The Influence of Atlantic Tropical Cyclones on Drought over the Eastern United States (1980–2007)

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ABSTRACT

To assess the influence of Atlantic tropical cyclones (TCs) on the eastern U.S. drought regime, the Variable Infiltration Capacity (VIC) land surface hydrologic model was run over the eastern United States forced by the North American Land Data Assimilation System phase 2 (NLDAS-2) analysis with and without TC-related precipitation for the period 1980–2007. A drought was defined in terms of soil moisture as a prolonged period below a percentile threshold. Different duration droughts were analyzed—short term (longer than 30 days) and long term (longer than 90 days)—as well as different drought severities corresponding to the 10th, 15th, and 20th percentiles of soil moisture depth. With TCs, droughts are shorter in duration and of a lesser spatial extent. Tropical cyclones variously impact soil moisture droughts via late drought initiation, weakened drought intensity, and early drought recovery. At regional scales, TCs decreased the average duration of moderately severe short-term and long-term droughts by less than 4 (10% of average drought duration per year) and more than 5 (15%) days yr^{-1}, respectively. Also, they removed at least two short-term and one long-term drought events over 50% of the study region. Despite the damage inflicted directly by TCs, they play a crucial role in the alleviation and removal of drought for some years and seasons, with important implications for water resources and agriculture.

1. Introduction

The North Atlantic basin provides a favorable environment for tropical cyclone (TC) genesis with high sea surface temperatures from late spring until early winter (Emanuel 1986). Landfalls of Atlantic TCs bring high winds and heavy rainfall to the eastern United States on time scales of a few days, causing significant societal and economic losses along the coastal states of the Gulf of Mexico and the North Atlantic (Pielke 2009). For example, Hurricane Katrina in 2005 was the costliest hurricane in U.S. history and the third deadliest since 1900 with $81 billion (all amounts are in U.S. dollars) in economic losses and over 1800 fatalities in the hurricane and subsequent floods (Beven et al. 2008). Despite the direct devastation and economic costs that are caused by TCs, they also have a beneficial side in terms of the amount of water they bring to the land and their role in drought recovery.

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Drought is a naturally occurring and prolonged climate phenomenon that, like TCs, is one of the most costly of natural disasters (Wilhite et al. 2000). For example, the estimated agricultural losses from the Texas 2011 drought were about $7.6 billion and thus it was the costliest drought in the state history (Fannin 2012). There is increasing awareness that TCs play a significant role in drought development and recovery, which has been highlighted in recent studies. Lam et al. (2012) discussed the role of TCs (typhoons) as drought breakers in Hong Kong, and their other benefits including contributions to wind energy and cooling effects. McGrath et al. (2012) observed that TCs are an important feature of vegetation dynamics and their quiescence along with other climate drivers may have induced the recent continental multiyear Australian drought from 1997 to 2011. For the example of the 2011 Texas drought, there were no landfalling TCs, which may have contributed to the development of the drought. Despite this growing awareness, the contribution of TCs to drought recovery has not been quantified and their role in drought dynamics is poorly understood, in part because of their different temporal and spatial scales.

Previous studies investigating droughts over the contiguous United States (CONUS) have focused mainly on identifying and characterizing historical drought events and have used monthly average time series of drought variables (e.g., Palmer 1965; McKee et al. 1993; Sheffield et al. 2004; Andreadis and Lettenmaier 2006; Mo 2008; Sheffield et al. 2009). Most recently, Mo (2011) studied the historical onset and demise of drought over the United States from monthly mean precipitation and simulated soil moisture. Since the lifetime of landfalling TCs is generally on the order of a few days to a week, the impact of TCs on drought is difficult to evaluate from monthly average time series.

The role of Atlantic TCs in the eastern U.S. drought regime has not yet been quantified. Hence, this study was designed to answer the following questions: 1) What is the contribution of Atlantic TCs to annual and seasonal total rainfall over the eastern United States? 2) What is the impact of TCs on the eastern U.S. drought regime at local to regional scales? 3) Do TCs play different roles in drought initiation, persistence, and recovery, and how does this depend on different types of drought? 4) How do TCs change the characteristics of drought during either their more active years (2004–05) or their more dormant years (2000–01)?

In this study, the Variable Infiltration Capacity (VIC) land surface hydrologic model was run for two simulations with different rainfall forcing datasets. An EXP-TC simulation was forced by observed rainfall, including the contribution of TCs, and an EXP-NOTC simulation was forced by rainfall excluding TCs. A drought was defined in terms of soil moisture as a prolonged period below a threshold corresponding to a certain soil moisture percentile and TC-related rainfall was defined as rainfall within a certain distance (500 km) from the centers of TCs (Shepherd et al. 2007; Jiang and Zipser 2010; Barlow 2011). Rainfall associated with TCs was determined from the Atlantic Hurricane Database (HURDAT) and the North America Land Surface Data System phase 2 (NLDAS-2). The analysis was carried out for 1980–2007 based on NLDAS-2 data availability. Detailed descriptions of the data and methods are given in section 2. Section 3 presents the historical contribution of Atlantic TCs during 1980–2007 to total rainfall, followed by an analysis of the impact of TCs on drought over the eastern United States, first for the example of Hurricane Katrina on local drought and second for the impact of all TCs on regional drought events. In section 4, we discuss uncertainties in our forcing data and potential impacts on the results, the sensitivity of changes in drought to TC frequency and intensity, and the implications of this under future potential climate change. In section 5, we summarize the findings of this study and highlight the benefits of TCs with regard to drought relief.

2. Datasets and methods

a. *Rainfall forcing dataset: The North Land Data Assimilation System phase 2*

The first phase of the North Land Data Assimilation System product (NLDAS-1) was initiated to support the development of more consistent and reliable initial land surface states for numerical weather prediction (Mitchell et al. 2004). Building on the experimental configuration of the first phase, the NLDAS-2 forcing data (Xia et al. 2012) cover a longer period from January 1979 to the present, via near-real-time updates. The data are acquired from diverse sources including atmospheric reanalysis, satellite remote sensing, and ground-based observations (Cosgrove et al. 2003; Xia et al. 2012). The NLDAS-2 has temporal and spatial resolutions of hourly and 0.125° (12.5 km), respectively. The NLDAS-2 precipitation forcing data are derived from the Climate Prediction Center (CPC) daily CONUS gauge data adjusted for topographical effect (Daly et al. 1994), hourly Doppler stage II radar precipitation data (Crum et al. 1993), the CPC hourly CONUS/Mexico gauge data (Higgins et al. 1996), the half-hourly CPC morphing method (CMORPH) data (Joyce et al. 2004), and 3-hourly North America Regional Reanalysis rainfall data (Mesinger et al. 2006). Details of the hourly NLDAS-2 rainfall forcing data are described by Xia et al. (2012).

b. *TC-related rainfall from the Atlantic Hurricane Database*

The Atlantic Hurricane Database (Jarvinen et al. 1984; Neumann et al. 1993) provides best storm track data for 1851–2011. We combined it with the NLDAS-2 forcing hourly rainfall dataset to identify TC-related rainfall for 1980–2007. The Atlantic HURDAT includes track information for the center of each TC at 6-hourly time steps, including maximum wind speed, minimum pressure, and their classification as a tropical storm (TS) or hurricane with category between 1 and 5 based on their sustained winds. Recent studies (Landsea et al. 2010; Kunkel et al. 2010) have used the Atlantic HURDAT to analyze the trend in the duration of TCs and to examine the contribution of TCs to heavy rainfall. Since the NLDAS-2 forcing data have an hourly temporal resolution, the HURDAT TC track data were linearly interpolated from 6-hourly to hourly. The data thus describe the evolution of the TC at hourly time steps (Villarini et al. 2011). The interpolated rainfall data have some uncertainties for a number of reasons. The centers of the TCs do not move linearly in time along the tracks between the 6-hourly positions from the HURDAT database and the associated rainfall may therefore be higher or lower than estimated depending on these dynamics. Furthermore, the spatial footprint of TC-related rainfall is generally not symmetric and rainfall may fall preferentially on one side of the TC center. Therefore, there are some uncertainties in the estimation of TC-related rainfall from our method and the datasets used. Although several studies (Shepherd et al. 2007; Prat and Nelson 2013) evaluated the contribution of TCs on total rainfall using the Tropical Rainfall Measuring Mission (TRMM) TC database, which has temporal and spatial scales of 3 h and 0.25°, the temporal coverage is only from 1998, which is too short for our purposes; therefore, NLDAS-2 is the best candidate dataset for this study. TC-related rainfall was assumed to fall within 5° from the center of TCs as used in previous studies (Shepherd et al. 2007; Jiang and Zipser 2010; Barlow 2011). The use of a threshold based on a fixed distance rather than fixed latitude would make a slight difference to the results but would not affect the overall conclusions.

We computed several metrics on a grid cell basis to describe the spatial distribution of TC-related rainfall and its contribution to total rainfall: frequency of TCs, total TC-related rainfall and its contribution to total rainfall, and TC rainfall intensity. TC frequency for each grid cell was calculated as the number of TCs whose center passed within 5° of the cell. The TC rainfall intensity is the total TC-related rainfall divided by the frequency of TCs. We also calculated the total number of affected TC days, for each grid cell.

c. *Offline land surface hydrologic model simulations*

The VIC model has been developed and previously applied to better understand land surface hydrologic systems at catchment, regional, and continental scales (Liang et al. 1994; Cherkauer et al. 2003; Nijssen et al. 1997, 2001; Pan and Wood 2006). It has also been used to identify and monitor drought events at continental and global scales (Andreadis and Lettenmaier 2006; Sheffield and Wood 2008; Luo and Wood 2007; Wang et al. 2011). The soil and vegetation parameters used in this study were calibrated by Maurer et al. (2002). The soil moisture at the beginning of 1980 was derived by running the model using forcing data from 1949 to 1979. From the initial condition on 1 January 1980, two VIC simulations were run: the first forced by the NLDAS-2 rainfall data and identified as the EXP-TC simulation and the second forced by non-TC-related rainfall data and identified as the EXP-NOTC simulation. The EXP-NOTC rainfall data were calculated by removing the TC-related rainfall, as described in section 2b, from the NLDAS-2 rainfall data. VIC simulations have temporal and spatial resolutions of daily and 0.125°, respectively, from 1 January 1980 until 31 December 2007 (28 yr). The VIC model was run in so-called water balance mode, which requires forcing data including daily total rainfall, daily maximum temperature, daily minimum temperature, and daily average wind speed. Therefore, the hourly NLDAS-2 rainfall and non-TC rainfall data were aggregated to daily.

Precipitation was the only forcing variable considered to be affected by TCs. However, other variables can be altered over a broad area around the center of TCs. For example, TC maximum sustained wind speeds are classified as being greater than 17 m s^{-1} (Blake et al. 2011). Latent heating can be significant with high evaporation rates and surface cooling (Trenberth et al. 2007). Therefore, TCs affect not only precipitation but also the three remaining forcing variables that are used as drivers of VIC. To generate the non-TC forcing scenarios more precisely, daily maximum and minimum temperature should be increased and daily average wind speed should decrease. Increased temperatures will likely increase evaporative demand and decreased wind speeds will reduce it. Therefore, their combined effects on evaporative demand and soil moisture may be negligible, and their impact will likely be overwhelmed by the rainfall forcing anyway.

d. *Definition and characteristics of drought*

A universal definition of drought is difficult because of the complex physical mechanisms and diverse effects on societal and economic sectors (Dracup et al. 1980; Mishra and Singh 2010). Several drought indices have been developed and applied to detect and characterize historical drought events based on precipitation, soil moisture, streamflow, or other hydrological variables and combinations of these (Palmer 1965; McKee et al. 1993; Byun and Wilhite 1999; Sheffield et al. 2004; Narasimhan and Srinivasan 2005; Sheffield and Wood 2007). Soil moisture from observations, remote sensing, and model simulation is a useful drought variable and has been used in past studies (Andreadis and Lettenmaier 2006; Hunt et al. 2009; Sheffield et al. 2009; Wang et al. 2011). In general, the shallow soil layer (surface to 30 cm) responds quickly to short-term meteorological events (e.g., rainfall, snowfall, and evaporation), whereas the deep soil layer (30 cm to 3 m) is driven mainly by longer-term drivers including moisture redistribution and the seasonal cycle of evapotranspiration (Hunt et al. 2009). Therefore, the total column soil moisture in VIC embeds signals of meteorological and climate phenomena at short and long time scales and is a good indicator of drought, and especially agricultural drought (Sheffield et al. 2004; Narasimhan and Srinivasan 2005). Agricultural drought is defined as a prolonged period of soil moisture under a certain threshold level that stresses vegetation and adversely impacts on its productivity. The threshold level can be set arbitrarily to detect a drought event and the relative magnitude of the drought can be defined for other parameters such as the intensity, duration, and severity of the drought (Dracup et al. 1980). Other drought indices could also be examined, such as the commonly used Palmer Drought Severity Index (PDSI; Palmer 1965). However, the PDSI is calculated at weekly or monthly time step and so is likely to be unsuitable for capturing the correct hydrological response to heavy rain rates that are typical of TCs (Alley 1984).

This study evaluated drought based on VIC simulated daily total column soil moisture depth. The use of monthly averages, as often used in previous studies, would not allow the true impact of TCs, which act at much shorter time scales, to be properly evaluated. We used the threshold method for identifying droughts as described in Dracup et al. (1980). Here, two different types of threshold values were chosen to characterize the magnitude and duration of drought. First, we calculated three low percentiles (10th, 15th, and 20th percentiles) based on daily total column soil moisture depth for each model grid cell in the EXP-TC simulation. These corresponding soil moisture depths were used as threshold values in measuring the magnitude of drought as a critical level of water availability in soil. We defined a drought as a period that has more than 30 continuous days (short-term drought) or 90 continuous days (long-term drought) below the soil moisture depth corresponding to each percentile threshold. We evaluated six types of drought ranging from moderately severe short-term drought to extremely severe long-term drought by combining the two durations (short and long term) with the three thresholds (10%: extremely severe; 15%: severe; and 20%: moderately severe). Since droughts were defined relative to the local soil moisture climatology as represented by a percentile threshold value, the total number of droughts will be similar among the study regions. To describe of the temporal characteristics of drought, three metrics were introduced as follows and shown in Fig. 1:

1) Drought initiation time (T_{ini}) is the day when a drought event starts.
2) Drought recovery time (T_{rec}) is the day when a drought event terminates.
3) Drought duration (D_d) is the total number of continuous days under a certain threshold level for one drought event.

To characterize the impact of TCs on drought, two further metrics were defined based on the differences between the EXP-TC and EXP-NOTC simulations:

4) Late drought initiation duration is defined as the total difference of drought initiation times between the two simulations [T^{INI}; Eq. (1)].
5) Early drought recovery duration is defined as the total difference of drought recovery times between the two simulations [T^{REC}; Eq. (2)].

For each model grid cell and each type of drought, we counted the total number of drought events (N_d) in both simulations and every occurrence of late drought initiation (N_i) and early drought recovery (N_r) during the period 1980–2007. Example time series illustrating these indices are shown in Fig. 1. Furthermore, we also computed averaged drought durations per event for each simulation (D_{avd}), the total difference in drought durations from both simulations (D_{diff}), averaged late drought initiation duration per event (T_{late}), and early drought recovery duration (T_{early}) during 1980–2007 for each grid cell:

$$T^{\mathrm{INI}} = \sum_{i=1}^{N_i} T_{\mathrm{ini,EXP-TC}}(i) - T_{\mathrm{ini,EXP-NOTC}}(i), \tag{1}$$

$$T^{\mathrm{REC}} = \sum_{i=1}^{N_r} T_{\mathrm{rec,EXP-NOTC}}(i) - T_{\mathrm{rec,EXP-TC}}(i), \tag{2}$$

$$D_{\mathrm{ave}} = \frac{\sum_{i=1}^{N_d} D_d(i)}{N_d}, \tag{3}$$

$$D_{\mathrm{diff}} = \sum_{i=1}^{N_d} D_{d,\mathrm{EXP-NOTC}}(i) - D_{d,\mathrm{EXP-TC}}(i), \tag{4}$$

$$T_{\mathrm{late}} = \frac{T^{\mathrm{INI}}}{N_i}, \tag{5}$$

$$T_{\mathrm{early}} = \frac{T^{\mathrm{REC}}}{N_r}. \tag{6}$$

3. Results

a. Summary of the Atlantic HURDAT database

The majority of landfalling TCs during 1980–2007 were tropical storms (33%) and category 1 hurricanes (27%), with 30% of all TCs occurring in August and September (Fig. 2). The greatest number of landfalling

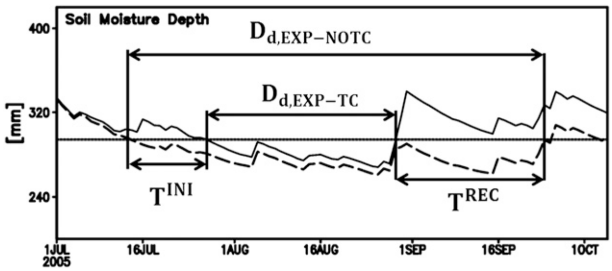

FIG. 1. Example of total column soil moisture time series from 1 Jul to 5 Oct 2005. The solid line represents soil moisture from the EXP-TC simulation and dashed line represents the EXP-NOTC simulation. Drought characteristics are described in the text.

TCs during 1980–2007 occurred in 2004, with eight out of the total of nine TCs occurring between August and September. The number of landfalling TCs has increased since 1995 (number of hurricanes in 1980–94 = 19; 1995–2007 = 26) and there have been more during the early TC season from May to June (number of TCs in 1980–94 = 6; 1995–2007 = 16). Summaries of landfalling TCs can also be found in several previous studies (Landsea et al. 1996; Hart and Evans 2001; Goldenberg et al. 2001; Shepherd et al. 2007; Landsea et al. 2010; Prat and Nelson 2013).

b. *Contribution of TC-related rainfall to total rainfall*

Four study regions were identified for further analysis based on the intensity and frequency of TC-related rainfall and their contributions to total precipitation: the Southeast (SE), South, Northeast (NE), and Midwest (MW) regions (Fig. 3a). The South region had the most intense TC rainfall over our study regions due to the longer residence time as derived from the total number of TC days (not shown) divided by the total number of TCs. There is a local maximum in TC rainfall intensity (>50 mm per event) over Oklahoma and Texas.

TCs have strong interannual and spatial variability because they are randomly occurring meteorological phenomena (Goldenberg et al. 2001). TCs contributed from 1% (1.5%) to 4% (7%) of annual (TC season) rainfall (Fig. 4a) and the seasonal timing of landfalling TCs varied (Fig. 4b) depending on the region. The maximum annual (TC season) contribution of TCs were 20% (28%), 17.7% (33%), 11% (17%), and 10% (17%) for the SE, South, NE, and MW regions, respectively, with the year of maximum occurring mostly in 2004 or 2005. The SE, NE, and MW regions showed increased contributions of TC-related rainfall in recent years whereas the South region showed relatively consistent contributions of TC-related rainfall over time. Rodgers et al. (2001) found that TCs contribute 4% of cumulative rainfall over the western North Atlantic and the southern and southeastern United States, which is in line with our results.

While TCs play an important role over the eastern United States for heavy rainfall events (Shepherd et al. 2007; Knight and Davis 2009; Barlow 2011), our results show that their contributions to annual and TC-season total rainfall are small compared to non-TC-related rainfall (Table 1). Furthermore, there is large interannual variability in the TC-related rainfall. Except for the SE region, the regional standard deviations in TC-related rainfall are larger than their averages (Table 1) and the contribution for active TC years can be considerable. For example, TCs contributed 10% and 17% of annual and TC season total rainfall, respectively, over the MW region during the most active TC year of 2005.

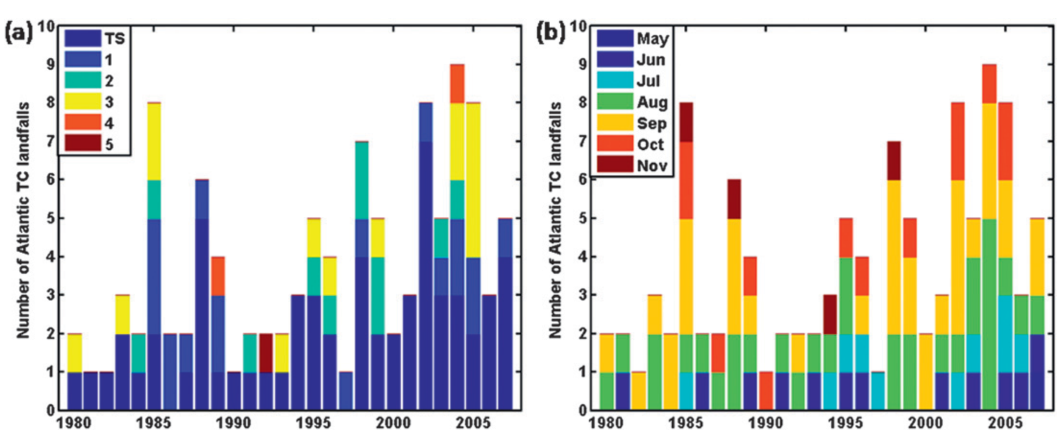

FIG. 2. Annual total number of Atlantic TC landfalls by (a) category and (b) timing vs month over the United States for 1980–2007. Numbers stand for the Saffir–Simpson hurricane wind scales and TS represents tropical storm. This scale is based on the speed of sustained winds and for winds (km h^{-1}) is: category 1: 119–153, category 2: 154–177, category 3 (major): 178–208, category 4 (major): 209–251, and category 5 (major): 252 or higher.

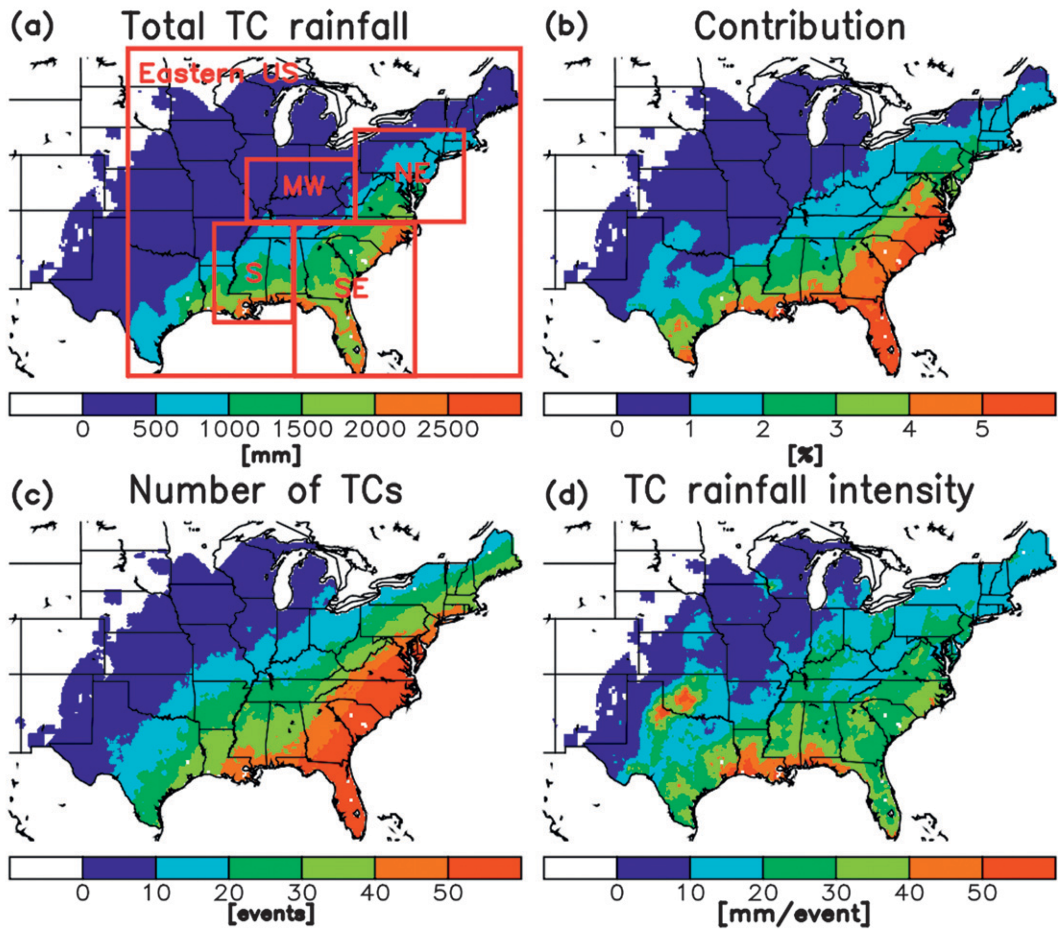

FIG. 3. Maps of Atlantic TCs and related rainfall for 1980–2007 over the eastern United States: (a) total TC-related rainfall, (b) the contribution of TC-related rainfall to total rainfall, (c) the frequency of TCs, and (d) TC rainfall intensity. The study regions and the units for the maps are shown in the boxes and the text, respectively.

c. Climatology of precipitation and soil moisture

In general, the seasonal cycle of precipitation drives the seasonal vegetation and soil moisture dynamics (Eagleson 1978) and is modulated by the seasonal cycle of solar radiation through atmosphere–land interactions that drive evapotranspiration (Yeh et al. 1998; Dai et al. 2004; Amenu et al. 2005). Our results indicate that the study regions have a seasonal cycle of soil moisture that has a peak during spring and then decrease until late summer and early fall due to high evaporative demand (Fig. 5b), whereas they have diverse seasonality of precipitation (Fig. 5a); that is, the subtropical region (30°–33°N) has two peak wet seasons (January–March and June–August) but the midlatitude region has a single peak wet season from April to August. Although TC-related rainfall is small (<5% of annual total), the TC season is generally coincident with the driest soil moisture conditions and thus is likely to have a significant impact. Furthermore, the high interannual variability in TC activity means that their influence will also vary greatly.

d. Impact of TCs on drought

1) A CASE STUDY AT POINT SCALES: HURRICANE KATRINA (2005)

We demonstrate the impact of TCs on drought by showing results for Hurricane Katrina in 2005 and its impact on drought at local scales by a comparison between the EXP-TC and EXP-NOTC simulations. In Fig. 6, the shaded regions indicate the spatial extent of drought on 31 August 2005. Here, drought was defined in terms of soil moisture lower than the 20th percentile of monthly average soil moisture from the EXP-TC simulation. Along the path of the hurricane, three points (points 1–3) were selected to examine its maximum impact on local scale droughts as it tracked inland. Each point experienced a different impact on drought: 1) late drought initiation, 2) weak drought persistence,

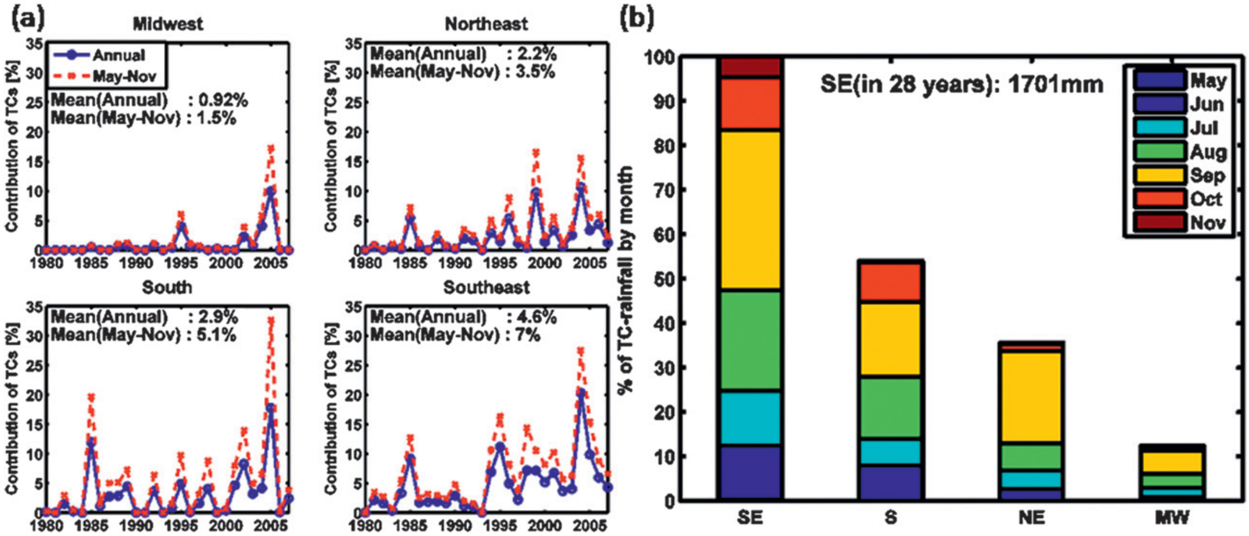

FIG. 4. (a) Regional contributions of TC-related rainfall to annual (blue line) and TC-season (red line) total rainfall. The average contribution of TCs to annual and TC-season total rainfall is given in the top left corner of each panel. (b) The relative size of TC-related rainfall over each region compared to total TC-rainfall over the SE region (100%) by month.

and 3) early drought recovery, shown in Fig. 7. The time period of the drought analysis is the same for each point, from 1 May 2005 to 31 December 2005. Point 1 (31.1°N, 89.6°W; Fig. 7a) had a large peak in total soil moisture on 29 August due to the intense rainfall from Katrina (over 100 mm). This caused soil moisture to take 11 days longer to reach the threshold value for drought in the EXP-TC simulation than from the EXP-NOTC simulation. The soil moisture time series from both simulations merged together in mid-November because of losses to evapotranspiration during the summer and fall, and lack of rainfall after Katrina. Winter rainfall resulted in drought recovery in both simulations. Point 2 (35.6°N, 88.0°W; Fig. 7b) had multiple TCs in 2005. Katrina brought the second most intense rainfall (over 45 mm) out of all TC events that was much lower than at point 1 because point 2 was farther inland. Tropical Storm Arlene (8–13 June) introduced the most intense rainfall (over 50 mm) to point 2. During May, low non-TC-related rainfall led to large decrease in soil moisture with drought initiation in mid-May. Without the contribution of TCs, the drought did not recover until winter with a total duration of drought of about seven months. With multiple TCs the drought initiated three months later and terminated 14 days earlier and therefore point 2 in the EXP-TC simulation experienced only a 3-month drought. At point 3 (40.0°N, 82.9°W; Fig. 7c), low non-TC rainfall initiated drought conditions in mid-July before Hurricane Katrina alleviated drought in late August by one month earlier than in the EXP-NOTC simulation. That is, heavy rainfall from the TC can terminate the drought immediately while non-TC-related rainfall accumulates slowly and thus local drought recovers later.

2) REGIONAL DROUGHT ANALYSIS

The average duration of drought per event is shown in Fig. 8 as the distribution of values over each region. We show results for six types of drought during two periods, 2004–05 and 1980–2007. Because of the large interannual variability of Atlantic TCs as shown above, we focused on the most active TC years (2004–05) to show the maximum impact on drought due to TC frequency alone. Rainfall from Atlantic TCs sometimes affects soil moisture until early spring of the next year while the

TABLE 1. Climatology for annual total rainfall, non-TC-related rainfall, and TC-related rainfall and their standard deviations for the period 1980–2007. Percentages of non-TC-related and TC-related rainfall are shown in parentheses.

Region	Area (10^3 km^2)	Annual		Non-TC related		TC-related	
		Mean (mm)	Std dev (mm)	Mean (mm)	Std dev (mm)	Mean (mm)	Std dev (mm)
Midwest (36°–41°N, 90°–81°W)	394	977	104	968 (99)	105	9 (1)	20
Northeast (36°–43°N, 81°–72°W)	387	1148	141	1122 (98)	134	26 (2)	34
South (29°–36°N, 93°–86°W)	389	1395	174	1355 (97)	182	40 (3)	53
Southeast (25°–35°N, 86°–76°W)	475	1319	152	1258 (95)	157	61 (5)	59

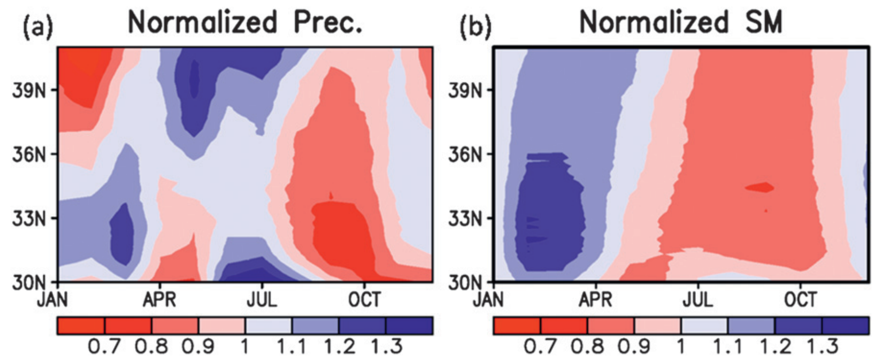

FIG. 5. Seasonal cycle of zonal averages (93°–73°W) of (a) monthly precipitation and (b) monthly total column soil moisture normalized by the mean of monthly precipitation and soil moisture depth from 1980 to 2007 along 30°–41°N (y axis).

TC season usually starts in late May and ends in early November (not shown). Hence, our drought analysis period for 2004–05 was from 1 May 2004 to 30 April 2006. For each region, the average duration of drought per event [Eq. (2)] for 1980–2007 was used as a reference to evaluate the impact of TCs during the most active TC years, 2004–05. For moderately severe short-term (long-term) droughts, the medians of the average durations derived from Eq. (2) were 53 (119), 54 (120), 56 (122), and 52 (122.5) days over the SE, South, NE, and MW regions, respectively, in the EXP-TC simulation for the period 1980–2007. Over all regions, the median drought duration was reduced by two weeks for increasing drought magnitude from moderately severe to extremely severe drought. In the EXP-NOTC simulation, however, the MW and South regions for 2004–05 had longer median values of the average durations of long-term droughts than those of their regional climatology. Comparison of the EXP-TC and EXP-NOTC simulation showed that Atlantic TCs in 2004–05 reduced the duration of moderately severe long-term droughts over the MW and South regions by one month, respectively. However, their impact on the SE and NE droughts was still minor since enough rainfall was provided during the warm season from other weather systems, including squall lines and mesoscale convective complexes (Knight and Davis 2009).

Given a drought in the EXP-TC simulation, its duration in the EXP-NOTC simulation will be extended

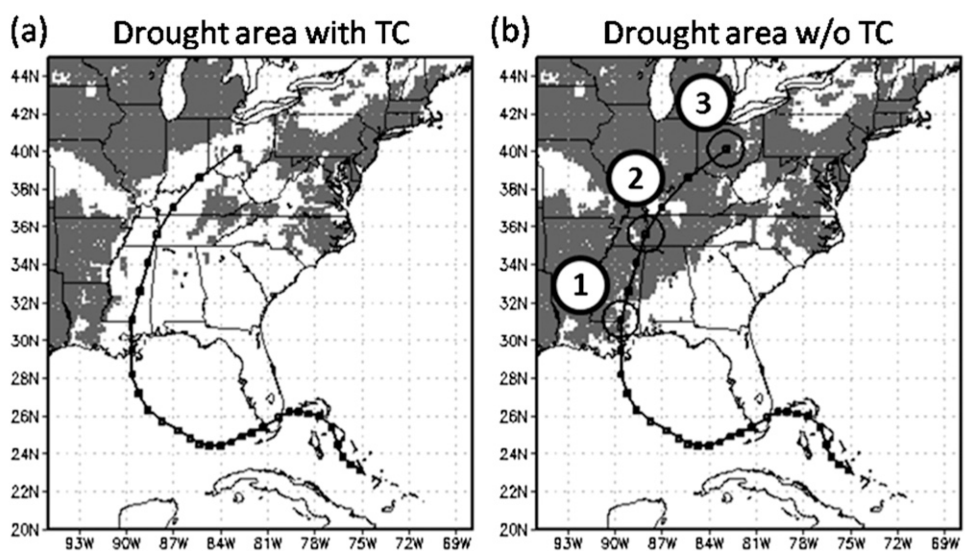

FIG. 6. Land surface conditions on 31 Aug 2005 from the (a) EXP-TC and (b) EXP-NOTC simulations along the path of Hurricane Katrina. Gray shaded areas represent dry soil moisture conditions that are less than the 20th percentile of monthly soil moisture for each grid cell. The three grid cells indicated on the path of Hurricane Katrina are used to analyze the impact of the hurricane on drought at local scale in Fig. 6b.

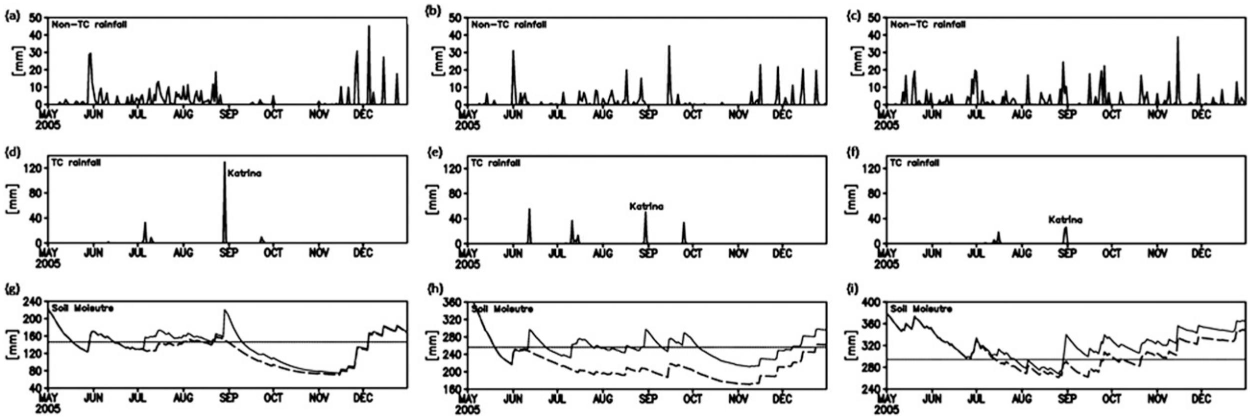

FIG. 7. Time series of (top) non-TC-related rainfall and (middle) TC-related rainfall for the three grid cells shown in Fig. 6: (a),(d): point 1; (b),(e) point 2, and (c),(f) point 3. (bottom) Time series of daily total column soil moisture from the EXP-TC simulation (solid line) and the EXP-NOTC simulation (dashed line) at the three grid cells: points (g) 1, (h) 2, and (i) 3; the solid straight line represents the 20th percentile soil moisture value calculated from the monthly simulated soil moisture in the EXP-TC run. The analysis period is from 1 May to 31 Dec 2005.

because of the lack of TC-related rainfall. The extended duration of drought in the EXP-NOTC simulation is partitioned into early drought initiation and late drought recovery. Comparison of the regional distributions of the average late drought initiation and average early drought recovery induced by TCs (Fig. 9) shows almost no difference in the regional median values for the SE and NE regions between 2004–05 and 1980–2007. The SE and NE regions had a slightly higher median value of late drought initiation days than the median of early drought recovery days in 2004–05, while TCs during 1980–2007 give a higher median value of early drought recovery than late drought initiation. This implies that TCs can play different roles in drought initiation and recovery over a region because of the large interannual variability in the number and timing of TCs. Over the South region, the spread of the distribution for average late drought initiation days for 2004–05 increased as the drought threshold increases, whereas the distribution for average early drought recovery did not change its shape regardless of the threshold. In other words, TCs caused the initial seasonal drying of the daily soil moisture in the southern United States to be shifted later.

Our results indicated that more than 50% of the NE, ME, and South regions experienced short-term drought in both simulations during 2004–05 (Fig. 10). However, TCs forced a decrease in the spatial extent of extremely severe short-term drought in the SE and MW regions to decrease from 50% to 25% and from 80% to 50%, respectively. This indicates that TC-related rainfall during 2004–05 plays a critical role in modulating extremely severe drought over these regions. About half of the long-term droughts (>90 days) over all the regions were terminated by rainfall from TCs. For example, there were two or three long-term droughts without TCs and one or two droughts with TCs, depending on the region. A greater fraction of the SE and NE regions experienced late drought initiation rather than early drought recovery whereas 40% of the South region experienced early drought recovery rather than late drought initiation. The MW region had an equal benefit of late drought initiation and early drought recovery of extremely severe short-term drought from TCs during 2004–05.

During the period 1980–2007, the average numbers of short-term and long-term droughts over all four region were 17 and 6 (22 and 7.5), 15 and 3 (16 and 4), and 11 and 1.7 (12 and 2.6) for moderately severe short-term and long-term drought, respectively, in the EXP-TC (EXP-NOTC) simulation (Fig. 11). Over the MW region, TCs decreased the occurrence of extremely severe long-term droughts from three to one over 1980–2007. The South region had the same number of events of severe and extremely severe long-term droughts in both simulations because only two types of drought occurred over the South: either moderately severe or extremely severe long-term droughts.

3) AREAL DISTRIBUTION OF TC IMPACTS BY REGION

Figure 12 shows the area fraction of each region that exceeds a certain difference in the total duration of drought (D_{diff}), drought initiation times (T^{INI}), and drought recovery times (T^{REC}) over the period 1980–2007 between the EXP-TC and EXP-NOTC simulations for different types of drought. TCs reduced the duration

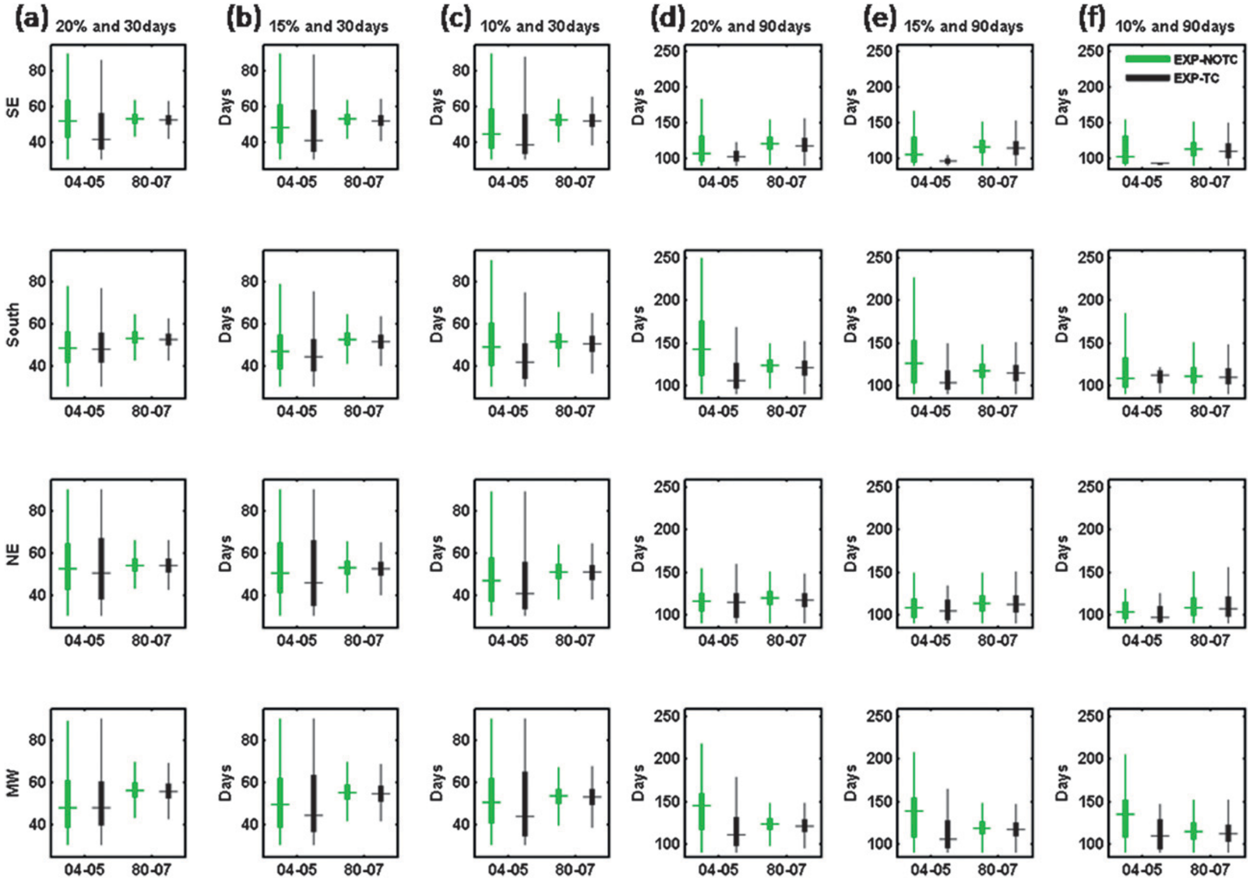

FIG. 8. Regional distributions for average duration of drought per event during 2004–05 (first two bars in each panel) and 1980–2007 (last two bars) for (a)–(f) six different types of drought and (top to bottom) four regions. Black bars represent the EXP-TC simulation ($D_{\mathrm{ave,EXP\text{-}TC}}$) and green, the EXP-NOTC simulation ($D_{\mathrm{ave,EXP\text{-}NOTC}}$). The horizontal line represents the median and the box represents the interquartile range [third quartile (q_3) − first quartile (q_1)] over the region. The vertical line represents the range between $q_1 - 1.5(q_3 - q_1)$ and $q_3 + 1.5(q_3 - q_1)$.

of moderately severe short-term droughts by 90 days (10%), 130 days (9%), 150 days (14%), and 180 days (16%) over 50% of the MW, NE, South, and SE regions, respectively. The ordering of the regions follows that of the regional contribution of TCs to total rainfall. The percentages in parentheses are calculated as the difference of total duration of drought between the two VIC simulations relative to EXP-NOTC simulation. For moderately severe long-term drought, the area of each region that exceeds a certain difference in total drought duration between the two simulations decreased rapidly as the threshold increased with less spatial variation among the regions. For more than 50% of our four study regions, TCs decreased the total duration of moderately severe long-term drought by more 150 days. For moderately severe short-term drought, more than half of the SE region had total late drought initiation days of greater than 30 days and more than 50% of the South region had total early drought recovery days by 42 days.

4) Spatial patterns of drought occurrence, late initiation, and early recovery

Late initiation and early recovery of drought can provide economic benefits to agriculture especially if they coincide with key times during the growing season, although TCs can also impart agricultural losses through direct physical damage on crops and flooding. In Fig. 13, we showed spatial distributions of differences in drought duration (D_{diff}; Figs. 13a,e), the area with significant changes in drought durations based on a Wilcoxon signed rank test at the 90% level (Figs. 13b,f), the total late drought initiation durations (T^{INI}; Figs. 13c,g), and total early drought recovery durations (T^{REC}; Figs. 13d,h) during the period 1980–2007 for moderately severe short-term and long-term droughts, respectively. We presented the results only for moderately severe drought, since the spatial patterns are similar for other types of

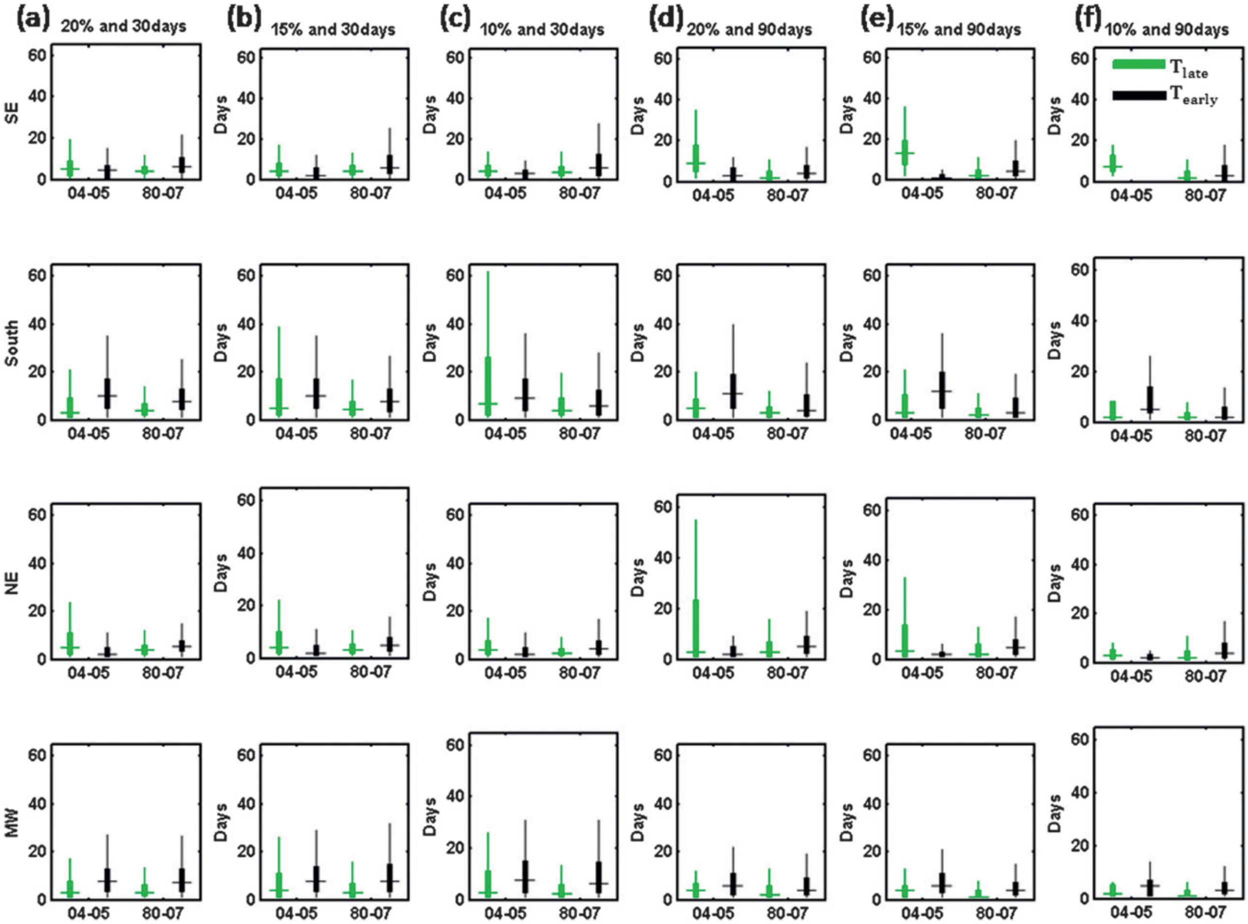

FIG. 9. The difference between the EXP-TC and EXP-NOTC simulations [first two bars in each panel (last two bars) for 2004–05 (1980–2007)] for drought initiation (T_{late}; green bars) and drought recovery (T_{early}; black bars) times for (a)–(f) six different types of drought and (top to bottom) four regions. The box and whiskers are as in Fig. 8.

drought (not shown). During the period 1980–2007, TCs reduced the duration of moderately severe long-term droughts by more than 150 days (>15% of the total drought duration from the EXP-TC simulation during the period) while their impact on short-term droughts was small (<10%) on a regional basis (Table 2). The Wilcoxon singed rank test showed that there were statistically significant reductions in the annual total duration of short-term droughts for the SE region at the 90% significance level. The results for moderately severe long-term droughts are limited by the small sample size of coincident TCs and drought events at the grid scale. TCs delayed drought mainly along the Gulf of Mexico and the mid-Atlantic coasts and the South and NE regions have more early recovery days than other regions. There were local minimums for drought initiation around Atlanta, Georgia, and for drought recovery along the Appalachian Mountains, respectively. Possible explanations for the location of these minimums included the local minimum of the contribution of TCs over the region (Fig. 4) and the topographic effect on the tracks of TCs as shown in model simulations by O'Handley and Bosart (1996). Still, understanding the mechanisms of how TCs move across land is a challenge for predicting and forecasting not only tracks of TCs, but drought initiation and recovery as well (Lin et al. 2006).

5) Comparison between droughts in 2000–01 and 2004–05

We explored whether the SE droughts were more severe when TCs were less frequent by comparing data for 2000–01 and 2004–05, which were less and more active TC periods, respectively. The SE region had total TC-related (non-TC related) rainfall of 90 mm (2531 mm) over 2000–01, and 318 mm (2609 mm) over 2004–05. In 2000 and 2001, a high pressure anomaly over the central United States blocked moisture fluxes from the Gulf of Mexico and reduced moisture convergence over the

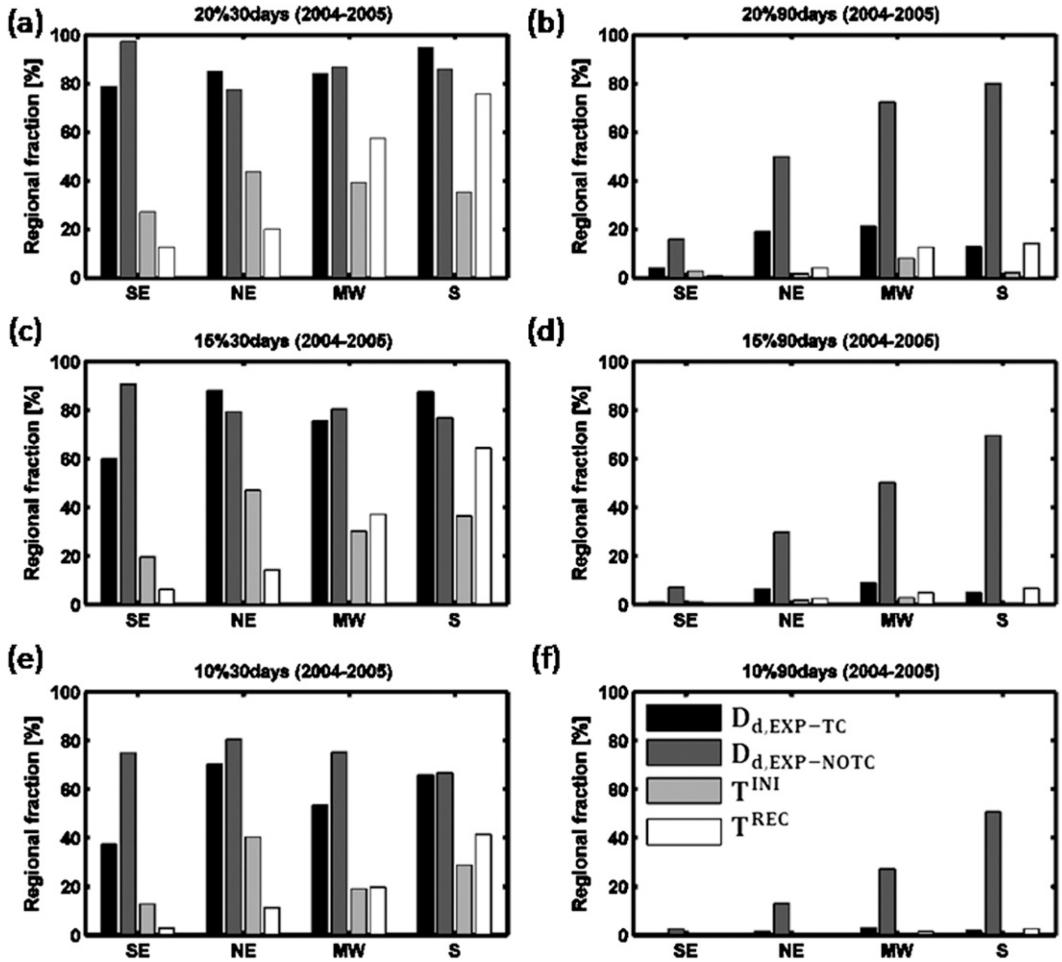

FIG. 10. Fractions of grid cells over the four study regions (vertical bars) that experienced drought, late drought initiation, and early drought recovery at least once in 2004–05 from the EXP-TC and EXP-NOTC simulation. The quantities $D_{d,\text{EXP-TC}}$ and $D_{\text{ave,EXP-NOTC}}$ represent the areal fractions that experienced drought from the EXP-TC simulation and the EXP-NOTC simulations, respectively; T^{INI} and T^{REC} are the areal fractions that experienced late drought initiation and early drought recovery days, respectively, during 2004–05: (a) 20% and 30 days, (b) 20% and 90 days, (c) 15% and 30 days, (d) 15% and 90 days, (e) 10% and 30 days, and (f) 10% and 90 days.

southeastern United States (Liu et al. 2004), and thus non-TC rainfall was below normal. At the same time, it introduced less cloudiness and more evaporative demand. This period also experienced a lack of TCs (a total of three tropical storms and two hurricanes). As a result, severe drought was reported over the SE region and its estimated cost from agriculture losses was \$689 million (NCDC 2012). What if the TCs of 2004–05 (a very active TC period) occurred over the SE region during 2000–01? We compared the average duration of drought per event during 2000–01 and 2004–05 (Fig. 14) to gain an insight into how much more severe droughts were when TCs were less frequent over the region. This showed a large change in average duration. The SE region experienced more severe short-term and long-term drought during 2000–01 than during 2004–05 due to less TC-related precipitation for 2000–01 than for 2004–05.

4. Discussion

a. *Uncertainties in data sources*

There are a number of uncertainties in the approach that we use that warrant discussion. We use a single land surface model, VIC, to assess the impact of TCs from the Atlantic basin on drought over the eastern United States. Other models could be used and would give different values of the statistics of the impact of TCs because of differences in their soil moisture parameterizations. However, the differences are likely to be small because different models produce similar patterns

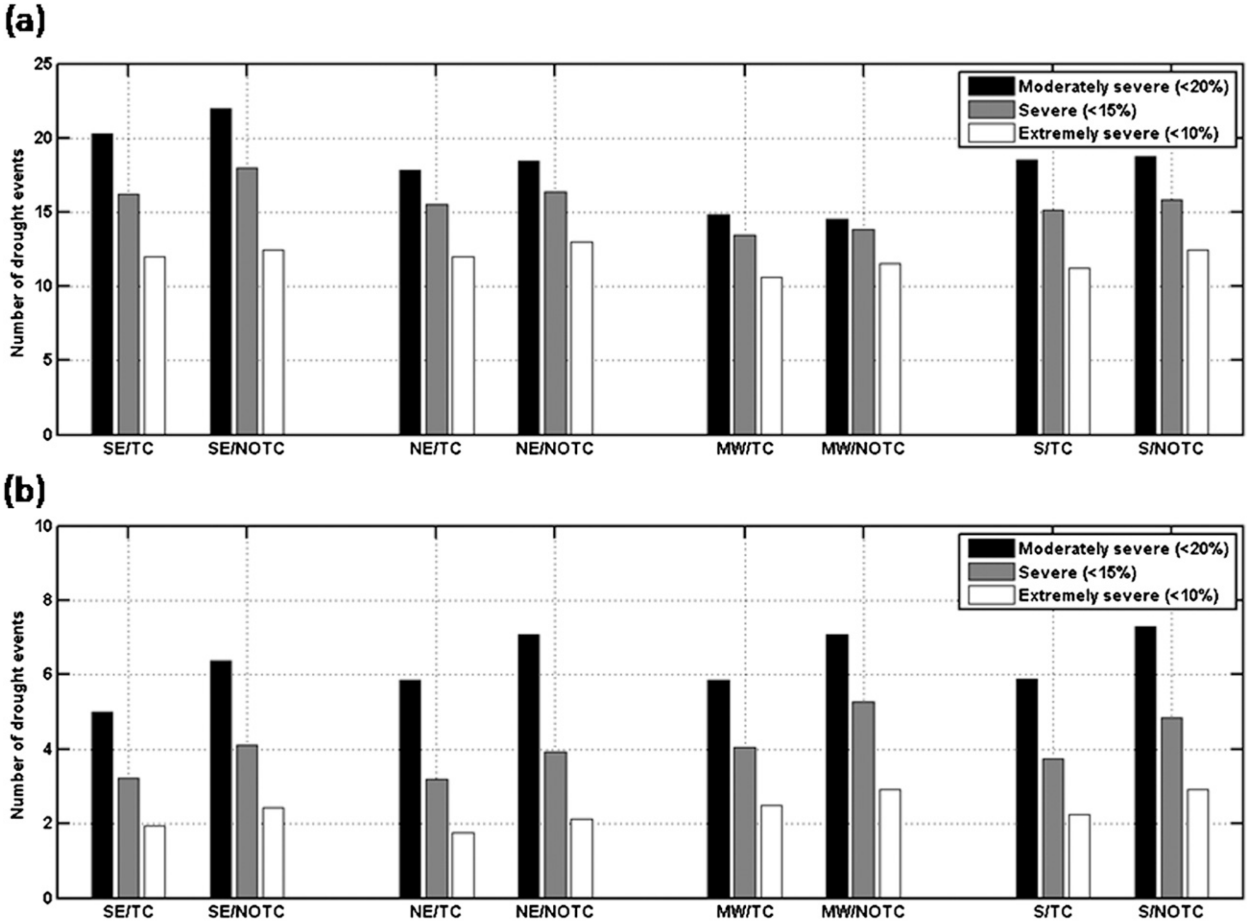

FIG. 11. Total number of (a) short-term and (b) long-term drought events by region average and types of drought. TC (NOTC) stands for the EXP-TC (EXP-NOTC) simulation for the period 1980–2007.

of drought at regional scales when forced by the same meteorological data (Mo 2008; Sheffield et al. 2012) and the overall conclusions of this study would likely be the same. Although multimodel comparisons indicate that there are broad-scale similarities, there still exist uncertainties from modeled soil moisture itself due to lack of knowledge about the role of soil moisture in the interaction between the land surface and atmosphere even though the capability of VIC to detect drought has been validated during the last two decades. The results are likely sensitive to the depth of the soil column considered, as upper soil layers respond more quickly to rainfall events than lower soil layers. This is pertinent to the choice of model because different models have different soil column depths, which affects the representation of drought dynamics (e.g., Wang et al. 2009, 2011), and therefore care must be taken when comparing results between models. We chose the total soil column as this is most representative of agricultural drought in terms of depth, but note that the impact of TCs on drought is likely higher for shallower soils and lower for deeper soils.

Uncertainties in the NLDAS-2 forcing data have been discussed by several previous studies, especially for heavy rainfall events. Villarini et al. (2011) found that the NLDAS-2 rainfall data have lower rainfall amounts than the stage IV multisensor radar data product. However, both datasets were able to detect TC-related rainfall events and the timing of their peaks for multiple TCs events in 2004. In that study (Villarini et al. 2011), the NLDAS-2 rainfall was found to be smaller than accumulated runoff interpolated from observed streamflow during September 2004 over regions affected by TCs, which could be considered as a lower boundary on accumulated rainfall. One of the reasons for the underestimation of rainfall in NLDAS-2 was gauge undercatch during heavy rainfall events with high winds (Xia et al. 2012). The NLDAS-2 rainfall forcing data were derived mainly from daily CONUS gauge data and these could be corrected with wind speed information

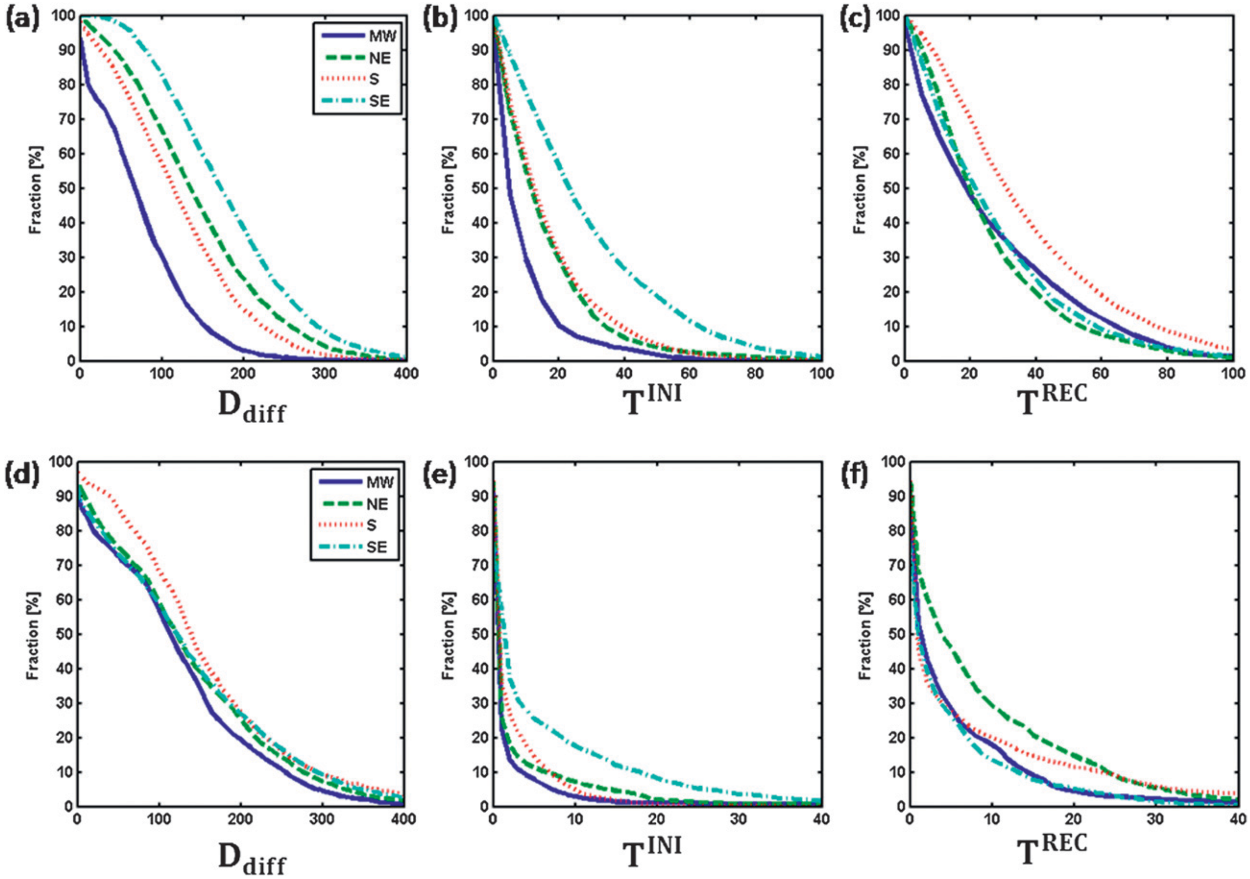

FIG. 12. The areal fraction of each region that exceeds certain differences of (a),(d) total drought duration (D_{diff}), (b),(e) drought initiation times (T^{INI}), and (c),(f) drought recovery times (T^{REC}) from the (a)–(c) EXP-TC and (d)–(f) EXP-NOTC simulations for 1980–2007.

using empirical corrections such as Medlin et al. (2007), although such methods are still uncertain. We therefore regard our results as conservative estimates of the rainfall associated with TCs and their impact on drought initiation and recovery was likely underestimated.

b. *Sensitivity of regional drought to TC frequency and TC rainfall intensity*

It is important to understand the sensitivity of drought to changes in TC frequency and TC rainfall intensity, given that TC frequency is highly variable from year to year, and in its spatial impacts. This is especially important in the context of potential future changes in TCs due to climate change (Trenberth 2005; Knutson et al. 2010). We evaluated the impact of changes in TC frequency and TC rainfall intensity on decreases in drought on a regional basis over 1980–2007. The frequency of TC events over the eastern United States ranged from 0 to 74 with the maximum occurring over the Florida peninsula. The TC rainfall intensities were 29, 30.8, 20, and 17.1 mm per event for the SE, South, MW, and NE regions, respectively, during the period. For each grid cell, we computed the Spearman rank correlation to measure the significance in the relationship between the TC metrics and drought duration. For all regions, there was a statistically significant linear relationship between TC frequency and decreases in duration (Fig. 15a; 99% level). Furthermore, the TC rainfall intensity was significantly positively correlated with the decrease in short-term droughts for all regions (Fig. 15b; 99% level). Only the MW region has a significant relationship between TC rainfall intensity and decreased duration of moderately severe long-term drought (correlation coefficient: 0.43). According to these results, more frequent intense TCs in the future would be expected to ameliorate short-term droughts over all regions and long-term droughts over the MW region.

c. *Past and potential future changes in TC impacts on drought*

Changes in the impact of TCs on drought over the past few decades are an important issue and especially given

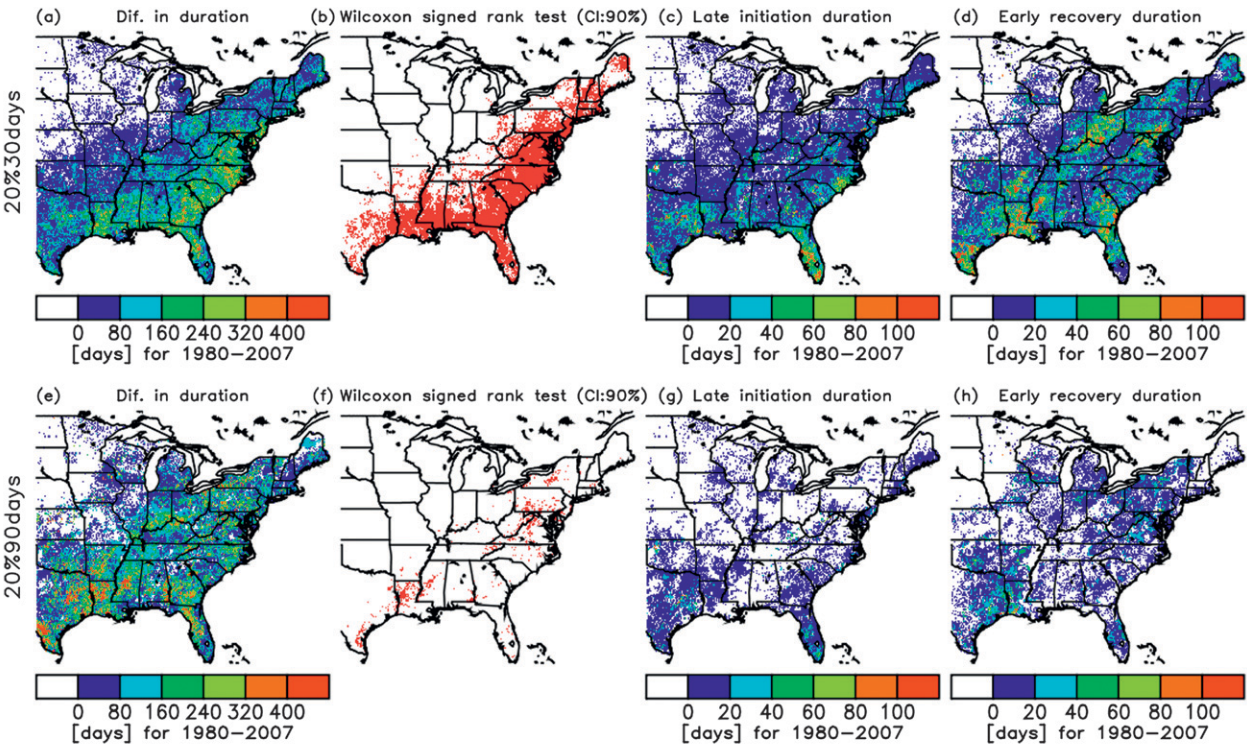

FIG. 13. Spatial distributions of each region that exceeds certain differences of (a),(e) total drought duration (D_{diff}); (b),(f) the area with significant changes in drought duration based on a Wilcoxon signed rank at the 90% level; (c),(g) the total late drought initiation duration (T^{INI}); and (d),(h) total early drought recovery duration (T^{REC}) for the period 1980–2007: (a)–(d) 20% and 30 days and (e)–(h) 20% and 90 days.

potential future climate change (Knutson et al. 2010; Sheffield and Wood 2008). This is complicated by the multiple competing factors on changes in TC impact, including changes in the frequency of landfalling TCs, their associated tracks, and footprint; changes in the intensity of TC rainfall; and changes in drought frequency, timing, and severity. It is also important to put this in the context of whether observed changes in TCs and drought are due to natural variability and/or anthropogenic influences, as this can help inform evaluations of climate models and assessments of their future projected changes. The attribution of changes in TCs to natural variability (Goldenberg et al. 2001; Elsner et al. 2008; Knutson et al. 2010), anthropogenic causes (Trenberth 2005), and other factors (Klotzbach 2006; e.g., improved observational technology) has been discussed extensively, but there remains considerable uncertainty as to the variability and anthropogenic impacts. Studies on trends over the last several decades have shown ambiguous results with both decreases (Chan and Shi 1996; Landsea et al. 1996) and increases (Goldenberg et al. 2001; Webster et al. 2005; Klotzbach 2006; Briggs 2007) in TC frequency depending on the study period, data sources, and metrics used. Analyses of the most recent 10–15 years indicate that the frequency and intensity of TCs have remained unchanged worldwide (Knutson et al. 2010) but have been more intense with a large increase in the North Atlantic (Knutson and Tuleya 2004; Elsner et al. 2008; Knutson et al. 2010).

While this implies that the impact on drought in the eastern United States has not changed due to TC frequency alone and especially over the period of this study for which observational data are more reliable and uniform, the other factors may be relevant and warrant further discussion. There appears to have been no trend in TC rainfall over 1980–2007 from our study, although this is masked by the high interannual variability in the TC statistics and subject to our interpretation of TC-related rainfall. However, during the last few decades, Atlantic TCs have contributed increasingly to extreme rainfall events over the coastal states along the Gulf of Mexico and the North Atlantic (Knight and Davis 2009). Based on the HURDAT database, landfalling tropical storms for the CONUS have become more frequent during May and June since 1995, when Atlantic TCs have been more active due to the warmer phase of the Atlantic multidecadal oscillation (Trenberth and Shea 2006). Also, the destructiveness of tropical cyclones in the North Atlantic has increased over the past three decades (Emanuel 2005). Droughts over the United

TABLE 2. Total number of days under the 10th, 15th, and 20th percentile moisture storage for the period 1980–2007. The difference as a percentage of the total duration of drought for EXP-TC simulations is shown in parentheses.

Region	EXP-TC Days (<20%)	EXP-TC >30 days duration	EXP-TC >90 days duration	(EXP-NOTC) − (EXP-TC) >30 days difference	(EXP-NOTC) − (EXP-TC) >90 days difference
Southeast (Total days: 10 227)					
20	2404	1074	607	99.7 (9.3)	173.1 (28.5)
15	1831	849	379	107.3 (12.6)	111.1 (29.3)
10	1290	625	219	101.4 (16.2)	58.4 (26.6)
South (Total days: 10 227)					
20	2299	974	710	27.5 (2.8)	192.3 (27.1)
15	1755	784	438	53.9 (6.9)	135.3 (30.9)
10	1238	572	255	77.2 (13.5)	79.2 (31.0)
Northeast (Total days: 10 227)					
20	2192	968	700	41.3 (4.3)	151.2 (21.6)
15	1670	820	366	53.4 (6.5)	89 (24.3)
10	1202	615	196	55.3 (9.0)	42.5 (21.7)
Midwest (Total days: 10 227)					
20	2167	815	938	15.5 (1.9)	154.6 (16.5)
15	1641	784	532	53.9 (6.9)	100.3 (18.9)
10	1158	564	287	54.9 (9.7)	53.1 (18.5)

States have not changed much over the twentieth century (Andreadis and Lettenmaier 2006), although regional changes are evident. For example, the Southwest and parts of the interior West have become drier, which has been attributed to warming temperatures, and it is estimated that drought has decreased in frequency, severity, and spatial extent over much of the rest of the United States, including the eastern United States, due to increases in precipitation over the second half of the twentieth century (Andreadis and Lettenmaier 2006). Therefore, although drought appears to have decreased in the region and TCs have remained stationary in their frequency, it is unclear whether TCs have contributed to these changes in drought because of uncertainty in the data, high interannual variability in TCs, and the intermittent temporal and spatial nature of TCs.

Although a climate change signal is not detectable in recent years for the North Atlantic, the future risk of TC-related disasters is expected to increase because warmer SSTs are expected to enhance the frequency of more intense TCs (Knutson and Tuleya 2004; Emanuel 2005; Trenberth 2005; Webster et al. 2005; Elsner 2008; Elsner et al. 2008; Knutson et al. 2010). Our analysis suggests more intense tropical cyclones, delivering more rainfall per event, would reduce the severity of droughts slightly across the region.

Future changes of TC impacts are also dependent on how drought might change. Projected changes in drought over the eastern United States indicate an overall increase in drought, although only changes in short-term droughts (4–6-month duration) are statistically significant because of the large range of projected changes across climate models (Sheffield and Wood 2008). The attribution of these changes is unclear at present because of the uncertainty across climate models and the complexity of controls on the eastern U.S. climate (Seager et al. 2009), but is partly due to an increase in the evaporative demand from a warmer atmosphere. Furthermore, climate models are generally unable to simulate realistic TC events and their historic frequencies (Sheffield et al. 2013, manuscript submitted to *J. Climate*), mostly due to their coarse resolution, and so most current climate models such as those that contributed to the recent phase 5 of the Climate Model Intercomparison Project (CMIP5; Taylor et al.

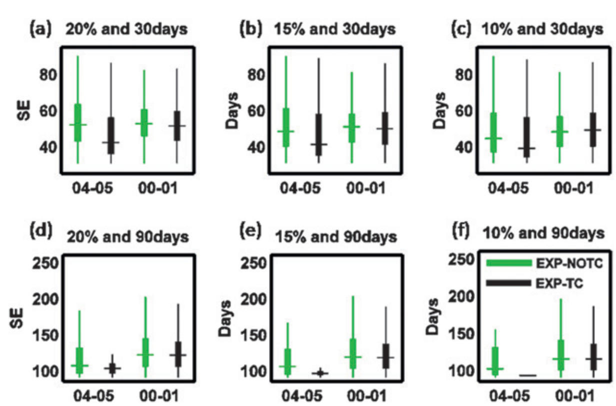

FIG. 14. As in Fig. 9, but for the analysis periods 2000–01 and 2004–05.

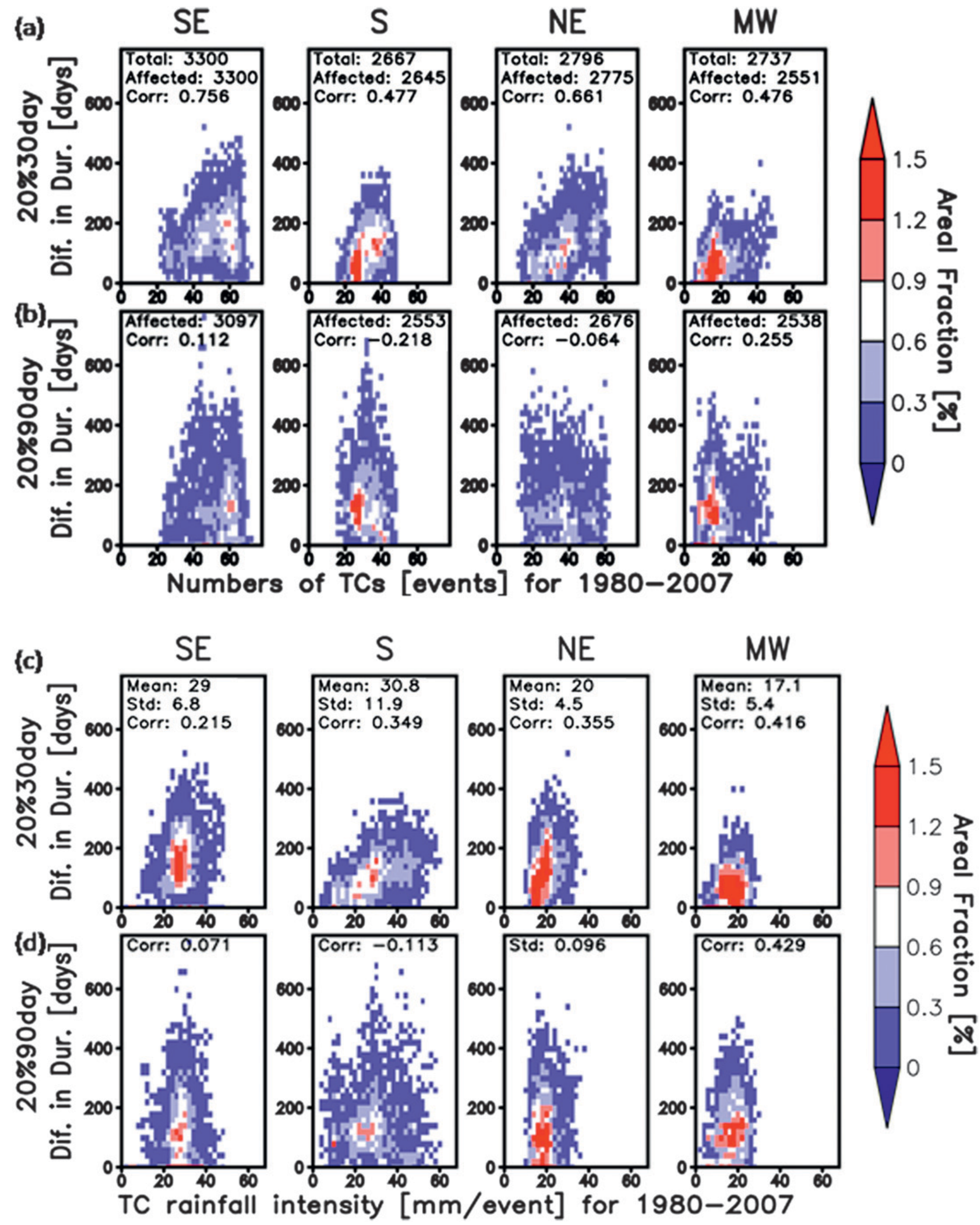

Fig. 15. Fractions of grid cells over the study regions that experienced the corresponding differences in drought durations from both simulations (D_{diff}) along with the (a),(b) frequency and (c),(d) intensity of TCs, respectively, for 1980–2007: (a),(c) 20% and 30 days and (b),(d) 20% and 90 days. Colors represent the percentage of a region. Each scatterplot represents total number of grid cells and affected grid cells by TCs; the Spearman rank correlation coefficients between differences in drought duration and TC metrics are shown in the text.

2012) are generally not able to give a realistic assessment of the impact of TCs on future drought. However, it is likely that TCs will play a more important role in the future as drought becomes more frequent and severe, irrespective of whether TCs change in frequency and intensity.

5. Conclusions

This study was the first that we were aware of to quantify the influence of TCs from the Atlantic basin on drought regime over the eastern United States. We used daily simulated soil moisture from a land surface model to show the impact of TC events, which were short-term and localized, on the longer-term and broad spatial scale of drought. We argued that the impact of TCs on drought cannot be appreciated properly without evaluation at the scale of the TCs, rather than at coarser scales such as monthly (Maxwell et al. 2012).

We found that the contribution of TCs to total rainfall was small over all four study regions (<6%) for the period 1980–2007 but was moderate (>15% of rainfall during the TC season) for very active TC years. The impact of TCs on drought included shorter drought duration, late drought initiation, early drought recovery, and an overall decrease in the spatial extent of drought. This was expected from our experimental setup because removal of rainfall, of any type, would increase drought duration, severity, and spatial extent. Other types of rainfall, such as convective systems and frontal storms, and even antecedent snowfall, will have (potentially more significant) impacts on drought than TCs. However, by their nature, TCs have a unique and identifiable impact on drought that is important to understand in isolation from other types of rainfall. At local scale, a single TC (e.g., Hurricane Katrina in 2005) can play very different roles in drought initiation, persistence, and recovery depending on the location, the timing of the TC relative to the drought event, the number of other TCs during the season, and the antecedent land surface state. At regional scale the impact of TCs on drought varied depending on the region, drought type, and year-to-year variation in TC activity. TCs decreased the duration of moderately severe long-term droughts by more than 150 days (15%) while their impact on short-term droughts was smaller (less than 100 days) on a regional basis. Over our study regions, they removed at least two short-term and one long-term drought events during the period 1980–2007. Also, they impeded drought initiation mainly along the coastline of the Gulf of Mexico and the Atlantic Ocean and advanced drought recovery, especially in the South and NE regions.

The linkages between TCs and drought have been poorly understood in the past because of their different temporal and spatial scales. This study used a quantitative approach to highlight the major role of TCs in drought relief at local to regional scales and therefore the possible benefits of what are usually devastating natural hazards to local communities and economies. A pertinent question is how future changes in TCs may affect drought regimes. The findings of Knutson et al. (2010) indicate that multiple climate models predict an increase in the frequency of intense tropical cyclones globally in the future but no increase in their overall number. Based on these results, we speculate that TCs will play a more crucial role in pluvial and drought regimes over the eastern United States in the future, both in terms of direct losses to infrastructure, property, and agriculture but also societal benefits from drought relief. Whether the direct benefits of TCs to drought relief will be offset by projected increases in drought frequency and intensity due to warming temperature and changes in non-TC rainfall (Sheffield and Wood 2008) is unclear.

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