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REVIEW

Hydroclimatology of the Southeastern USA

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ABSTRACT: We provide an overview of the hydroclimatology of the Southeastern USA, and review the primary factors that influence hydroclimatic variability on seasonal to interannual timescales. The Southeastern USA is characterized by high mean annual precipitation, but with significant variability. Precipitation variability is on the rise in this region, with more frequent, longer duration dry periods and infrequent, short duration, but heavy precipitation events. Hydroclimatic extremes are a relatively common occurrence in the region. Seasonal to interannual hydroclimatic variability in the Southeast is primarily controlled by El Niño/Southern Oscillation (ENSO), the Pacific North American (PNA) pattern, the Bermuda High, and tropical cyclones. Future research should focus on providing a better understanding of current and future drivers of hydroclimatic variability, including interactions between human-dominated components, such as urban areas, and the hydroclimatic system. Additional research is also needed on hydroclimatic extremes (droughts and floods).

KEY WORDS: Drought · Precipitation · Climate variability · Water resources

1. INTRODUCTION

The Southeastern USA (or Southeast) has a humid subtropical climate with hot summers, mild winters, and generally high amounts of precipitation throughout the year. According to the US Census Bureau (2013), the Southeast is home to over 50 million people, and this figure is on the rise. Several large urban centers have climatic conditions that are largely regarded as favorable, including Charlotte, Memphis, Nashville, Jacksonville, Miami, Tampa Bay, and Atlanta, and in recent decades many areas in the Southeast have seen an increase in urban land use/land cover, LU/LC (Nowak et al. 2005). With the increasing population, particularly in these metropolitan areas, comes an increased demand for water resources to supply industry, energy, agriculture, and municipalities. Also, pollution degrades water resources, leaving less clean water available for ecosystems and human consumption (Dyer 2008). Future climatic changes may cause substantial changes in spatial and temporal patterns of the availability of water resources, making it more difficult to meet water demands in the region. In addition to population growth and urban development, hydroclimatic variability is increasing and extreme wet and dry events are becoming more common (Karl & Knight 1998, Groisman & Knight 2008, Wang et al. 2010). It is therefore important to characterize the hydroclimatology of the Southeast and to understand its controls.

To date, no comprehensive review of the hydroclimate of the Southeast has been performed. A review by Soulé (1998) is the most recent paper that addresses the climate of the Southeast. Soulé (1998) focuses on describing how factors such as latitude, elevation, air masses, tropical cyclones (TCs), midlatitude cyclones, and convective activity influence the climate of the Southeast. The present study describes general hydroclimatic patterns in the Southeast, including mean precipitation and variability, flooding, and drought. It also reviews the primary, large-scale seasonal to interannual controls of the hydroclimate of the Southeastern USA, including El Niño/Southern Oscillation (ENSO), the Pacific North

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American (PNA) pattern, the Bermuda High, and TCs. In addition, a brief overview of recent significant hydroclimatic events in the region are presented, including the near record setting drought in 2007, the severe Atlanta floods in 2009, and examples of TCs that alleviated drought conditions. The paper concludes by identifying important directions for future hydroclimatic research in the Southeast.

We define the Southeastern USA as consisting of the following states: Virginia, North Carolina, South Carolina, Georgia, Florida, Alabama, Mississippi, and Tennessee (see Fig. 1). This area encompasses the region covered by the Southeast Regional Climate Center with the addition of Mississippi and Tennessee. Others have defined the Southeast in a similar fashion, including Soulé (1998). We acknowledge that defining regions is somewhat subjective and that others may choose to define the Southeastern USA differently.

2. HYDROCLIMATIC PATTERNS

2.1. Precipitation regimes

Mean annual precipitation from 1895 to 2011 is depicted in Fig. 1. Locations in the eastern half of the region (generally east of the Appalachian Mountains) are drier, and western and southern areas are wetter. While station resolution is insufficient to adequately characterize precipitation regimes in the Appalachians, it is clear that the mountain range has an effect. The highest mean annual precipitation occurs in far western North Carolina near the Great Smoky Mountains (2103 mm). The lowest mean annual precipitation is in northwestern Virginia (894 mm).

Low coefficient of variation (CV) values tend to occur in the northeastern half of the region, particularly in a band running from the North Carolina and Virginia coast into central Tennessee, as depicted in Fig. 2. Highest CV values are found in isolated patches throughout the study area, particularly in the central Gulf Coast states, but also along coastlines. Fig. 3 presents mean monthly precipitation at selected stations throughout the region from 1895 to 2011. While September, October, and November tend to be drier, precipitation is fairly evenly distributed throughout the year. One exception is Bartow, Florida where there is a pronounced wet and dry season. Mo & Schemm (2008b) maintain that the lack of seasonal precipitation cycles in the Southeast reduces drought persistence.

During recent decades (1978 to 2007), the Southeasten USA region has witnessed an increase in summer precipitation variability with more frequent drought and pluvial events compared to 1948–1977 (Wang et al. 2010). Other studies also confirm the findings of Wang et al. (2010). For example, over the

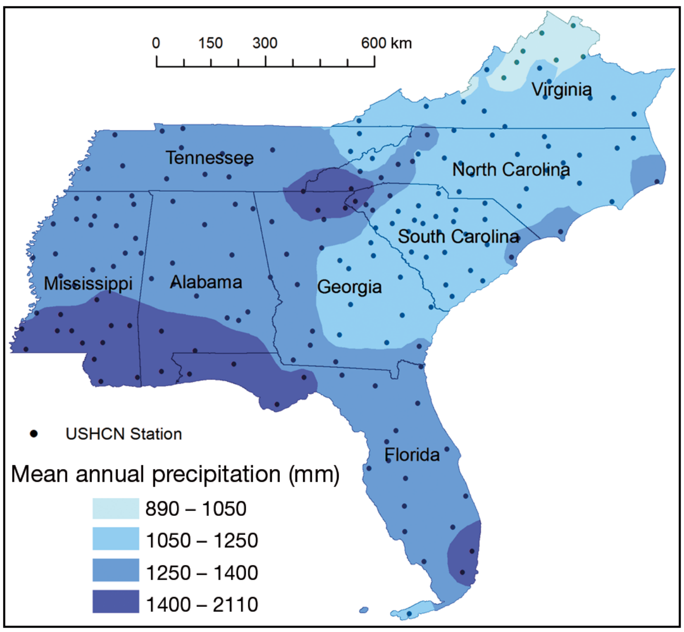


Fig. 1. Mean annual precipitation for Southeastern USA. Data obtained from the US Historical Climatology Network (USHCN; http://cdiac.ornl.gov/epubs/ndp/ushcn/ushcn.html) for 1895–2011. Interpolation completed using ordinary kriging

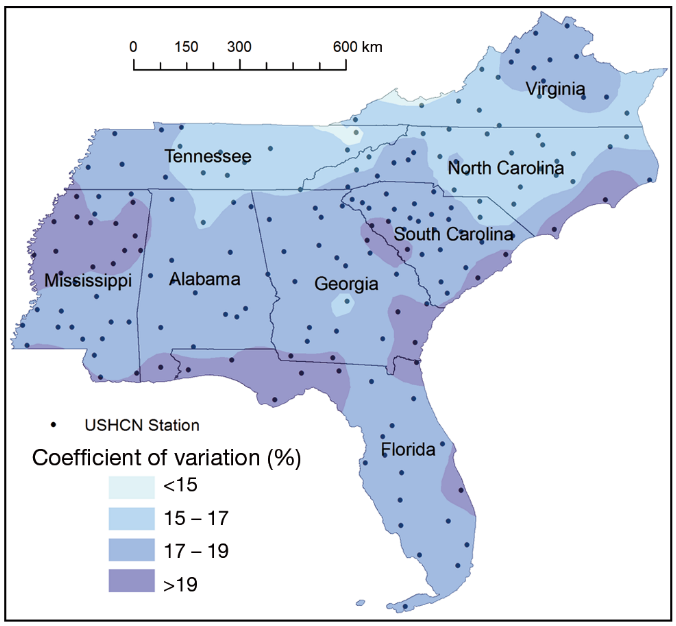


Fig. 2. Annual coefficient of variation (CV) for Southeastern USA for 1895–2011. See Fig. 1 for details on data

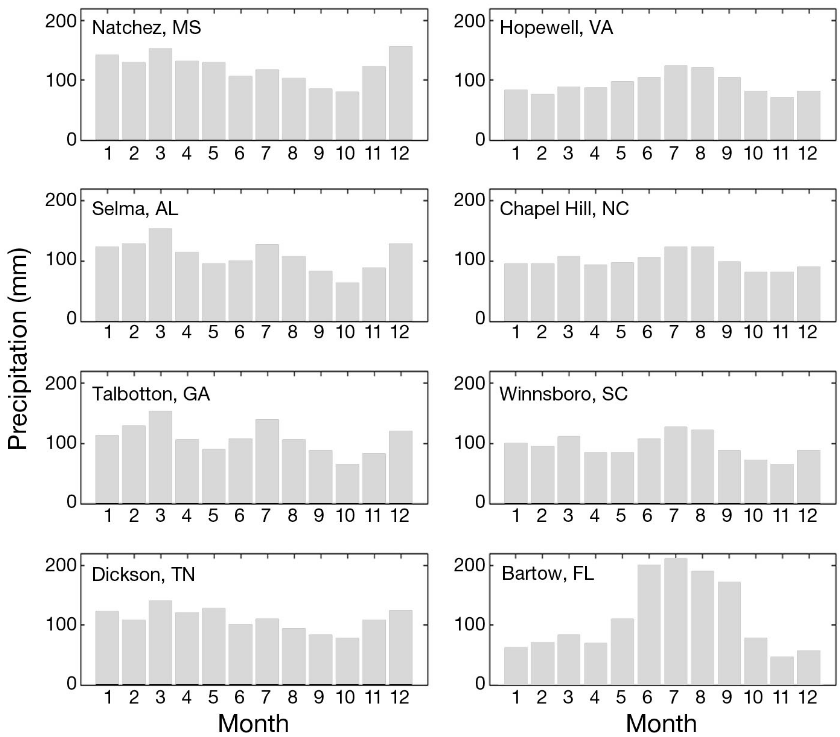


Fig. 3. Mean monthly precipitation for selected stations for 1895–2011. See Fig. 1 for details on data

last century precipitation has increased in the Southeast due to increases in heavy and extreme precipitation (Karl & Knight 1998, Groisman et al. 2001). Groisman & Knight (2008) observed an increase in the mean duration of warm season dry periods in the eastern US during the past 40 yr accompanied by a decrease in return interval from 15 to 6–7 yr for these dry events. Consequently, it seems that the Southeastern precipitation regime is becoming more variable, with both longer and more frequent dry periods and more heavy to extreme precipitation events.

Heavy or extreme precipitation events are characteristic of Southeastern climatology. Keim (1997) examined spatial and temporal variability of heavy precipitation events, defined as 76.2 mm over a period of 2 consecutive days. The central Gulf Coast regions experienced the highest number of annual events on average, followed closely by peninsular Florida (Keim 1997), results also broadly supported by Faiers & Keim (2008) when examining 3 and 24 hr storm magnitudes. Heavy precipitation events were less common in the western extremes and in the interior of the study region (Keim 1997). Keim (1997) found that the trend in the number of heavy precipitation events increased over time in a band extending from Texas to the Tennessee Appalachians.

2.2. Flooding

Given the prevalence of heavy precipitation events, along with the compounding factors of local topography and LU/LC, the Southeast is susceptible to flooding. Gamble (1997) examined flood seasonality in the Southeast, identifying 5 distinct regions with similar seasonalities, and suggested potential mechanisms behind the homogenous regions. Winter is the primary flood season in Tennessee, northern Mississippi, and northern Alabama due to the prevalence of extratropical cyclones in the season. Along the Gulf Coast into central Mississippi, through Alabama, and northern Georgia and into South Carolina, floods primarily occur during the spring. Such floods are also attributable to extratropical cyclones. In Peninsular Florida, floods are most prevalent in the fall because this is associated with the peak in TC activity. Coastal Georgia and portions of northern Florida have a spring flood season. Interestingly, no dominant flood season is found in North Carolina and Virginia, possibly due to the variety of geographic (i.e. Appalachian Mountains and proximity to Atlantic Ocean) and synoptic factors, as reported in Keeter et al. (1995). Lecce (2000) found similar results when performing a cluster analysis on streamflow data in the Southeast. The states of Mississippi, Alabama, Georgia, and Tennessee have a late winter/spring flood season. Like Gamble (1997), Lecce (2000) suggests that the northern portion of this region experiences most floods in winter, and the southern portion, closer to the Gulf Coast, experiences most floods in the spring. Florida experiences floods in both spring and late summer/early fall with over half occurring in the months of August, September, and October. Finally, similar to Gamble's (1997) findings, Lecce (2000) found that flooding in the Carolinas has no true dominant flood season. However, flooding was slightly more common in the months of January through April (Lecce 2000). In a follow-up study to Gamble (1997), Gamble & Meentemeyer (1997) examined extreme unseasonable flooding, defined as the 10 highest magnitude flood events from 1950 to 1990 during the season of lowest flood frequency (summer). Gamble & Meentemeyer (1997) found that localized storm systems rarely produce unseasonable extreme flooding, but instead large-scale extratropical and tropical systems are more associated with these events, and land surface characteristics also play a role.

It is also important to compare the patterns of flooding in the Southeast with flooding patterns in the continental USA. Michaud et al. (2001) examined peak discharges throughout the US to contrast spatial patterns of floods. Analysis of the median and 25 yr floods suggests that portions of the central and western Southeast into the Great Plains experience the largest floods (Michaud et al. 2001). However, when the analysis focuses on the most rare flood events, the spatial pattern shifts westward, with events in the Southeast generally smaller than the rest of the country (Michaud et al. 2001).

While extratropical and tropical cyclones certainly play a role in flooding, it is the interaction between atmosphere and local land surface characteristics that dictate flood duration and severity. Studies have demonstrated that heavy precipitation is not the sole cause of flooding, and even moderate amounts of precipitation can cause flooding, suggesting an interaction with the local land surface (Gamble & Meentemeyer 1997). LU/LC, topography, watershed characteristics, vegetation, baseflow conditions, temperature and antecedent rainfall all interact to induce flooding (LaPenta et al. 1995, Gamble 1997, Gamble & Meentemeyer 1997). Studies suggest that antecedent soil moisture is of particular importance in determining flooding (LaPenta et al. 1995, Gamble & Meentemeyer 1997, Legates et al. 2011).

The flood event in Atlanta, Georgia, in September 2009 provides an example of how multiple factors can contribute to flood conditions. Severe flooding took place in the greater Atlanta area, which in some cases exceeded the 500 yr flood (Shepherd et al. 2011). Shepherd et al. (2011) suggest significant antecedent precipitation from a stalled cut-off low aided in setting the stage for the Atlanta flood event. Previous studies have documented the connection between these systems, heavy precipitation, and flooding, but research involving these systems is limited in the Southeast (Shepherd et al. 2011). In addition, moisture advection from Tropical Storms Marty and Fred may have also contributed to the flood event on 20 to 22 September. It is clear from the analysis of Shepherd et al. (2011) that soils in the region were at or near field capacity prior to the actual flooding event. Topography and urban LU/LC may have also enhanced the precipitation events and certainly influenced runoff and infiltration processes (Shepherd et al. 2011). Other studies pertaining to Atlanta flood hydrology have identified urbanization-related land cover changes as an important factor (e.g. Shepherd et al. 2002, Wright et al. 2012) and may play a role in other large Southeast cities as well (Shepherd et al. 2002).

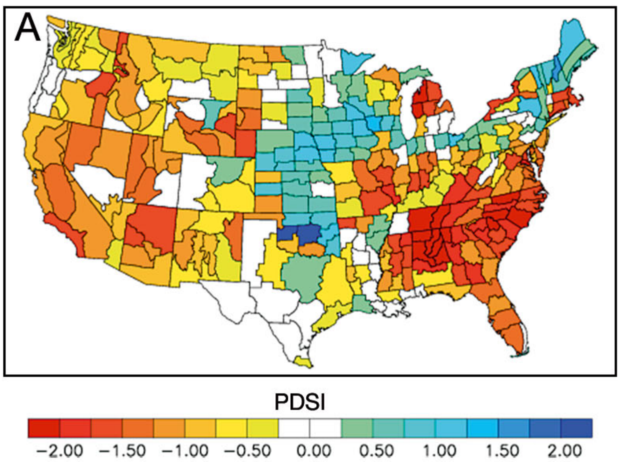
2.3. Drought

Despite the generally humid and wet climate, the Southeastern USA is prone to periodic droughts, which are an important feature of the hydroclimatology of the region (Seager et al. 2009). Doublin & Grundstein (2008) examined drought from the standpoint of soil moisture deficits from 1895 to 2005. They used Principle Component Analysis (PCA) to regionalize annual accumulated warm season soil moisture deficit and identified 5 distinct regions in the southern USA, including from the Southeast the eastern region (Carolinas, Georgia, much of Tennessee, and northeast Florida), the Gulf Coast (Alabama, panhandle of Florida, the southeastern half of Mississippi, and Louisiana), and southern Florida. Others have also found central and southern Florida to be isolated in terms of drought behavior, possibly due to the influence of land-sea breezes (Henry & Dicks 1988). Average soil moisture deficits were highest in Texas and areas west of the Mississippi River, and decreased eastward where south Florida had the lowest average soil moisture deficits (Doublin & Grundstein 2008). Different regionalizations are possible depending on how drought is quantified, and on the methodology used to define homogeneous regions. For instance, Ortegren et al. (2011) found that most of the Southeast, with the exception of Mississippi, far west Tennessee, and eastern Virginia, behaved similarly when examining warm season Palmer Hydrological Drought Index data. Others have also performed similar analyses, creating regionalizations based on drought conditions, including Eder et al. (1987) using the Palmer Drought Severity Index (PDSI).

Tree ring-based reconstructions are commonly used to put contemporary droughts into historical context. A number of reconstructed datasets have been created for both drought and precipitation in the Southeast using baldcypress *Taxodium distichum*. These reconstructions show variability in both intensity and duration of wet and dry periods in the region (Stahle et al. 1985, 1988, Stahle & Cleaveland 1992, 1994) and some suggest an approximate 30 yr cycle between wet and dry periods (Stahle et al. 1988, Stahle & Cleaveland 1992). Generally speaking, no significant long-term drought trend exists in the instrumental record (Karl & Heim 1990, Doublin & Grundstein 2008), but decadal cycles do seem to exist with the 1920s, ‘50s, and ‘80s being dry and the 1940s and ’70s being wet (Doublin & Grundstein 2008). However, some studies have noted trends towards a wetter climate on smaller spatial scales (e.g. Yin 1993 with climate divisions). The drought measure, spatial scale, and instrumental record length all have a large influence on whether trends in drought conditions are detected.

Not surprisingly, drought in the Southeast is associated with above normal temperatures and below normal precipitation (Doublin & Grundstein 2008), unlike other climatic regimes where temperature is not as strongly associated with drought (e.g. Northeast US; Leathers et al. 2000). In a study of warm season drought, potential evapotranspiration and precipitation were found to be strongly correlated with soil moisture deficits, particularly in more inland regions such as northwestern Mississippi into western Tennessee (Doublin & Grundstein 2008), suggesting possible land–atmosphere feedbacks. However, studies examining these feedbacks in the Southeast are limited. Droughts also tend to be more strongly associated with decreases in precipitation event frequency than with decreases in precipitation intensity (Doublin & Grundstein 2008).

Impacts from severe droughts are often thought to be mostly limited to the Great Plains and western USA, but droughts also represent a serious threat to water resources in the Southeast. For instance, drought conditions in the Southeast have been implicated in the demise of the settlements at Jamestown and Roanoke in the late 16th and early 17th centuries (Stahle et al. 1998). The most recent severe drought began during the winter of 2005–2006, continuing through to the fall/winter of 2007–2008 and was responsible for significant economic losses due to crop failures, lack of hydropower generation, wildfires, and water shortages (Manuel 2008, Maxwell & Soulé 2009). The drought also reignited tensions between Georgia, Alabama, and Florida over the use of limited water from Lake Sidney Lanier, Atlanta’s main municipal water supplier (Manuel 2008). Fig. 4 depicts the PDSI, temperature anomalies, and 500 mb geopotential height anomalies for the fall months of 2007. As expected, positive temperature



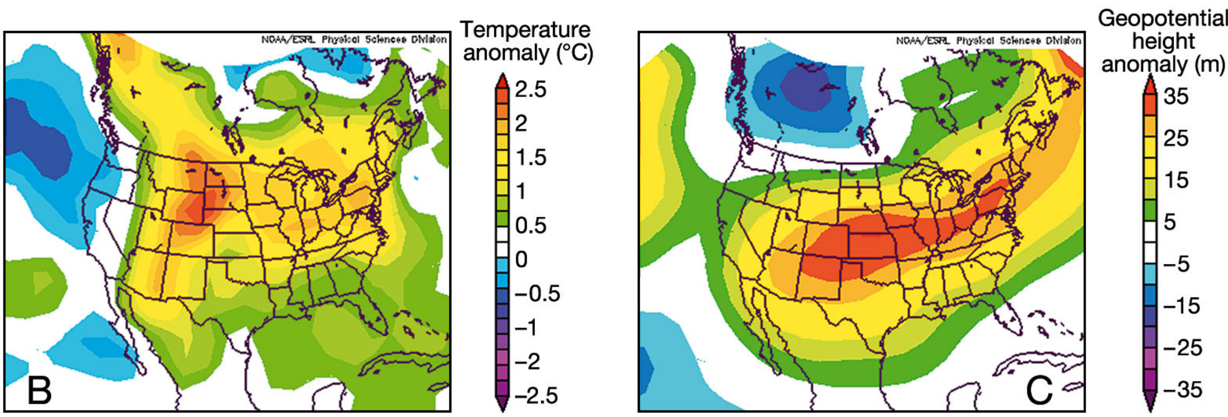


Fig. 4. (A) Standardized Palmer Drought Severity Index (PDSI) for the USA in September, October, November (SON) 2007. Anomalies in (B) surface air temperature and (C) 500 mb geopotential height for SON 2007. All variables are relative to 1981–2010 climatology. Data are obtained from NCEP/NCAR reanalysis data. Figures created using Earth System Research Laboratory Plotting and Analysis tool (ESRL; www.esrl.noaa.gov/psd/cgi-bin/data/getpage.pl). For more information see Maxwell & Soulé (2009)

anomalies dominated much of the impacted region during this time period, along with positive geopotential height anomalies. A thorough explanation of the atmospheric conditions leading to the 2007 drought is provided in Maxwell & Soulé (2009).

During the 2007–2008 drought the Southeast experienced some of the driest conditions on record (relative to the period 1895–2007), underscoring the necessity of proper planning, management, and conservation (Maxwell & Soulé 2009). From a historical standpoint, this recent drought was not particularly unusual (Maxwell & Soulé 2009, Seager et al. 2009). While drought conditions in November 2007 were the worst witnessed by many climate divisions during the instrumental record, the drought was relatively localized. Recurrence intervals for climate divisions in November 2007 show that only 2 (one in northeast Alabama and one in western South Carolina) witnessed a >100 yr drought event (Maxwell & Soulé 2009). Drought reconstructions suggest that events of this magnitude and duration are a relatively common feature of the hydroclimatic regime in the region, and more severe and longer duration droughts are found in the paleo-record (Pederson et al. 2012). Especially important is the suggestion that many water management policies were put into place during some of the wettest years on record. This underscores the need for current and future water management policies to take into account hydroclimate variability on longer timescales (Pederson et al. 2012).

Tree-ring reconstructions provide important information on moisture conditions prior to the instrumental record. Pederson et al. (2012) reconstructed PDSI in the Apalachicola-Chattahoochee-Flint river basin and found that from 1696 to 1820 droughts were frequent and long lived. Interestingly, the tree-ring record identifies the 1986 drought as one of the most severe and rare drought events on record (Cook et al. 1988, Pederson et al. 2012). Cook et al. (1988) estimate the recurrence interval of the 1986 drought to be ~287 yr. Using the shorter instrumental record, Karl & Young (1987) confirm the severity of the 1986 drought in terms of impacts on agriculture, but suggest that the drought was not unprecedented in terms of streamflow.

3. MAJOR ATMOSPHERIC CONTROLS ON HYDROCLIMATOLOGY

There are many controls on the hydroclimatology of the Southeastern USA that range in scale from local surface heating that gives rise to convective thunderstorms to hemispheric/global-scale teleconnections that influence the position of the jetstream. This paper emphasizes large-scale processes and does not deal with smaller scale processes, although they are also important for the hydroclimatology of the Southeast. There are also processes that influence the hydroclimate of the Southeastern USA on different timescales (i.e. daily, decadal, and longer). This review limits the discussion to those features and processes that are important on a seasonal to interannual scale.

3.1. ENSO

The dominant mode of climatic variability in the tropics, and the most well-studied, is the ENSO (Curtis 2008). The ENSO has been used to examine a number of other phenomena in the Southeast, including wildfires (e.g. Harrison & Meindl 2001, Beckage et al. 2003), vegetation health (e.g. Mennis 2001, Peters et al. 2003), and crop yields (e.g. Royce et al. 2011) among others. The ENSO involves changes in the interactions between oceanic (El Niño) and atmospheric (Southern Oscillation) circulation components that influence the Walker Circulation in the equatorial Pacific (Bjerknes 1969, Curtis 2008). El Niño periods consist of anomalously warm sea surface temperatures (SSTs) in the eastern tropical Pacific along with anomalously low sea level pressure (Bjerknes 1969, Curtis 2008). La Niña periods, on the other hand, are indicative of anomalously cool SSTs in the eastern Tropical Pacific and higher sea level pressures (Curtis 2008). While phases of the ENSO are often referred to as opposites of one another, research shows that atmospheric-oceanic oscillations are frequently non-linear, and that this assumption is therefore not appropriate (Sheridan & Lee 2012).

Cold and warm phases of the ENSO differentially impact precipitation patterns across the globe (Kiladis & Diaz 1989, Curtis 2008). Ropelewski & Halpert (1986) first identified the primary US regions where precipitation consistently responded to the ENSO, including the Southeast from October through March. Warm phase El Niño events are associated with increased precipitation throughout much of the Southeast into Mexico, and cold phase La Niña events are associated with drier than normal conditions (Kiladis & Diaz 1989). Eichler & Higgins (2006) also suggest increased precipitation east of the Appalachians during El Niño winters as the storm-tracks on the Atlantic Coast become enhanced. With increased precipitation comes increased streamflow, which has also been linked to ENSO phases in the Southeast (Kahya & Dracup 1993).

The aforementioned studies take a continental to global-scale perspective, but these same relationships have also been observed on smaller scales within the Southeast. Douglas & Englehart (1981) found that wet winters in Florida were typically preceded by warmer SSTs and increased precipitation in the ENSO region and vice-versa, suggesting that cyclogenesis increases in the Gulf of Mexico with El Niño phases. This same relationship has also been seen in terms of surface hydrology and groundwater recharge (Sun & Furbish 1997). Senkbeil et al. (2012) performed a manual and automated classification of extratropical cyclones in the Southeast and found that moderate to strong warm ENSO phases generally resulted in the strongest associations with extratropical cyclones. In particular, stronger El Niño phases provided for a tendency to produce more intense extratropical cyclones (Senkbeil et al. 2012). In an analysis of weather type occurrences between winter phases of ENSO in New Orleans, McCabe & Muller (2002) found statistically significant differences during La Niña events as certain wet weather types became less frequent and dry weather types became more frequent. They also found precipitation for 'stormy weather types', such as Gulf Return, Frontal Gulf Return, and Frontal Overrunning, to be greater during El Niño events than for neutral or La Niña events (McCabe & Muller 2002). McCabe & Muller (2002) suggest that this reflects a shift in the position of storm tracks between ENSO phases, further demonstrating the link between ENSO, cyclogenesis, and precipitation suggested by Ropelewski & Halpert (1986). Curtis (2006) reports that during winter El Niño periods, cyclogenesis is common in the western Gulf of Mexico and Atlantic Coast around North Carolina. In addition, storm counts in the Southeast increase along with the number of intense storms (Curtis 2006).

ENSO has also been shown to influence drought events in the Southeast. Studies suggest that winter drought is most commonly associated with La Niña phases (Mo & Schemm 2008a). There is, however, disagreement over the controls on interannual variability of summer drought in the Southeastern USA. Some have argued that summer drought is controlled by internal atmospheric processes and is only weakly associated with ENSO (Seager et al. 2009), while others argue that oceanic-atmospheric conditions in the North Atlantic also play a significant role (Enfield et al. 2001, McCabe et al. 2004, Ortegren et al. 2011). More research into the interannual variability and persistence of summer drought in the Southeast is needed to address this disagreement.

3.2. Pacific North American (PNA) Pattern

Horel & Wallace (1981) suggested a mechanism by which ENSO effects could be propagated to North America. During warm phases in the equatorial Pacific, geopotential heights in the North Pacific and the Southeastern USA tend to be anomalously low while anomalously high geopotential heights reside over western Canada (this was later termed the PNA). The PNA relates geopotential height anomalies between the northern Pacific and the North American continent (Horel & Wallace 1981, Leathers et al. 1991). During a positive phase of PNA, meridional flow dominates while zonal flow is characteristic of the negative phase (Leathers et al. 1991). Studies relating the PNA and spatiotemporal patterns of precipitation are limited in the Southeast, despite the region being one of the primary centers of action (Leathers et al. 1991). Henderson & Vega (1996) demonstrate that there is significant spatial variability in the impacts of PNA on precipitation variability in the Southeast. During the winter when the teleconnection is most prevalent, positive PNA patterns often lead to positive precipitation anomalies in much of the region with the exception of northern portions of the region west of the Appalachians as cyclones tend to form and traverse east of the mountain range (Henderson & Vega 1996). The reverse occurs during a negative PNA phase, as much of the region experiences negative precipitation anomalies (Henderson & Vega 1996). Potential evaporation and soil moisture deficits during the warm season have also been linked with PNA phases, as positive phases, advect cooler air into the region and decrease atmospheric demand (Doublin & Grundstein 2008).

PNA may also influence the number of cyclones that transverse the Southeast, as evidenced by the work of Henderson & Robinson (1994). Henderson & Robinson (1994) found meridional flow to be linked with less frequent winter cyclones and more frequent cyclones in the summer. Results also show that the longer duration cyclones that generate greater amounts of precipitation tend to be associated with meridional flow east of the Appalachians, supporting results from Henderson & Vega (1996). This suggests that the Southeast is far from a homogenous climate and does not respond uniformly to climatic variability. Furthermore, this demonstrates the importance of the Appalachian Mountains in generating climatic spatial variability.

3.3. Bermuda High/Atlantic Subtropical High

The Atlantic subtropical high pressure center, also termed the Bermuda High or Azores High (Davis et al. 1997), influences the climate of the Southeastern USA throughout the year, but it is most important during the spring and summer. The Bermuda High/Atlantic subtropical high is also part of a larger oceanic–atmospheric oscillation termed the North Atlantic Oscillation (NAO). The 2 centers of action in the NAO are the Icelandic Low and the Azores High. and together they represent the main circulation feature in the Atlantic (Serreze & Barry 2009). A positive NAO indicates that both centers are anomalously strong and tend to shift poleward and a negative NAO indicates that both centers are anomalously weak and tend to shift equatorward (Serreze & Barry 2009). Storm tracks are influenced by the strength and positioning of positive and negative phases, which play a significant role in eastern US winters (Marshall et al. 2001). Positive NAO phases have been shown to result in increased moisture advection into the eastern US (partially as a result of the Bermuda High circulation to be discussed; Hurrell 1995). On the other hand, a negative NAO results in weaker zonal flow allowing for intrusions of colder, dryer air in the Southeast (Yin 1994, Hurrell 1996). There is also debate surrounding whether the NAO is simply a regional manifestation of the Arctic Oscillation (e.g. Thompson & Wallace 1998); however, this is beyond the scope of this paper. With this in mind, the focus of this section will remain on the Bermuda High.

In an examination of the characteristics of the Atlantic subtropical high, Sahsamanoglou (1990) calculated mean annual central pressures from 1873 to 1980 and found it to be 1023.5 hPa, with very little variation (SD of 1.2 hPa). The semi-permanent anticyclone migrates on a seasonal basis from ~30°N, 25°W near the Azores (Azores High) during the winter to ~30°N, 40°W near Bermuda (Bermuda High) during the middle of summer (Sahsamanoglou 1990, Barry & Carleton 2001). From this location, the high pressure cell moves north to 35°N in late summer and then to 20°W by the middle of fall (Sahsamanoglou 1990, Barry & Carleton 2001). However, Davis et al. (1997) show that these changes can occur suddenly, and therefore a smooth, seasonal progression does not always occur. The Bermuda High central pressure values are highest in January and July and reach their minimum values in March and October (Sahsamanoglou 1990). Similarly, Davis et al. (1997) report peak intensities in January over the Southeastern USA, and in July over the central Atlantic, with the spring and fall acting more as transitional periods. The Atlantic subtropical high also influences weather from the eastern half of the USA to portions of Europe and northwest Africa (Davis et al. 1997). For a more thorough explanation of the characteristics and significance of this circulation feature see Davis et al. (1997).

The strength and positioning of the Bermuda High has a strong influence on moisture conditions in the Southeast, particularly during the spring and summer. Typically, tropical easterlies flow south of the Bermuda High bringing warm, moist, unstable air masses from the Atlantic and Gulf of Mexico onshore along the Atlantic Coast and Florida (Coleman 1988, Keim 1997). However, when summer temperatures are higher than normal, a contrasting situation develops where the Bermuda High intensifies and expands due to an increased gradient between land and sea temperatures (Coleman 1988). This situation leads to subsidence of more stable air as the tropical easterlies are forced westward, and consequently drier conditions occur in Florida (Coleman 1988). Research from Stahle & Cleaveland (1992) confirms this mechanism with composite analyses of sea level pressure during the 10 driest and 10 wettest periods from the early 20th century to the mid-1980s along the Atlantic Coast, showing westward ridging during dry extremes and contraction eastward during wet extremes.

Trends in the strength and positioning of the Bermuda High and the implications for summer precipitation in the Southeast have also been examined. Using 850 hPa geopotential heights from National Centers for Environmental Prediction (NCEP) and European Centre for Medium Range Weather Forecasts (ECMWF) ERA-40 reanalysis datasets, Li et al. (2011) show that the center of the Bermuda High has shifted westward and the intensity has increased since the late 1970s. The north–south position of the western ridge also influences precipitation, and Li et al. (2011) suggest that the ridge has expanded over the last 30 yr. During periods when the western ridge is positioned in a more northerly location, Southeast summer precipitation decreases, and when it is positioned towards the south, summer precipitation tends to increase (Li et al. 2011). However, other studies (e.g. Diem 2013) have contradicted these findings and consequently continued research is warranted.

The Bermuda High has been quantified with the Bermuda High Index (BHI) (Stahle & Cleaveland 1992). The BHI is defined as the difference between normalized sea level pressures in Bermuda and New Orleans, Louisiana (Stahle & Cleaveland 1992) where positive values are indicative of strong southerly flow in the western Atlantic and increased moisture advection into the Southeast, along with reduced atmospheric stability (Henderson & Vega 1996). Negative values indicate weaker southerly flow in the western Atlantic (Henderson & Vega 1996).

While studies relating precipitation and BHI are somewhat limited in number, conclusions drawn from these studies tend to agree. Henderson & Vega (1996) showed strong correlations between the BHI and seasonal precipitation in the southern USA, suggesting that even during the winter subtropical circulation patterns are important in determining precipitation patterns in the Southeastern USA. During the spring, positive correlations between BHI and precipitation indicate that a stronger Bermuda High results in increased moisture advection into the region. Similar results based on reconstructed spring precipitation were found for North Carolina, South Carolina, and Georgia (Stahle & Cleaveland 1992), as well as relationships with soil moisture deficits in the southern USA (Doublin & Grundstein 2008) and drought variability (Ortegren et al. 2011). Diem (2006) examined wet versus dry 13 d periods from 1953 to 2002 in the Greater Atlanta metropolitan area, and found that wet periods are associated with troughing and negative geopotential height anomalies in the Midwest and Southeast, and dry periods are associated with ridging and positive geopotential height anomalies in the interior Southeast. However, the BHI was more strongly correlated with dry than with wet period frequency (Diem 2006). While these studies provide evidence of the importance of subtropical circulation as a factor in precipitation regimes of the Southeast, research by Keim (1997) shows a very weak relationship between BHI and seasonal heavy precipitation events. As Keim (1997) suggests, precipitation patterns are not solely explained by the existence of precipitable water, and it is important to consider other factors.

3.4. Tropical cyclones (TCs)

TCs are a common occurrence in the Southeast region during the hurricane season (June through November). Spatial and temporal patterns of landfalling TCs in the Southeast have been studied by multiple sources and results can be dependent on the methods used to identify landfalling locations (Simpson & Lawrence 1971, Elsner & Kara 1999, Muller & Stone 2001, Keim et al. 2007). The most active areas for landfalling TCs in the US over the past century include the northern Gulf Coast, south Florida, and the Outer Banks of North Carolina, with tropical cyclone (regardless of intensity) return periods of 3 to 4 yr for the northern Gulf Coast, 3 yr for south Florida, and 2 to 3 yr for the Outer Banks (Keim et al. 2007). Major hurricanes, classified as greater than Category 3 on the Saffir-Simpson scale, are most frequent in south Florida, with return periods of between 13 and 18 yr (Keim et al. 2007). Property loss data presents similar findings with the most losses occurring in Florida, followed by North Carolina from 1949 to 2006 (Changnon 2009).

Research into the contemporary hurricane record shows significant spatiotemporal variability. Some regions tend to experience frequent events for a period of time while another region experiences very little activity during the same period (Muller & Stone 2001). For instance, south Florida had many landfalling TCs in the 1920s to the 1940s, but very little activity in the 1960s to 2005 (Muller & Stone 2001, Keim et al. 2007). Unlike south Florida, North Carolina experienced more activity during the 1950s and 90s (Muller & Stone 2001, Keim et al. 2007). Keim et al. (2007) report that region-wide (south Texas to north Maine), the 1920s to 1960s and 1995 to 2005 have been the most active periods over the past century. The ENSO has been linked to spatiotemporal patterns of landfalling TCs (Muller & Stone 2001). Fig. 5 depicts the number of TCs making landfall in the Southeast from 1900 to 2008, along with the 10 yr moving average.

Relationships between TC activity and large-scale circulation variability are an active area of research. Elsner et al. (1999), in a time series analysis to determine modes of oscillation in hurricane frequency, found a biennial oscillation on the scale of 2.5 yr related to the Quasi-Biennial Oscillation (QBO), a semidecadal oscillation on the scale of 5 to 6 yr related to the ENSO, and a near decadal-oscillation of 7 to 9 yr. Earlier research also suggests relationships between the QBO and tropical cyclone activity in the Atlantic (e.g. Gray 1984, Shapiro 1989, Landsea et al. 1998). Likewise, other studies have shown a link between the ENSO and tropical cyclone activity in the Atlantic, including Gray (1984), Shapiro (1987), Landsea et al. (1998), and Emanuel et al. (2008). However, the ENSO and QBO, while important, are not necessarily sufficient to explain tropical cyclone activity as suggested by Lander & Guard (1998). SSTs in the North Atlantic

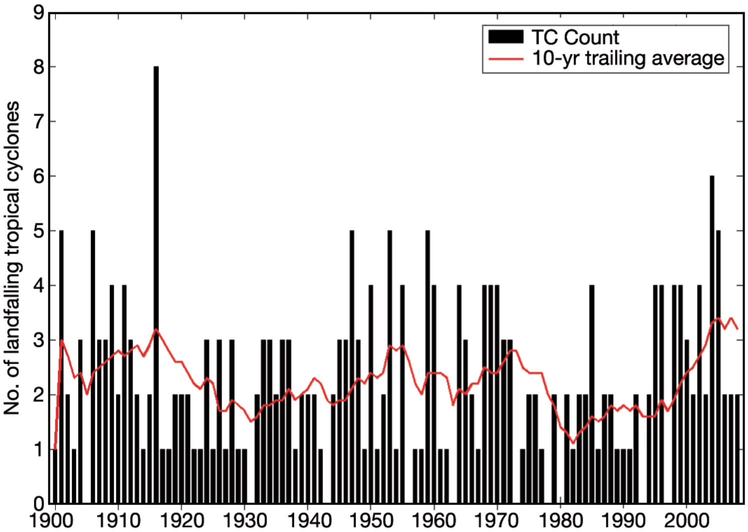


Fig. 5. Number of landfalling tropical cyclones (TCs) in the southeast US for 1900–2008. TC counts: derived from HURDAT dataset. Landfalling TCs: determined using same procedure as Zhu & Quiring (2013). Trailing average = 10 yr mean. Prior to 1909, the average is determined based on available years

(Goldenberg et al. 2001), the Arctic Oscillation (AO) and western Sahelian precipitation (Gray 1990, Landsea et al. 1992), as well as interactions with other teleconnections like the ENSO (Larson et al. 2005), are among other influential factors in tropical cyclone activity impacting the Southeast.

Landfalling TCs are known to contribute potentially significant amounts of precipitation to the Southeastern USA. While obviously detrimental in terms of loss of life and property, TCs aid in replenishing reservoirs, lakes, groundwater, and streamflow as well. Spatial and temporal patterns of tropical cyclone-induced precipitation in the Southeast have been examined by both Knight & Davis (2007) and Nogueira & Keim (2011). As expected, coastal areas receive the most tropical cyclone-induced precipitation with declining values inland; the Appalachian Mountains acting as a topographic barrier with increased local precipitation along the windward slopes (Knight & Davis 2007, Nogueira & Keim 2011). In an analysis of station data from 1980 to 2004, Knight & Davis (2007) found that precipitation associated with tropical cyclones accounts for as much as 14 to 16% of total hurricane season rainfall in the Carolinas, and between 8 and 14% along the Gulf Coastal Plain and Piedmonts. Broadly similar patterns were found by Nogueira & Keim (2011) over the period 1960–2007 with 12 to 14% of total hurricane season precipitation along the Atlantic Coast into Florida, and 8 to 12% along the Coastal Plain and Piedmonts, the highest values being in the extreme south of Texas and an isolated portion of coastal North Carolina.

For the Southeast as a whole, TC-precipitation contributes the most to monthly precipitation totals during September, with relatively small contributions made at the beginning and end of the hurricane season in June and November, respectively, due to fewer tropical systems making landfall (Knight & Davis 2007, Nogueira & Keim 2011). In fact, Nogueira & Keim (2011) demonstrate that there is much less TC activity in June and November, and that September experiences the greatest amount of TC activity. This agrees with the findings of Knight & Davis (2007). During June, most TC-associated precipitation is associated with the western and central Gulf Coasts (Knight & Davis 2007). It is not until July and August that significant TC-precipitation is seen along the Atlantic Coast (Knight & Davis 2007). During September, an area stretching from eastern Georgia to southern Virginia receives >24% of its mean monthly precipitation from tropical cyclones (Knight & Davis 2007). Nogueira & Keim (2011) suggested that this peak in September precipitation attributable to TCs may be more limited to North Carolina and Virginia, in addition to an area of south Alabama. By November, TC-precipitation is mostly confined to Florida (Knight & Davis 2007, Nogueira & Keim 2011).

Estimates of TC-induced precipitation have also been obtained using satellite observations. Rodgers et al. (2001) used passive microwave imagery from the Special Sensor Microwave Imager to estimate TC-induced precipitation in the North Atlantic and found that portions of the Southeast may receive 10% of hurricane season precipitation from tropical cyclones, but as little as 1 to 5% in other areas of the region. Other studies have also used satellite imagery to determine tropical cyclone-induced precipitation (e.g. Cerveny & Newman 2000, Lau & Wu 2007). While the previous studies broadly agree, there are some differences that are likely due to the use of different datasets (e.g. station versus satellite-derived), methodologies (e.g. determining what constitutes TC precipitation), and spatial and temporal scales of analysis. Regardless of the differences, these studies all demonstrate the importance of tropical cyclone-induced precipitation to the sustainability of water resources in the Southeast, and that this contribution varies significantly over time and space.

Trends in TC-induced precipitation explain a significant amount of variation in precipitation in the Southeast. Knight & Davis (2007) found statistically significant increasing trends in TC-induced precipitation along the East Coast and along the Gulf Coast as far as southeastern Louisiana. In contrast, they found only weak trends in non-TC-induced precipitation in the region. In a robust follow-up study using multiple measures and datasets to characterize extreme precipitation attributable to tropical cyclone activity, Knight & Davis (2009) found that positive trends in extreme precipitation were primarily attributable to tropical cyclones. Others have also found similar positive trends in TC-precipitation. From 1994 to 2008, the number of heavy precipitation events attributable to TCs doubled as compared to the long-term average of 1895 to 2008 (Kunkel et al. 2010). This can be partly explained by increases in landfalling TCs. However, Kunkel et al. (2010) point out that the increase in landfalling TCs is not enough to account for all of the increase in TC-associated heavy precipitation events. Shepherd et al. (2007) developed a heavy precipitation metric, termed the millimeter-day, based on the same concept behind heating degree-days and cooling degree-days. Shepherd et al. (2007) found that wet millimeter days (extreme precipitation days) are strongly correlated with major hurricanes (Categories 3–5) in the Southeast over the period 1998–2006. More localized studies have also been performed examining the trends in TC-precipitation. For instance, Konrad & Perry (2010) examined TC-precipitation in the Carolinas and found that along the coastal plain and eastern Piedmonts, the vast majority of heavy precipitation events from 1950 to 2004 were associated with TCs.

Landfalling TCs cause extensive injuries, loss of life, and economic damage from storm surge, high winds, inland flooding, and severe weather. Changnon (2009) analyzed hurricanes categorized as catastrophes, those costing >$1 million in insured property, and found that 50 of the 79 hurricanes analyzed from 1949 to 2006 occurred within the boundaries of the Southeast. The Galveston Hurricane of 1900 was responsible for the most deaths in US history (~8000) followed by the Lake Okeechobee Hurricane in 1928 (~2500). From an economic loss standpoint, Hurricane Katrina was responsible for the largest economic losses, followed by Hurricane Andrew in 1992 (adjusted for inflation; Blake et al. 2011). Inland flooding is the biggest threat to lives and property (Rappaport 2000). For instance, almost 200 deaths were recorded as a result of inland flooding from Hurricane Diane in 1955 (Rappaport 2000).

Despite their destructiveness, tropical cyclones are an important source of precipitation to the region. To underscore the importance of TC-induced precipitation for water resources, Knight & Davis (2007) calculated soil moisture deficits during hurricane season with TC precipitation removed. Results show significant increases in soil moisture deficits, with a 16 to 32% deficit in much of the region with isolated areas of higher deficits. Tropical cyclones have the ability to alleviate drought conditions. Maxwell et al. (2012) examined the impact of TCs on drought conditions in the Atlantic southeast from 1950 to 2008 and found that ~1 in 5 droughts were ended by TC precipitation (Maxwell et al. 2012). These ‘drought busters’ can end both short-term agricultural droughts and long-term hydrological droughts (Maxwell et al. 2012). Two examples of TCs that have alleviated drought conditions in the Southeast include Tropical Storm Marco in 1990 and more recently Tropical Storm Alberto in 2006, which both provided relief from moderate drought along the Atlantic Coast states in the span of 24 to 48 hr (Maxwell et al. 2012). The link between tropical cyclones and soil moisture deficits/droughts has not been well explored, but represents a critical and unique component in Southeastern hydroclimatology.

4. CONCLUSION AND FUTURE DIRECTIONS

This study provides an overview of the hydroclimatic characteristics of the Southeastern USA and reviews the primary factors that influence seasonal to interannual variability. The Southeast has a humid climate with an abundance of precipitation. Recent studies however, suggest that the region is characterized by significant precipitation variability marked by heavy, intense precipitation, interspersed with dry periods. Consequently, both floods and droughts may become more common in the future.

The relationship between phases of ENSO and precipitation in the Southeast has been well established. Generally speaking, warm El Niño phases lead to positive precipitation anomalies in much of the region, while cold La Niña phases result in negative precipitation anomalies. However, some studies suggest that there is spatial variability to this relationship and some studies also debate the strength of this relationship particularly when it comes to understanding drought. Less well-studied are other established oceanic–atmospheric indices, including the PNA, the Pacific Decadal Oscillation, and the AO.

The Bermuda High is present throughout the year, but tends to influence Southeast precipitation during the spring and summer months. Moisture advection into the region usually takes place in the Atlantic Coast states giving rise to increased precipitation and at times, heavy precipitation. The Bermuda High, however, can expand and intensify such that troughing is pushed farther west and ridging takes place along the Atlantic Coast and eastern parts of the region. This circulation pattern typically leads to increased subsidence and drier conditions in the eastern half of the region and wetter conditions along the margins of the western edge of the anticyclone. The reverse is also true when the Bermuda High contracts and/or weakens. The BHI has proven to be a useful measure of the strength of the Bermuda High and has been related to precipitation in the region. Recent research suggests that the high pressure cell has expanded westward in recent decades and may be influencing an increase in precipitation variability in the region, but more research is needed to fully understand trends and variability in the Bermuda High.

Despite their destructive potential, TCs contribute heavily to the Southeast's annual precipitation and are fundamental to the region's hydroclimatology. TC-induced precipitation plays a significant role in the spatial and temporal patterns of water resources throughout the region, especially in coastal and near-coastal areas. TC-precipitation accounts for a significant proportion of precipitation in many locations in the Southeast, and a lack of it can lead to serious soil moisture deficits and droughts. Likewise, TCs have the potential to alleviate drought conditions. Increasing trends in TC-induced precipitation are present throughout parts of the region.

With a large population and many growing urban centers adjacent to valuable agricultural areas and rich ecosystems that provide a plethora of services, it is critical to understand the spatial and temporal patterns of precipitation and other hydroclimatological parameters and mechanisms by which these patterns arise in order to meet the needs of society. Based on what is already known about the hydroclimate of the Southeast, we suggest that future research should focus on:

(1) **Current and future hydroclimatic variability.** Observations and projections of future climate conditions suggest that extreme wet and dry events have been increasing and will continue to do so under projected climatic changes. Increased variability will make water resource planning not only more difficult, but also more important for the region's many stakeholders. More investigation of precipitation variability on intrannual and interannual timescales is necessary. While year to year variability and total annual precipitation may remain constant, variability may shift within years leading to significant management and planning implications. It is also not well understood what factors drive the recent variability seen in the region. Future studies will need to decipher natural versus anthropogenic drivers, as well the degree to which each influences hydroclimate variability. Furthermore, downscaling of climate model output will be necessary to make climate projections more useful for the water resource manager. Alongside future hydroclimatic change are also changes in LU/LC and population growth that will also contribute to the already complex hydroclimatology of the Southeast.

(2) **Interannual variability of drought.** The role of ocean–atmospheric oscillations in understanding drought is still not well understood and the relative roles of the Pacific and Atlantic teleconnections (and how they vary by season) are not well defined. Much of the variation that can be found across the literature is a result of differences in spatial extent of the study, instrumental record length, and the selected drought index. Furthermore, as new drought events occur, it is always important to put these events into a historical context, which our short instrumental record does not allow. Drought and other climatic reconstructions are of fundamental importance to these studies and help inform management and planning policies. Drought persistence is also a poorly understood topic; it is important for short term regional climatic forecasts and the agriculture and water resource planning that depend on the accuracy of those forecasts. Persistence studies suggest that the Southeast lacks persistent dry or wet conditions due to the differential effects of both ENSO and the Bermuda High on precipitation (Stahle & Cleaveland 1992, Mo & Schemm 2008a,b). However, further research into regional and sub-regional drought persistence is required.

(3) **Understanding spatial patterns of soil moisture.** There is a dearth of soil moisture data in the Southeast, despite its importance. Soil moisture is an important variable in the climate system because it influences land–atmosphere interactions in the climate system by modifying energy and water fluxes. Improved characterization of these land–atmosphere interactions will lead to better flood modeling and drought prediction. Until recently, little work was done to assemble and homogenize *in situ* measurements of soil moisture. The North American Soil

Moisture Database (NASMD) addresses this need by assembling data from nearly 2000 stations with soil moisture observations in the USA (T. Ford & S. Quiring unpubl. data). Although the NASMD contains some stations from the Southeast, soil moisture in this region remains under-measured.

(4) **Improved understanding of how teleconnections influence regional precipitation.** A better grasp of the influence teleconnections have on precipitation variability and water resources will allow for improved short and long-term hydroclimate predictions, and will facilitate better planning and resource management. Many excellent studies exist that examine teleconnections in isolation. While these studies are useful, it is also important to identify how teleconnections interact with one another. Future research should focus on interactions between teleconnection patterns and investigate teleconnections that are not traditionally associated with the Southeastern USA (i.e. Higgins et al. 2000, Kurtzman & Scanlon 2007, Budikova 2008).

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