Drought-Busting Tropical Cyclones in the Southeastern Atlantic United States: 1950–2008

By: **Peter T. Soule**, Justin T. Maxwell, Jason T. Ortegren, & Paul A. Knapp

Abstract

Droughts and tropical cyclones (TCs) are climatologically common events in the southeastern United States, yet little research has examined the potential for TCs to ameliorate drought impacts. Here, we identify the frequency of TCs that abruptly end drought conditions (i.e., drought busters, or DB) and determine possible influences of coupled ocean–atmosphere teleconnections on the likelihood of a TC-induced DB (TCDB). Using the HURDAT database and Palmer Drought Severity Indexes from 1950 through 2008, we identified every TCDB for thirty-one climate divisions in the southeastern Atlantic United States. We present the spatial patterns of the total number of TCDBs and the percentage of all droughts ended by TCs using choropleth maps. To determine what teleconnections influenced TCDBs, we used logistic regression analysis and included multiple synoptic-scale circulation indexes as predictor variables. In addition, we used a Fisher's exact test to examine the association between the North Atlantic Oscillation (NAO) and TCDBs. We found that up to 41 percent of all droughts and at least 20 percent of droughts in three fourths of the climate divisions were ended by TCDBs. NAO was a significant predictor ($p = 0.005$) in the logistic regression model ($\chi 2 = 10.91$, $p = 0.001$), and the Fisher's exact test showed a significant association between NAO and TCDBs ($p = 0.003$). An odds-ratio calculation showed that TCDBs are 5.8 times more likely to occur during a negative NAO phase than a positive NAO phase.

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Droughts and tropical cyclones (TCs; i.e., hurricanes, tropical storms, and tropical depressions) are common events in the southeastern United States (Henry and Dicks 1984; Bettinger, Merry, and Hepinstall 2009; Konrad and Perry 2010) and are most influential during late summer and early autumn. Although the negative societal impacts of both droughts (Cook et al. 1999; Morehart et al. 1999; Hayes et al. 2004) and TCs (Crossett et al. 2008; Pompe and Rinehart 2008) have received substantial attention, little research has examined the potential drought-ameliorating benefits associated with high-precipitation TC events. Understanding the likelihood that TCs can alleviate existing droughts might provide better information for municipal and agricultural drought mitigation plans, as TC frequency and sustained warm-season droughts both appear to follow multidecadal (approximately thirty-year) oscillations of peak and reduced activity (Shapiro 1982; W. M. Gray 1984a; Stahle, Cleaveland, and Hehr 1988; Stahle and Cleaveland 1992, 1994; Elsner and Kara 1999; Keim et al. 2007; Ortegren 2008). Accordingly, in this study we discuss how heavy precipitation events associated with TCs in the southeastern United States can serve as "drought busters" (DB) that ameliorate the effects of drought during the peak water-demand months and could serve as a catalyst to rapidly end moderate to exceptional droughts.

The costs to society imposed by natural climatic events such as drought are well documented. For example, the U.S. Federal Emergency Management Agency (FEMA) estimated economic losses during the year 2007 due to drought at well over $5 billion (FEMA 2008). The National Climatic Data Center (NCDC) reported that of the fifty weather-related disasters with losses greater than $1 billion for the period from 1980 to 2006, twelve were droughts and an additional six were wildfires, which are often related to drought (NCDC 2007). The 1980 summer drought cost the United States approximately $16 billion, which is equivalent to approximately $43.8 billion in 2009 U.S. dollars (Stahle and Cleaveland 1988). Widespread drought in 1999 resulted in agricultural losses estimated at $1.35 billion (~ $1.7 billion in 2009) over a total of 1,383 counties, which were home to approximately 109 million people and an estimated 919,000 farms comprising roughly 25 percent of U.S. cropland and 32 percent of U.S. pastureland (Morehart et al. 1999).

Depending on its severity, drought can be viewed as an inconvenience initiating minor restrictions (e.g., odd/even calendar-day watering) or a pervasive event that negatively affects agricultural productivity (Changnon and Kunkel 1999; Ferris 1999; Howden et al. 2007) and nonagricultural businesses and activities (Changnon and Kunkel 1999; Carbone and Dow 2005) for several years or longer (Riebsame, Changnon, and Karl 1991; Woodhouse and Overpeck 1998). Economic loss data rarely reflect all crop losses and generally do not account for indirect effects of drought, such as increased energy for cooling (Hayes et al. 2004). Beyond the impacts on agriculture and energy production, drought can also significantly increase demand on urban and rural water resources and carry implications for water quality (Cook et al. 1999). Other noneconomic impacts include reductions in stream flow, groundwater, and reservoir levels, which can have severe ecological impacts (Morehart et al. 1999).

Although the southeastern United States has not experienced multidecadal droughts like those reported for the southwestern and central United States (Fye, Stahle, and Cook 2003, 2004; Cook et al. 2004; McCabe, Palecki, and Betancourt 2004; Cook et al. 2007; Seager 2007), short-duration droughts of one to three years do occur (Manuel 2008). The 2005/2006 and 2007/2008 droughts in portions of the Southeast are recent examples. Both droughts caused multi-million-dollar economic losses (FEMA 2008; Manuel 2008). The 2007 drought ranked among the worst on record in much of the Southeast (Maxwell and Soulé 2009), placed stress on municipal water supplies (Hernandez 2007; O'Driscoll and Copeland 2007), and provoked legal confrontation between states over control of water releases (Manuel 2008).

The societal costs associated with TC landfalls in the southeastern United States have been widely reported (e.g., Pompe and Rinehart 2008). Direct economic impacts of TCs in the southeastern coastal United States have increased in recent years, in part because of increasing numbers of landfalling TCs (Pompe and Rinehart 2008) but also because of population growth and increases in coastal property values (AIR Worldwide Corporation 2005; Crossett et al. 2008). Combined, these factors have led to dramatic increases in TC-related insurance payouts. The 2005 hurricane season was the most costly in U.S. history, with $60.2 billion in insured losses (Insurance Information Institute 2008). Landfalling TCs induce noneconomic costs as well, including damage to woody vegetation (with implications for carbon sequestration) and decreased water quality in affected areas (Loope et al. 1994; Mallin et al. 1999).

TCs often produce intense daily precipitation during summer and autumn in the southeastern United States (Keim and Faiers 1996). Furthermore, TCs account for approximately 4 to 10 percent of all rainfall during the TC season in the Southeast (Rodgers, Adler, and Pierce 2001; D. B. Knight and Davis 2007) and as much as 15 percent of the TC season precipitation in the Carolinas (D. B. Knight and Davis 2007). Thus, in areas that receive a large percentage of precipitation from TCs, such as the southeastern United States (Rodgers, Adler, and Pierce 2001), TC-induced rainfall could be critical to the success of nonirrigation agricultural pursuits and various commercial pursuits that are water dependent.

Lehmiller, Kimberlain, and Elsner (1997) developed one of the first multivariate statistical models of TC activity in the North Atlantic basin. They considered several important factors when examining hurricane activity in the southeastern United States: Sahel precipitation the previous autumn, the stratospheric quasi-biennial oscillation, 700- to 200-mb vertical wind shear near Miami–West Palm Beach, July sea level pressure at Cape Hatteras, and July U.S. East Coast sea level pressure. More recent TC forecasts use the El Niño–Southern Oscillation (ENSO), the Atlantic Multidecadal Oscillation (AMO), and the North Atlantic Oscillation (NAO). ENSO has been shown to influence TC activity (W. M. Gray 1984a, 1984b; Shapiro 1987), with El Niño conditions leading to a reduction in Atlantic hurricanes, while the opposite holds true for La Niña conditions (Goldenberg and Shapiro 1996). The relationship between ENSO and TC activity has been confirmed by more recent studies (Larson, Zhou, and Higgins 2005; Elsner and Jagger 2006; Elsner, Murnane, and Jagger 2006). Although ENSO does influence TC activity, it has been shown to be a less important predictor of landfalling hurricanes in the Atlantic basin (Elsner and Jagger 2006) and of global TC activity (Elsner and Kocher 2000) than AMO or NAO. The AMO has a multidecadal influence on TCs landfall frequency in the Southeast (J. R. Knight, Folland, and Scaife 2006; Miller et al. 2006). The NAO has been shown to have a statistically significant relationship with both Atlantic TC tracks (Elsner and Kara 1999; Elsner and Kocher 2000; Elsner and Jagger 2006) and landfall frequency (Elsner, Jagger, and Niu 2000; Elsner, Liu, and Kocher 2000; Elsner 2003; Dailey et al. 2009). When the NAO is negative, both Atlantic TC activity and U.S. TC landfall probability increase. Conversely, when the NAO is positive, activity and probability decrease.

In this study we examine the frequency of TC-induced drought busters (TCDBs) within the Southeastern Atlantic coastal states (SACS) between 1950 and 2008. Specifically, we identify how often there is a transition from at least one month of drought conditions to near-normal or wetter than normal soil moisture conditions caused by TC-generated rainfall. In addition, because the NAO, AMO, and ENSO influence TC track, frequency, and intensity in the Atlantic basin, we examine the possible influence of NAO, AMO, and ENSO on the likelihood of a TCDB. Both droughts and tropical cyclones are climatologically common events in the southeastern United States, making this region an ideal location to examine the potential benefits of heavy precipitation from TCs. Although it seems intuitive to include the Gulf States (e.g., Alabama, Mississippi, and Louisiana), Dailey et al. (2009) found that landfalling TCs of the East Coast have different characteristics in both genesis and intensity than those of the Gulf Coast. Atlantic sea surface temperatures and the location of the subtropical high pressure influence on which coastline a TC could potentially make landfall. Dailey et al. (2009) also found that warm sea surface temperatures had a stronger positive association with the likelihood of a TC landfall on the Gulf Coast. The location of the subtropical high pressure creates a seesaw effect in TC activity between the Gulf Coast and the East Coast. Thus, in this article we limit our discussion to the SACS and exclude from our analyses other "southeastern" states commonly affected by TCs.

Data and Methods

We used the Palmer Drought Severity Index (PDSI; Palmer 1965) as a measure of moisture conditions. We obtained monthly data from 1950 to 2008 for all thirty-one climate divisions within the SACS. The PDSI is the most commonly used metric of drought severity in the United States and allows for the comparison of droughts in different climatic regions because it is standardized to a given region's soil-moisture regime (Palmer 1965). The PDSI is ideal for examining meteorological drought because it is a retrospective index of drought and does not take into account human demand. Increases in human demand can make a climatologically mild drought appear to be much worse; thus, the PDSI provides a standardized measure of meteorological drought. The PDSI incorporates moisture-balance variables before and after the time of reference and therefore is not a useful operational measure of drought (Heddinghaus and Sabol 1991; Guttman and Quayle 1996). The use of the PDSI instead of an operational measure of drought such as the Palmer Meteorological Drought Index provides a conservative way to examine the abrupt end of drought conditions.

To determine which TCs could potentially alleviate SACS droughts, we used the North Atlantic Hurricane Database (HURDAT), which is compiled by the National Hurricane Center (Jarvinen, Neumann, and Davis 1984; Neumann et al. 1999). The data set provides the position of TCs every six hours along with wind speed, barometric pressure (when available), direction of movement, and the TC strength classification. Because aircraft reconnaissance of TCs started in the 1940s, the locations of TCs—especially those that made or came close to making landfall—are considered more accurate from this time period forward (Vecchi and Knutson 2008). In this study we use data from the period 1950 to 2008 ($n = 59$ years).

To ensure that we captured the total amount of precipitation that the TC provided relative to the rest of the precipitation for the month, we obtained daily precipitation totals from the Cooperative Observer Network's Cooperative Summary of the Day (NCDC 2006). We used every station within the climate division that was in operation for each day of the month that the TC influenced the region. We then determined if the majority of precipitation for the month occurred during the same dates that the TC passed over the area. These daily weather station observations were most commonly recorded at 07:00 or 08:00 EST; however, recording times varied as much as seventeen hours at select stations. For stations that made recordings at 07:00 or 08:00 EST, some of the precipitation recorded for a given day might have occurred on the previous calendar day. We examined the time of recording for each station during the month of the TC passing from the National Oceanic and Atmospheric Administration (NOAA) Climatological Data Publication to ensure that the reported precipitation did occur on the same day(s) as the TC. Additionally, we used NOAA's Central Library Data Imaging Project's Daily Weather Maps to determine the spatial range of the TC precipitation. The Daily Weather Maps allowed us to identify all three storm types (i.e., frontal, air mass, and tropical; Faiers, Keim, and Hirschboeck 1994; Keim and Faiers 1996) and determine what storm type caused the heavy precipitation that ended the drought.

We used a PDSI monthly value of ≤ -2.0 (moderate drought or worse) for a given month to determine when a drought began or was ongoing. We defined drought cessation as the first month postdrought initiation with a PDSI value of ≥ -0.49 (near normal or better). From these criteria we calculated the total number of droughts that affected the study region during the hurricane season (June–November) for each climate division. We then determined the number of DBs in the record (i.e., how many of the droughts ended abruptly) by using the criteria that a monthly PDSI value of ≤ -2.0 was immediately followed by a monthly PDSI value of ≥ -0.49. Once we identified a DB, we calculated the percentage attributable to precipitation from TCs (i.e., TCDBs). We determined whether the event was TC-induced by (1) examining the HURDAT data set to confirm whether a TC storm track was near the climate division during the month of heavy precipitation classified as a DB; (2) examining the Cooperative Summary of the Day reports for that month to identify if high daily precipitation amounts coincided with the day of TC landfall or near landfall; and (3) examining NOAA's Daily Weather Maps to determine the spatial area that the TC's precipitation influenced.

We used logistic regression analysis to determine what type of teleconnections (e.g., ENSO) influenced TCDBs and to predict the probability of a TCDB occurring in a given year. We assigned a "one" for years that had at least one TCDB and a "zero" for those years absent a TCDB. Logistic regression is a common technique (Ramsey and Schafer 2002) when working with a binary dependent variable (e.g., the presence of a TCDB in a given year). Several problems can occur when using ordinary least squares regression with a binary dependent variable (Kutner et al. 2004), including non-normally distributed errors, unequal error variances, and a linear response function generating outcome values outside the needed zero to one range. Logistic regression uses a logistic mean response function to address these problems (Kutner et al. 2005) as predictor variables can be in any form (e.g., categorical or continuous), and normality is not one of the assumptions of the analysis.

We examined two monthly indexes of ENSO in the logistic regression models: (1) the Southern Oscillation Index (SOI) from the Climate Research Unit calculated using the Ropelewski and Jones (1987) method; and (2) the Multivariate ENSO Index (MEI) from Wolter and Timlin (1993; Wolter 1998). SOI has been shown to influence both drought (Stahle et al. 1998) and tropical cyclones (Elsner, Murnane, and Jagger 2006), but the MEI might be a better measure of ENSO variation (Ortiz-Tánchez, Ebeling, and Lanius 2002), as it has been shown to better represent ENSO during transitional phases. Furthermore, we examined NAO and AMO indexes (NOAA 2009). All indexes were averaged for the hurricane season and used to predict the probability of TCDBs occurring during the same season. Because SOI and MEI were strongly correlated, we created two multivariate logistic regression models. Both models included AMO and NAO; however, one model included SOI, whereas the other included MEI. We used a backward stepwise method on the two models to determine which of the predictor variables were important to the probability of a TCDB.

We created a contingency table between NAO, the best and only significant predictor in the logistic regression model, and the TCDB variable. In the logistic regression analysis all four predictor variables were continuous; thus, we needed to convert NAO to a binary variable for the contingency table. We assigned the value of "zero" if NAO was in a negative phase and a value of "one" if it was in positive phase. The contingency table allowed us to examine the significance of the association between the two variables using a Fisher's exact test (Ramsey and Schafer 2002). Additionally, from the contingency table we calculated an odds-ratio statistic, which is the odds of a TCDB occurring during a negative NAO phase divided by the odds of a TCDB occurring during a positive NAO phase. The odds ratio allowed us to examine the multiplicative effects that NAO has on the odds of a TCDB occurring (Ramsey and Schafer 2002). Finally, to demonstrate the potential for a TC to alleviate drought conditions, we examined two TCs in detail. To provide an example of the typical influence a TCDB has in the SACS, we examined Tropical Storm Alberto (2006). We examined Tropical Storm Marco (1990) in more detail because it represented one of the most widespread TCDBs in the region. For each day these storms produced rainfall in the SACS, we obtained daily total precipitation values for all weather stations and interpolated the precipitation using the inverse distance-weighted method with the fifteen nearest neighbors as weights using ArcGIS 9.2 (ESRI 2006).

Results and Discussion

In twenty-four of the thirty-one climate divisions (Figure 1), at least 20 percent of the droughts were ended by TCDBs. The influence of TCDBs was spatially distinct, with three regions most affected: south-central Georgia, central North Carolina, and southeast Florida (Figure 2). Climate divisions in those three regions experienced the highest number (up to six) of TCDBs (Figure 1) and the greatest percentage (up to 41 percent) of droughts ended by TCDBs (Figure 2). Although the spatial patterns (Figure 2) resemble the return periods of landfalling TCs found by Keim et al. (2007) for the North Carolina coastal climate divisions and coastal south Florida, they poorly match those for the coastline of South Carolina into north Florida. The highest percentage and greatest number of TCDBs occurred in southern Georgia, yet Keim et al. (2007) found that the Georgia coastline did not experience a high frequency of TC landfalls. Bettinger, Merry, and Hepinstall (2009) also found that the Georgia coast experiences weaker storms relative to the other coastlines in the region, whereas south Florida, the Carolinas, and Alabama and Mississippi have stronger storms. Comparing our findings with these studies suggests that southern Georgia might be climatologically unique in that TCs that make landfall on the Atlantic Florida coast, Gulf Florida coast, and the Georgia coast can impact the area because TC rain shields can extend hundreds of kilometers from the eye of the storm. Our examination of the daily weather maps for storms that produced TCDBs in southern Georgia confirmed that Georgia often receives intense rainfall from TCs that did not make landfall on the Georgia coast. The lack of landfalling TCs on the Georgia coast does not imply that TCs rarely impact Georgia. Our results indicate that although Georgia might experience less structural damage from high winds that are associated with landfalling TCs, the state often does receive intense rainfall from TCs.

TCDBs influencing the SACS and especially southern Georgia might also influence the Gulf Coast states and vice versa. We found that 61 percent of TCDBs affecting the SACS originated in the Gulf of Mexico or Caribbean, suggesting the potential to impact both the SACS and the Gulf Coast states; however, 85 percent of the TCDBs impacting the SACS either made landfall or near-landfall in the SACS (Figure 3). A TC has the potential to be a TCDB simultaneously in the SACS and the Gulf Coast states, but our findings

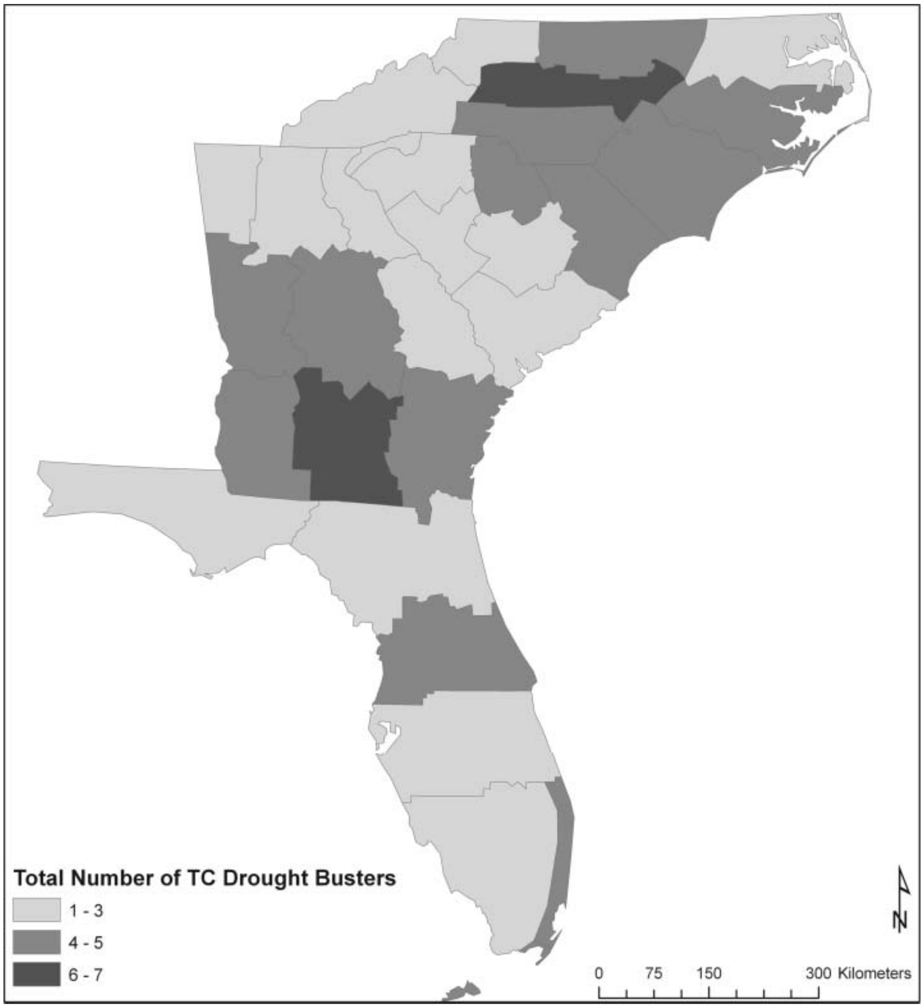

Figure 1. The number of tropical cyclone–induced drought busters from 1950 through 2008 using modified Jenks's natural breaks. TC = tropical cyclone.

suggest that this is uncommon and in agreement with the conclusion of Dailey et al. (2009) that the TCs influencing the Atlantic and Gulf states have different characteristics and thus should be examined separately.

Our findings also agree with Elsner, Liu, and Kocher (2000) and Elsner (2003), who found an inverse relation in landfalling major hurricanes between the East Coast and Gulf Coast states. They found that the longitude of TC formation might influence the inverse relationship of TC activity between the two coasts. Hurricanes originating in the eastern Atlantic are more likely to make landfall on the East Coast, whereas hurricanes forming in the western Atlantic are likely to make landfall along the Gulf Coast states. Furthermore, they found that sea-level pressures of the North Atlantic influence which coast experiences greater hurricane activity. Subtropical high pressure centered over the western Atlantic reduces recurving northward and steers hurricanes into the Gulf Coast states. Conversely, subtropical high pressure centered in the eastern Atlantic increases the northward recurving of hurricanes, and the East Coast receives more hurricane activity.

Differences exist in the multidecadal patterns in TC landfall frequency between the Gulf Coast and the East Coast in the Southeast (Keim et al. 2007). Specifically, sea surface temperatures in the Atlantic basin represented by AMO appear to influence long-term spatial variability in TC activity in the Southeast. The warm AMO periods of the 1950s and 1990s were extremely active tropical cyclone decades along the Outer Banks of North Carolina, whereas the intervening period of cool AMO included less TC activity in the same location. Conversely, the 1950s and 1990s were hurricane seasons with anomalously low activity in southern Florida, and active hurricane seasons dominated the interim (McCabe, Palecki, and Betancourt 2004; Keim et al. 2007). The East and Gulf Coasts are likely to have the same inverse relationship for TCDBs because of the requirement of a TC landfall.

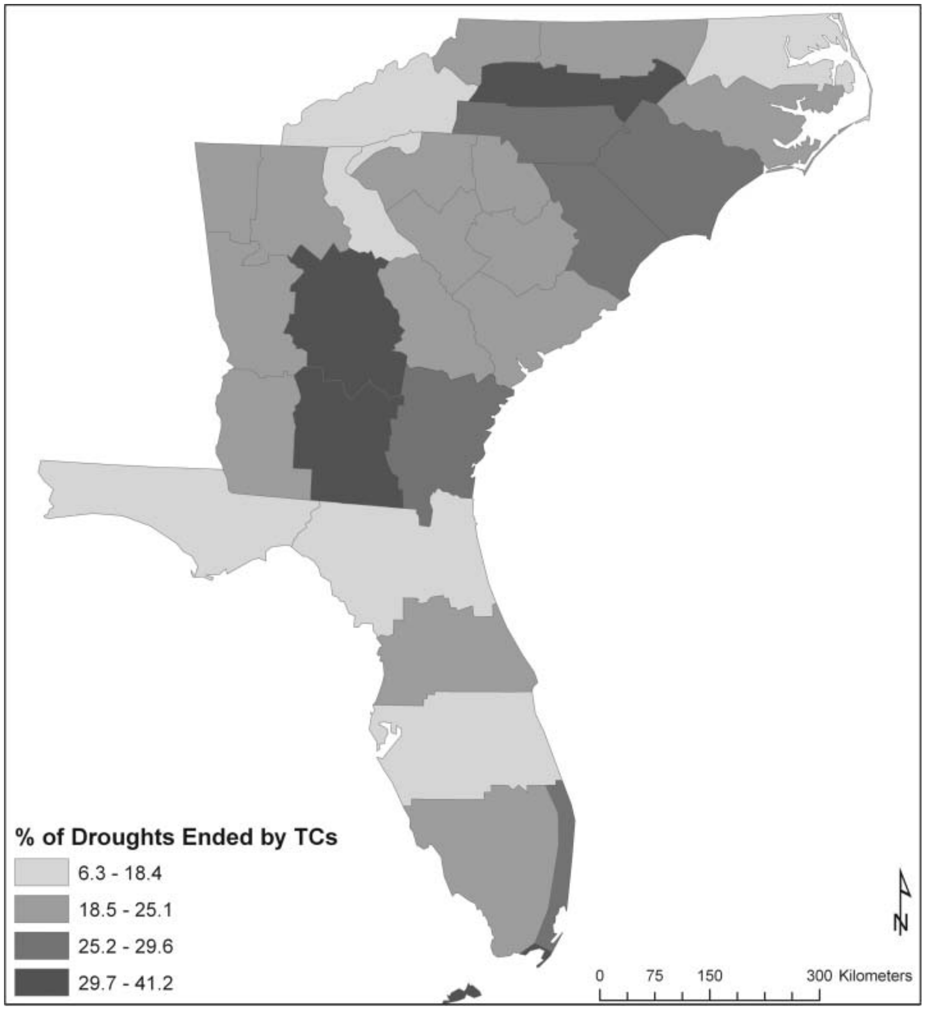

Figure 2. The percentage of droughts that were ended abruptly by tropical cyclones from 1950 through 2008 using modified natural breaks. TC = tropical cyclone.

The length of the existing drought did not influence the ability of TCs to end drought, as TCs ended long (> twelve months), medium (three–twelve months), and short (< three months) droughts during the last sixty years. We found that of the thirty-two long, fifty medium, and twenty-six short droughts that were ended by a TC, only once in one climate division did drought return during the same hurricane season. Thus, TCs end droughts of multiple lengths and for the remainder of the hurricane season with few exceptions. A TC can produce sufficient precipitation within days to ameliorate drought conditions that have persisted for over twelve months and restore soil moisture to near-normal conditions.

Many physical mechanisms influence TCs, including wind shear, sea-level pressure, and sea surface temperatures (W. M. Gray 1984a, 1984b; Goldenberg et al. 2001). The most influential variable on the likelihood of a TCDB occurring in a given year was NAO, and this was the only significant predicator ($p = 0.001$) in the logistic regression model, with a model χ^2 value of 10.91. Furthermore, the Fisher's exact test showed a significant association between NAO and the TCDBs ($p = 0.003$). The odds-ratio calculation revealed that the odds of TCDBs occurring during a negative NAO phase were 5.8 times greater than the odds of TCDBs occurring during a positive NAO phase. The six TCDBs that occurred during a positive phase were evenly distributed throughout the study period, indicating that there were no trends in the rare occurrence of a TCDB during the positive NAO phase.

Our findings of NAO influence on TCDBs agree with several studies that have found that lower pressures over the North Atlantic Ocean lead to more TC landfalling events in the SACS (Elsner and Kara 1999; Elsner and Kocher 2000; Keim, Muller, and Stone 2004; Elsner and Jagger 2006; Elsner, Murnane, and Jagger 2006; Dailey et al. 2009). Negative phases of NAO are

Figure 3. Tracks of the tropical cyclones that abruptly ended drought for (A) 1950–1959, (B) 1960–1969, (C) 1970–1979, (D) 1980–1989, (E) 1990–1999, and (F) 2000–2008. Legend for all figures is displayed on bottom left of (A). TCDB = tropical cyclone–induced drought buster. (Color figure available online.)

associated with winter precipitation decreases in the southeastern United States (Hurrell 1995; Greatbatch 2000; Stenseth et al. 2002), which could explain part of the connection between NAO and TCDBs. When NAO is in a negative phase during the winter, the Southeast is more likely to experience drought that could continue into hurricane season. If NAO is also negative in the summer months, the likelihood of TC landfall along the SACS coastline increases.

ENSO can influence southeastern U.S. winter precipitation (Cordery and McCall 2000; Rogers and Coleman 2003; Seager et al. 2005) and Atlantic TCs (W. M. Gray 1984a, 1984b; Shapiro 1987; Goldenberg and Shapiro 1996; Larson, Zhou, and Higgins 2005; Elsner and Jagger 2006; Elsner, Murnane, and Jagger 2006). Similarly, AMO influences winter precipitation in the Southeast (Enfield, Mestas-Nuñez, and Trimble 2001; McCabe, Palecki, and Betancourt 2004) and Atlantic TC strength (Elsner, Murnane, and Jagger 2006). During the instrumental period, sea surface temperature variance captured by the AMO has exerted a strong influence over the number of TCs in the Atlantic Ocean that develop into strong (Saffir-Simpson scale ≥ 3) hurricanes (J. R. Knight, Folland, and Scaife 2006; Miller et al. 2006). More than twice as many tropical cyclones per season develop into major hurricanes under positive (warm) AMO conditions than during cool AMO phases (McCabe, Palecki, and Betancourt 2004). The AMO has not been found to modulate the number of TCs that develop, only the number that strengthen into major hurricanes. The lack of retention of ENSO and AMO in the logistic regression model could be because both influence TC development and intensity (Elsner, Murnane, and Jagger 2006), whereas NAO is strongly associated with TC track (Elsner, Liu, and Kocher 2000; Elsner 2003; Elsner, Murnane, and Jagger 2006). In addition, in this study we examined the interannual variability of TCDBs, whereas other studies that have shown AMO linkages on landfalling TC activity in the Southeast examined possible multidecadal patterns in TC landfall frequency (S. T. Gray et al. 2004; Miller et al. 2006; Keim et al. 2007). Our results indicate that the probability of a TCDB occurring in the SACS on an interannual time scale is strongly dependent on a TC making landfall and thus is influenced by NAO.

Our results suggest that TCDBs are an important part of the synoptic climatology of the SACS and contribute to a paucity of long-duration droughts (i.e., longer than three years) in the region. To demonstrate the abrupt ameliorating ability of TCDBs, we present two examples. The first example, Tropical Storm Alberto (2006), provides insight as to how an average TCDB event affects the SACS. Our second example, Tropical Storm Marco (1990), demonstrates the potential amount of precipitation a TCDB can produce.

Examples of Tropical Cyclone Drought Busters

Tropical Storm Alberto formed over Central America and the Caribbean Sea on 8 June 2006. By 10 June the system was classified as a tropical depression and had tracked south of Cuba. The depression developed into a tropical storm on 11 June and was located east of the Yucatan Peninsula coastline. Alberto reached peak intensity of 995 hPa on 13 June, east of coastal Florida. The cyclone made landfall the same day near Adams Beach, Florida, and continued northeast (Figure 4). Alberto weakened until 14 June when it reentered the Atlantic off the coast of North Carolina and became a powerful extratropical storm south of Nova Scotia. Tropical Storm Alberto produced over 15 cm of precipitation throughout the SACS (National Hurricane Center 2006), and it provided enough precipitation in twenty-four hours to alleviate existing drought conditions (Figure 4).

Moderate drought (PDSI ≤ -2.0) was present in 52 percent of the SACS climate divisions in May 2006 (Figure 5). The percentage decreased to 29 percent after Tropical Storm Alberto passed through the SACS (Figure 5). Alberto did not alleviate all drought conditions in the SACS. Moderate drought conditions were present in Florida both before and after its passage. Conversely, Tropical Storm Alberto was a TCDB for North Carolina and South Carolina. The scattered relief of drought conditions that Alberto provided for the SACS is a common example of how TCDBs influenced the SACS in the last fifty-nine years.

The second example, Tropical Storm Marco, demonstrates the potential for extreme precipitation a TC can provide to a region experiencing drought conditions. Marco formed off the coast of Cuba on 10 October 1990 from the remnants of Tropical Storm Klaus. By 11 October, Tropical Storm Marco had reached peak intensity with a 989 hPa central pressure off the Florida coast near St. Petersburg. On 12 October, Tropical Storm Marco was downgraded to a tropical depression when it was over central Florida, and it was absorbed by a frontal system near Columbia, South Carolina, by 13 October (National Hurricane Center 1990). Marco

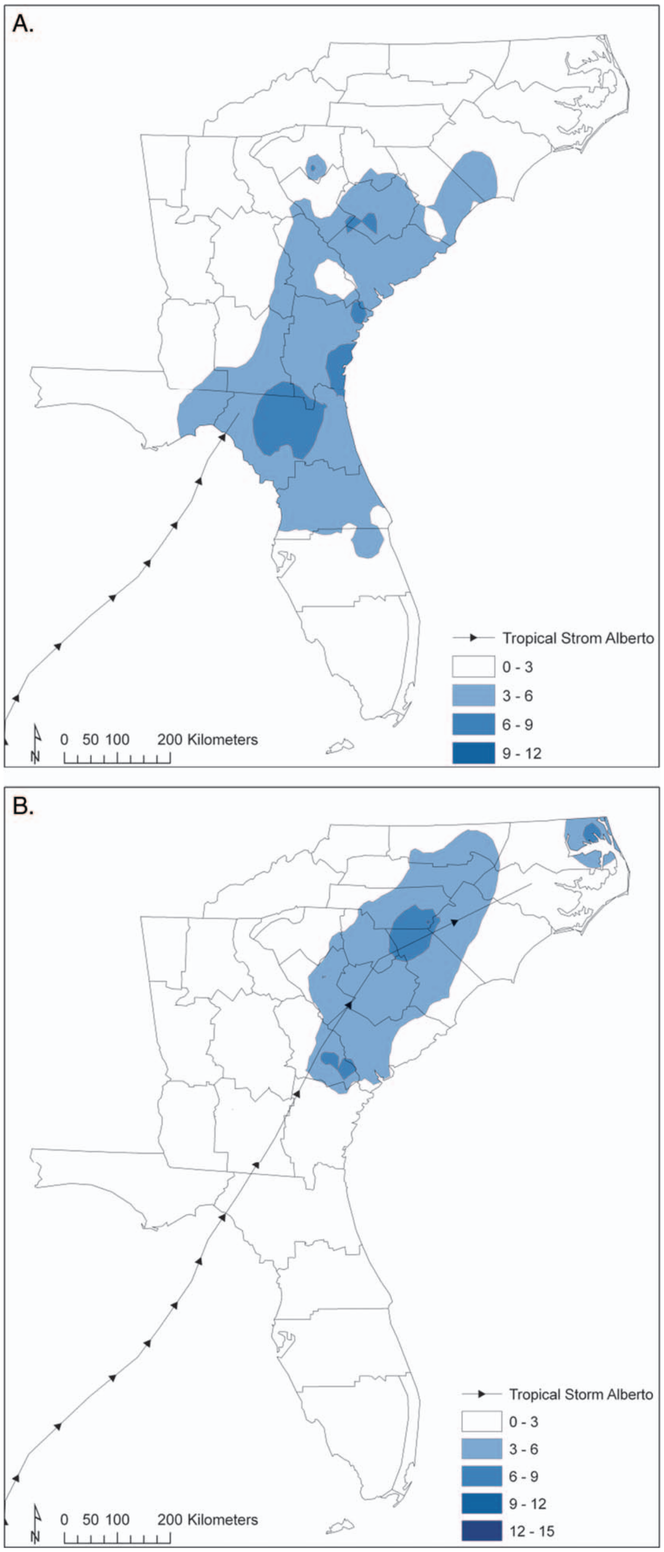

Figure 4. Daily precipitation for Tropical Storm Alberto and the associated storm track on (A) 13 June 2006 and (B) 14 June 2006. (Color figure available online.)

produced approximately 15 cm of precipitation (Figure 6) on the west Coast of Florida and, because of interactions with a frontal system, contributed to the large amounts of localized rain (as much as 40 cm) that Georgia and the Carolinas received (National Hurricane Center 1990). Although the National Hurricane Center listed the total precipitation amounts in its tropical cyclone report for Tropical Storm Marco, remnants

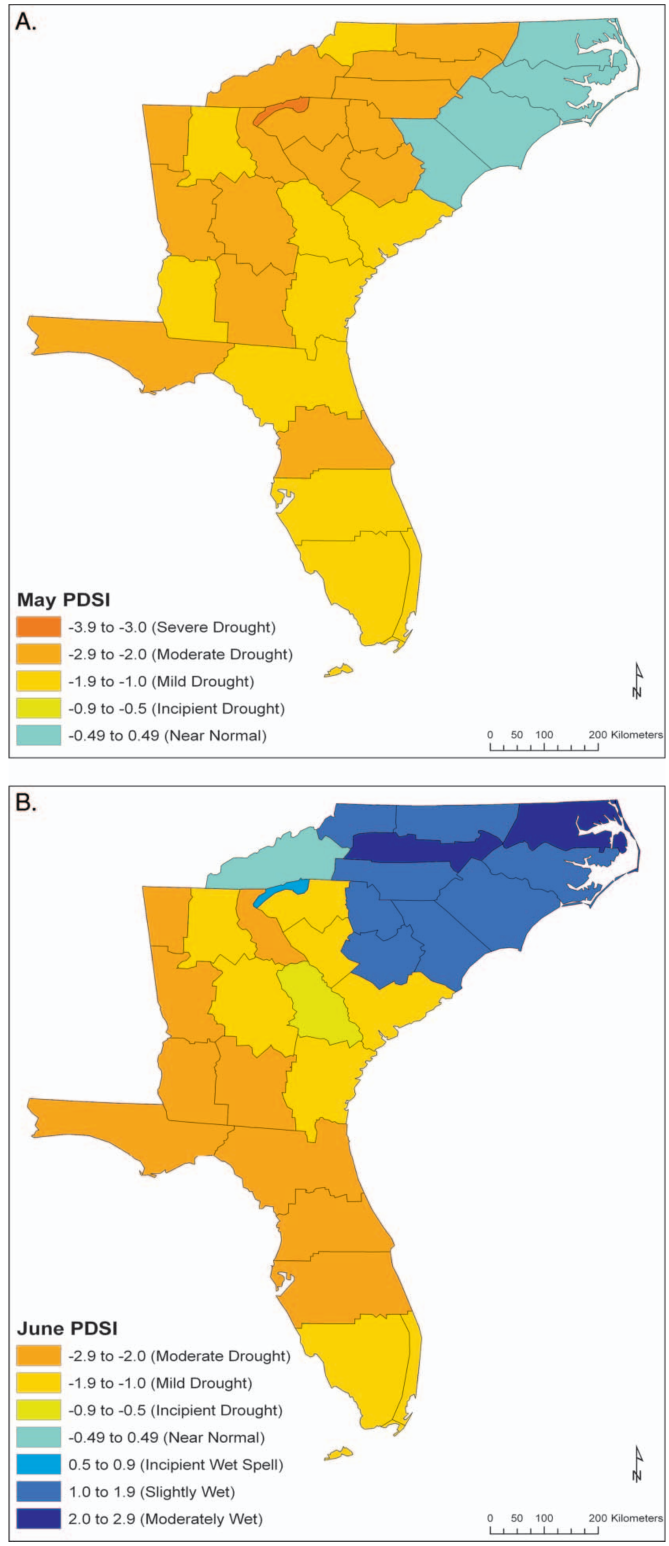

Figure 5. Drought conditions in (A) May 2006 prior to Tropical Storm Alberto; (B) drought conditions in June 2006 after Tropical Storm Alberto. PDSI = Palmer Drought Severity Index. (Color figure available online.)

of Tropical Storm Klaus contributed moisture needed for the large amounts of precipitation. Both TC's moisture plumes were lifted by a stationary frontal system that produced the dramatic amount of precipitation.

Prior to Tropical Storm Marco, the majority of the region (74 percent) was experiencing moderate drought conditions or worse (Figure 7). After Marco (Figure 7), 32 percent of the climate divisions were in the

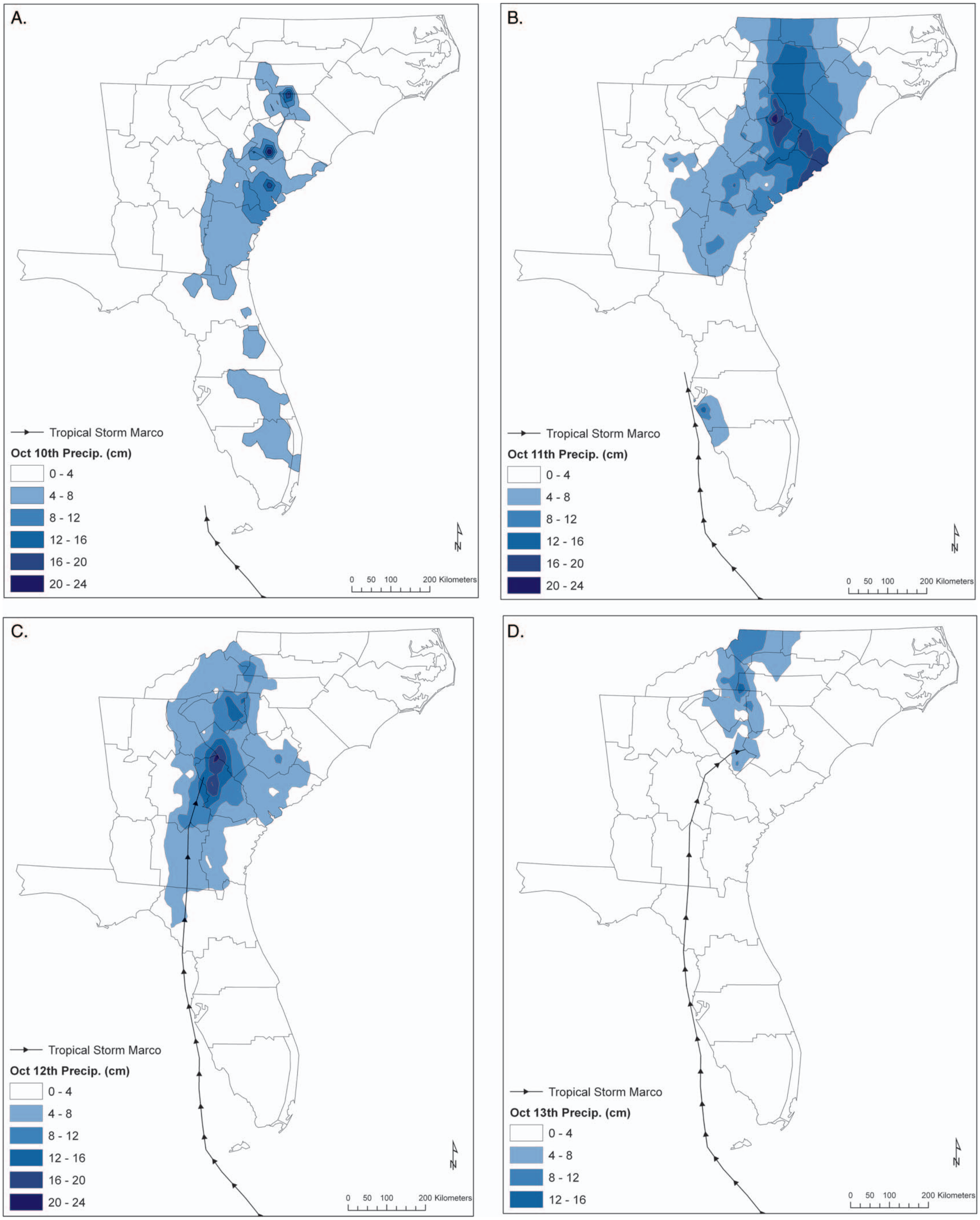

Figure 6. Daily precipitation for Tropical Storm Marco and the associated storm track on (A) 10 October 1990, (B) 11 October 1990, (C) 12 October 1990, and (D) 13 October 1990. (Color figure available online.)

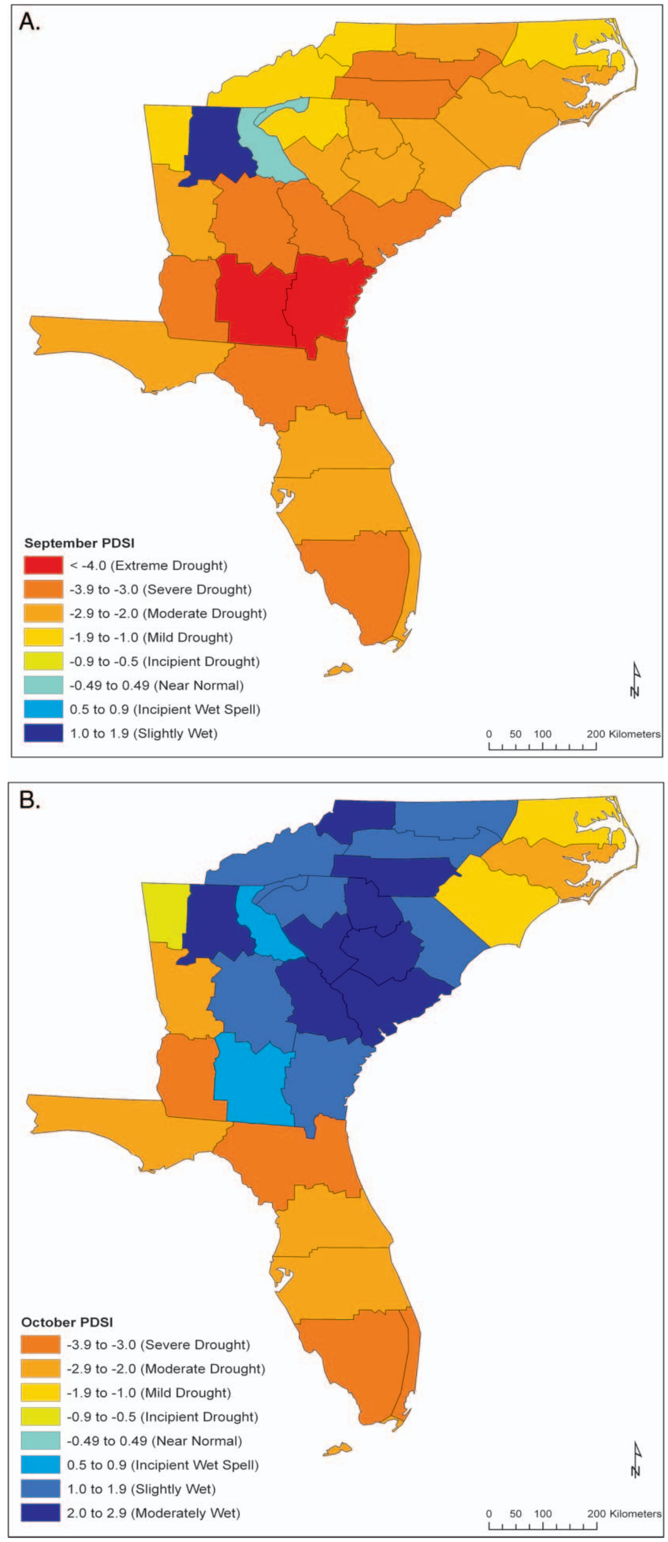

Figure 7. Drought conditions in (A) September 1990 prior to Tropical Storm Marco and (B) October 1990 after Tropical Storm Marco. PDSI = Palmer Drought Severity Index. (Color figure available online.)

moderate drought or worse category, and 58 percent of the divisions were classified as an incipient wet spell or better for October. The existing frontal system in the SACS became stronger because of the additional energy from the convergence of Klaus and Marco with the front, and moisture advected inland led to exceptional amounts of precipitation. Like Marco, the most extreme TCDBs occurred when TCs or extratropical remnants combined with a frontal system to produce high precipitation amounts. However, there were many cases where TCDBs occurred solely from a TC (e.g., Tropical Storm Alberto), suggesting that TCs coupling with frontal systems are not necessary to end a drought, but they generally create the most dramatic examples of TCDBs. TCs also provided drought relief to areas that were experiencing drought conditions less severe than the criteria we used for drought identification (i.e., PDSI ≥ -2.00). Although the ability of a TC to ameliorate less severe drought conditions is important, our results document how severe droughts can be abruptly alleviated by TCs.

Conclusions

TCs provide up to 15 percent of the TC season precipitation for the southeastern United States (D. B. Knight and Davis 2007). We found that in many years the precipitation associated with TCs abruptly alleviated drought conditions in the SACS. Between 1950 and 2008, at least 20 percent of the droughts were ended by TCs in twenty-four of the thirty-one climate divisions. In the remaining seven climate divisions, over 6 percent of the droughts were abruptly ended by TC-induced precipitation. Thus, TCDBs are a significant component of the SACS hydroclimatology.

We found that when the NAO was in a negative phase, the odds of TCDBs occurring were approximately six times greater in the SACS than when the NAO was in a positive phase. This information, coupled with the probability of TC genesis issued by the National Hurricane Center, can determine the likelihood of a TC to end an ongoing drought. In addition, we found that the majority (85 percent) of TCDBs that influenced the SACS made landfall on the coastline of one of those four states, supporting the finding that TCs that influence the SACS have different characteristics than those affecting the Gulf states (Elsner, Liu, and Kocher 2000; Elsner 2003; Keim et al. 2007; Dailey et al. 2009).

These results demonstrate how a single TC can terminate a multimonth to multiyear drought within days and during peak water-demand periods. Further, the influence of TCDBs as drought-ameliorating climatological events could help explain the lack of long-duration droughts (i.e., greater than three years) in the SACS region during the past 300 years (Ortegren 2008). The application of this method to investigate the possibility of other regions affected by TCs in the United States might reveal that these events have a larger geographical component than previously thought and that late spring and early summer predictions of TC activity might help identify the probabilities of drought-ending TCs during the summer and early fall months.

An enhanced awareness of the probability of a TCDB occurrence in a given year will help regional water resource managers make improved baseline forecasts regarding the likelihood of drought relief from tropical precipitation, as well as improve drought mitigation plans. In spite of the relative infrequency of prolonged (e.g., decadal-scale) drought in the SACS, and in spite of the ability of TCs to quickly ameliorate drought conditions, population growth has placed strain on water resources in the region, even to the point of legal conflict between southeastern states (Feldman 2008; Leitman 2008). The potential ameliorating effects of TCDBs on drought could have significant economic implications, particularly the reduction of drought-related economic losses. Our findings indicate a need to refine the assessment of TC costs to include the potential drought-ameliorating benefits of TCDBs.

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