study thereby provides a robust conclusion that irrespective of the dataset or methodology used the southeast region has become wetter during the recent decades especially during the agricultural seasons.

Applications Research Program (SARP), and the NOAA Regional Integrated Sciences and Assessments (RISA) Program for this study.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Appendix

See Tables 5, 6 and 7; Figs. 15, 16, 17, 18, 19, 20 and 21.

Table 5 Same as in Table 2, but for UD dataset

12SPI		12SPEI	
Year	Areal extent (%)	Year	Areal extent (%)
1954	72.38	1954	77.62
1904	58.47	1925	61.29
1963	49.60	1943	51.21
1943	48.79	1904	50.00
1981	47.38	1963	47.58
Year	DII	Year	DII
1954	1.00	1954	1.00
1904	0.63	1925	0.59
1963	0.60	1943	0.52
1943	0.54	1963	0.51
2000	0.48	1941	0.46

Table 6 Same as in Table 3, but for UD dataset

6-SPI-AG		6-SPEI-AG	
Year	Areal extent (%)	Year	Areal extent (%)
1954	66.33	1954	75.20
1952	55.44	1952	59.27
2000	55.24	2000	56.85
1931	49.19	1931	53.83
1963	46.37	1936	50.60
Year	DII	Year	DII
1954	1.00	1954	1.00
1952	0.76	2000	0.69
2000	0.76	1952	0.69
1931	0.66	1931	0.63
1924	0.58	1925	0.58

Table 7 Same as in Table 4, but for UD dataset	6-SPI-NAG		6-SPEI-NAG	
	Year	Areal extent (%)	Year	Areal extent (%)
	1981	83.06	1981	80.44
	1918	65.32	1967	75.60
	1910	64.92	1910	67.54
	1967	64.52	1918	63.71
	1986	59.27	1986	61.69
	Year	DII	Year	DII
	1981	1.00	1981	1.00
	1986	0.85	1967	0.88
	1910	0.67	1986	0.86
	1918	0.65	1910	0.75
	1967	0.65	1918	0.67
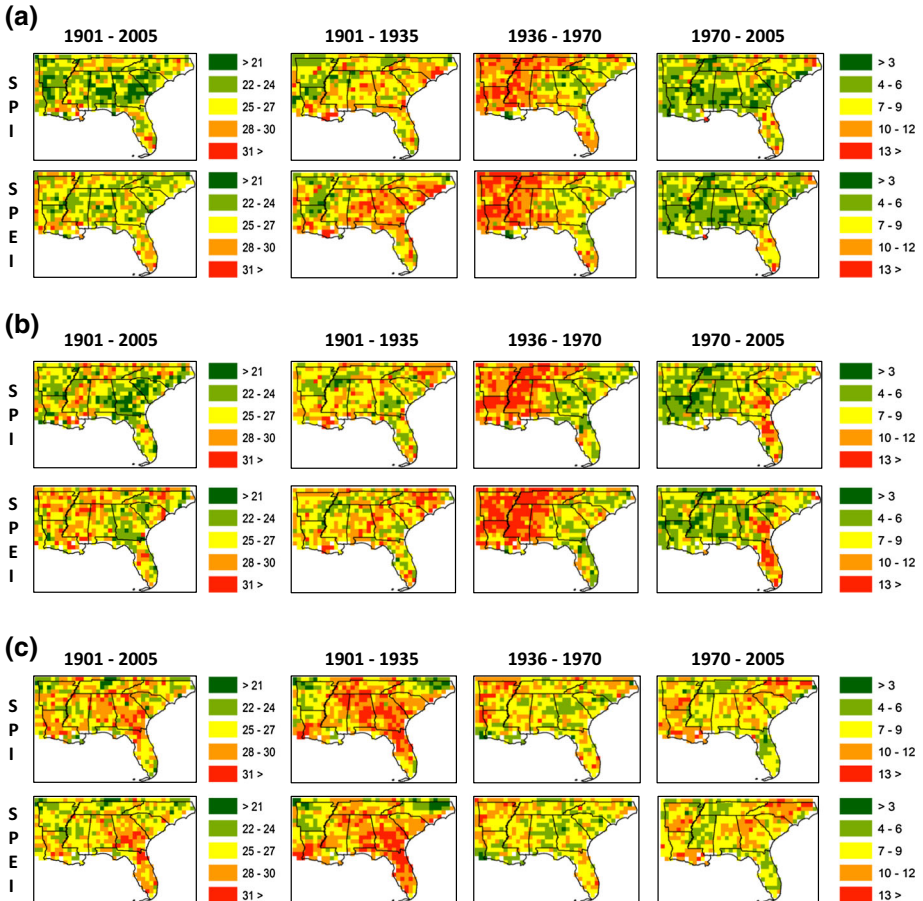
Fig. 15 Same as in Fig. 5, but for UD dataset
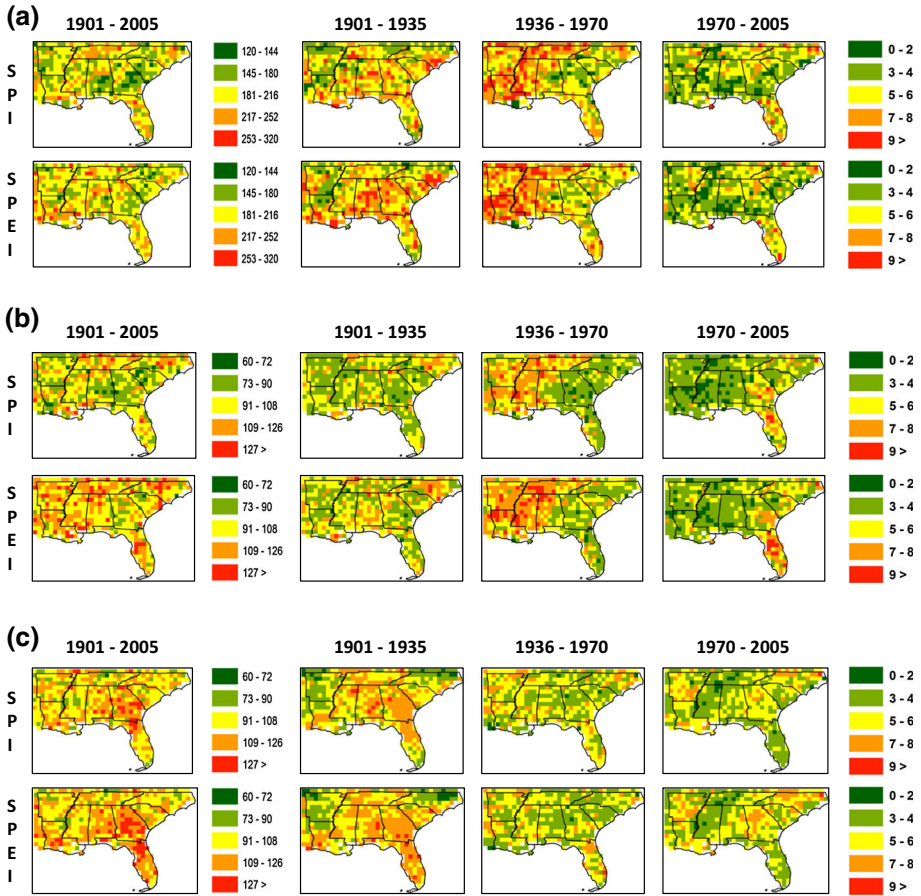
Fig. 16 Same as in Fig. 6, but for UD dataset
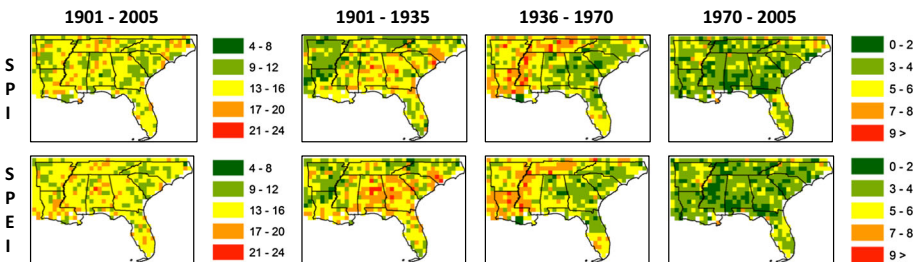
Fig. 17 Same as in Fig. 7, but for UD dataset
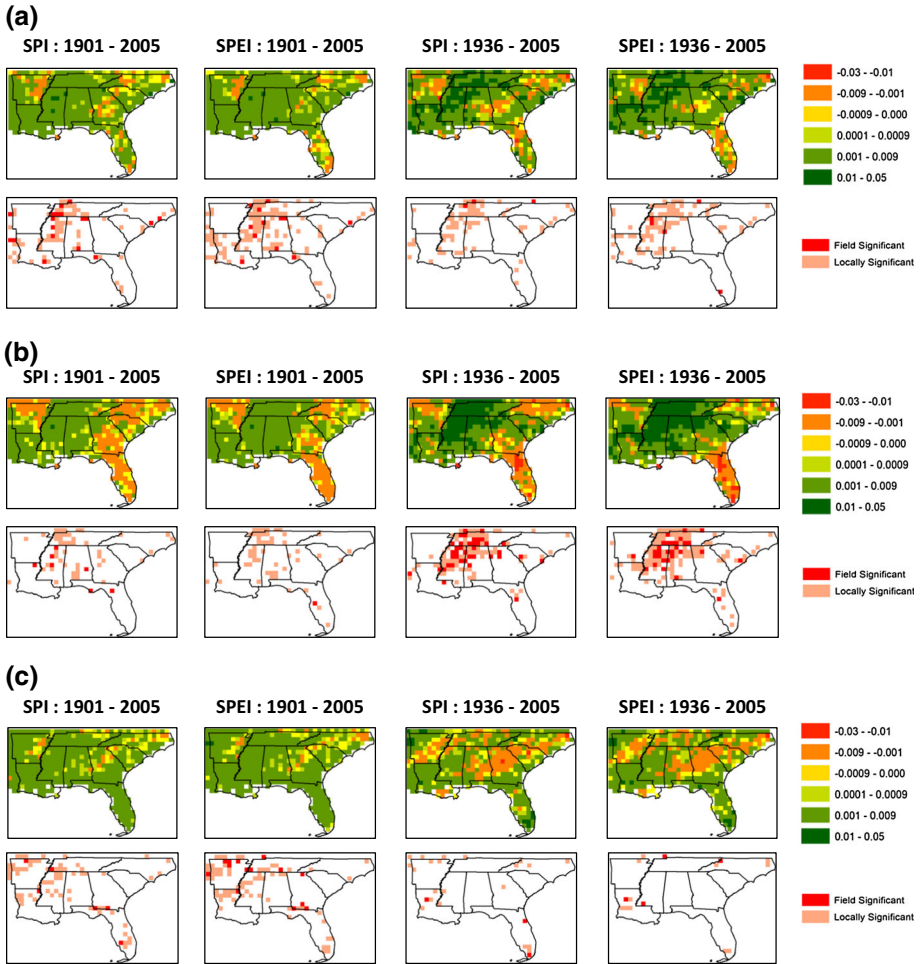
Fig. 18 Same as in Fig. 9, but for UD dataset
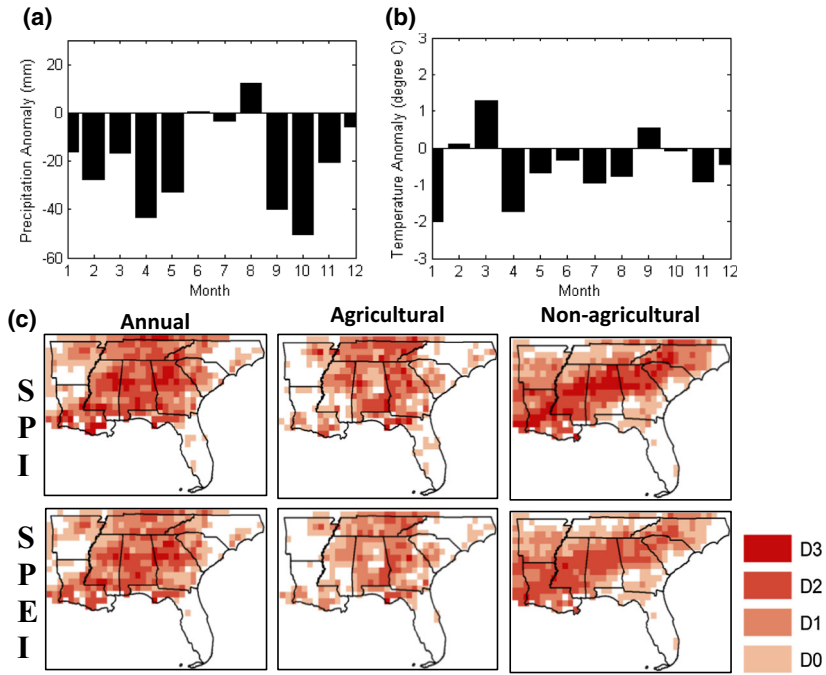
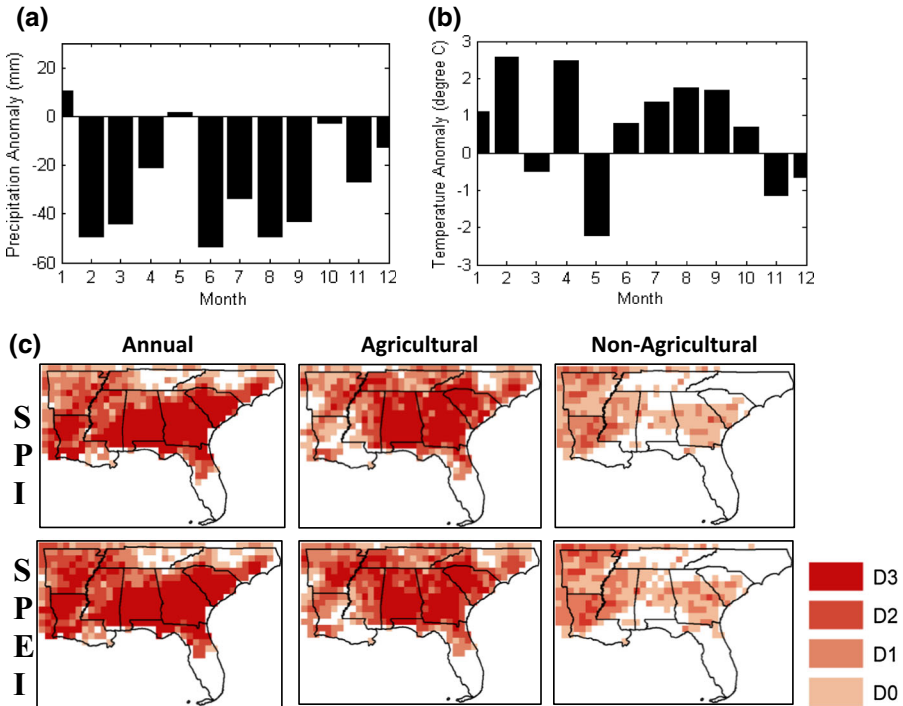Fig. 19 Same as in Fig. 11, but for UD dataset

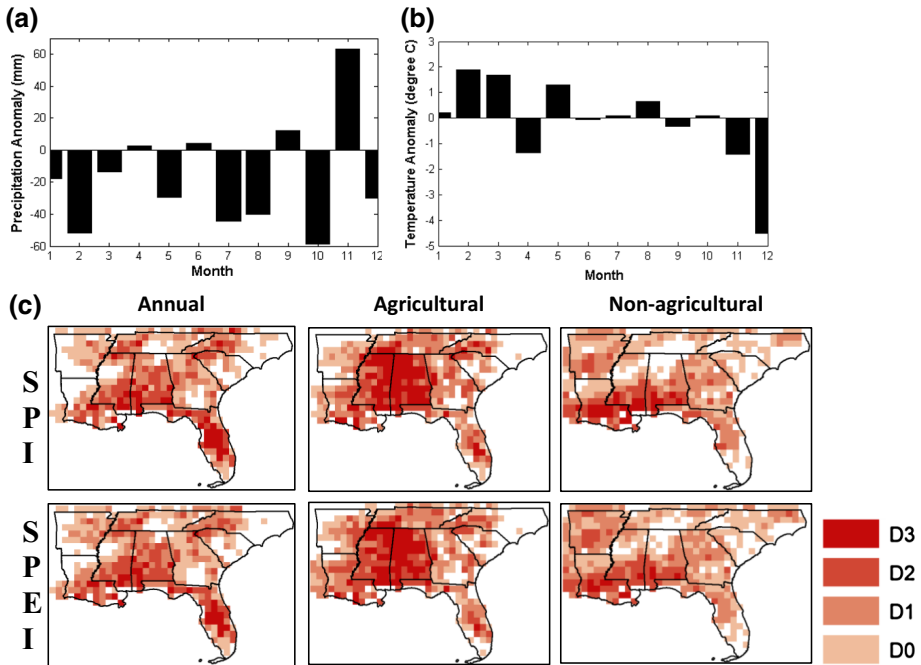

Fig. 20 Same as in Fig. 12, but for UD dataset

Fig. 21 Same as in Fig. 13, but for UD dataset

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