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Reconciling droughts and landfalling tropical cyclones in the Southeastern United States

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Abstract A popular perception is that landfalling tropical cyclones help to mitigate droughts in the Southeastern United States (SeUS). However intriguing paradigms on the role of large scale SST variations on continental US including SeUS droughts and seasonal Atlantic tropical cyclone activity confronts us. These paradigms suggest that in the presence of warm (cold) eastern tropical Pacific and cold (warm) Atlantic Ocean sea surface temperature anomaly (SSTA) lead to the increased likelihood of wetter (drier) conditions over the continental US including the SeUS. Juxtaposing this understanding with the fact that landfalling tropical cyclones contribute significantly to the annual mean total rainfall in the SeUS and in El Niño (La Niña) years with cold (warm) tropical Atlantic SSTA lead to reduced (increased) Atlantic tropical cyclone activity raises a conflict on the role of the large-scale SST variations in SeUS hydroclimate. This study attempts to investigate the apparent dichotomous role of the large scale SST variations on the SeUS hydrology by examining the role of rainfall from landfalling tropical cyclones in the SeUS to local seasonal droughts. Our study finds that the contribution of the rainfall from landfalling tropical cyclone on the mitigation of monthly drought in the 28 SeUS watersheds is relatively insignificant. So much so that the hydrological model uncertainty in estimating the drought index over the 28 SeUS watersheds is larger than the sensitivity exhibited by the drought index to the inclusion of rain from landfalling tropical cyclone. The conclusions of this study are justified by the fact that the timing of the landfalling tropical cyclone in relation to overall soil moisture conditions of the watershed does not coincide with a drought like situation in the 1948–2006 time period analyzed in this study. This largely stems from the fact that the large-scale flow pattern resulting in abundant (lack of) advection of moisture for anomalously wet (dry) summer and fall seasons in the SeUS emanating from the source region of the Caribbean Sea and the northwestern tropical Atlantic Ocean coincides with the steering flow of the Atlantic tropical cyclones bound to make landfall in the SeUS (recurving away from the SeUS).

Keywords Atlantic hurricanes · Droughts · Teleconnection · Hydrology

1 Introduction

The Southeastern United Sates (SeUS[1]) is characterized periodically by droughts at various spatio-temporal scales and landfalling Atlantic tropical cyclones (TCs). Therefore a prevailing perception is that landfalling TCs play an

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1 For the purposes of this study, SeUS refers to the five states, which include Florida, Alabama, Georgia, South Carolina, and North Carolina. This definition of SeUS domain has also been used in several other earlier studies (Chan and Misra 2010; Tian and Martinez 2012; Bastola et al. 2013; Nag et al. 2014).

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important role in mitigating droughts in the SeUS. The purpose of this paper is to test the validity of this prevailing thought in relation to seasonal droughts over the SeUS in the summer and fall seasons that is coincident with the seasonal Atlantic TC activity at the scale of the relatively small watersheds of the SeUS.

Schubert et al. (2009) as part of the activity of US CLIVAR working group on drought led a multi-institutional effort to isolate the SST patterns that could force regional droughts over North America. This coordinated multi-model two-tier experiments of Schubert et al. (2009) demonstrated that: (a) there is a general tendency for reduced (enhanced) precipitation when forced with a cold (warm) Pacific, (b) similarly warm (cold) SST anomalies in the north Atlantic produce reduced (enhanced) rainfall anomaly patterns over US that are opposite to that forced by Pacific SST, albeit, the response to an Atlantic SST anomaly pattern is not as robust as the response to a Pacific anomaly, and (c) the largest precipitation response over the continental United States tends to occur when the two oceans have anomalies of opposite signs. That is, a cold Pacific and warm Atlantic tend to produce the largest precipitation reductions, whereas a warm Pacific and cold Atlantic tend to produce the greatest precipitation enhancements. It may be noted that the anomalies of rainfall referred in Schubert et al. (2009) extend well into the SeUS. Similarly Hoerling and Kumar (2003) from their modeling study attribute cold eastern equatorial Pacific and warm western Pacific and tropical Indian Oceans to widespread mid-latitude drying. Similarly, on multi-decadal timescales McCabe et al. (2004) indicate that a combination of positive Atlantic multi-decadal Oscillation and negative Pacific decadal oscillation leads to increased frequency of droughts in the continental US including over the SeUS.

On the other hand the same SST pattern of cold (warm) tropical Pacific and warm (cold) North Atlantic would lead to more (less) Atlantic TCs (Gray 1968, 1984; Goldenberg and Shapiro 1996; Fig. 1). In fact frequency of Atlantic TCs is correlated with Main Development Region (MDR; 5°–16°N; 20°–60°W) SST anomalies at around 0.7 (Fig. 1; Shapiro and Goldenberg 1998). This relationship partly manifests on account of the thermodynamic arguments, which relate to the fact that TCs rarely form below a threshold value of 26.5 °C (Palmen 1948; Gray 1968). However, Shapiro and Goldenberg (1998) also show that the variability of the SST's in the north tropical Atlantic is associated with the overlying vertical shear, which significantly affects the Atlantic tropical cyclogenesis. Similarly, it is generally seen that warm (cold) ENSO events produce less (more) active seasonal Atlantic tropical cyclone activity (Gray 1968; Kozar et al. 2013; Fig. 1). For example, during a warm ENSO event, stronger than normal westerly winds often occur at 200 hPa over the tropical North Atlantic Ocean resulting in stronger than usual vertical shear. As a consequence of these upper level anomalous winds, the (westward moving) thunderstorms that are necessary for the formation and subsequent development of TCs are sheared off, resulting in fewer geneses of TCs in warm ENSO years. Furthermore, Bove et al. (1998) show that the probability of two or more hurricanes making landfall in the US during an El Niño year is 21 % while in neutral and La Niña year it rises to 48 and 66 % respectively. In a related study Prat and Nelson (2013a, b) using Tropical Rainfall Measuring Mission multi-satellite precipitation analysis product 3B42 found that rainfall from TCs contributed 10–15 % of the total annual rainfall in Florida peninsula and 8–10 % along the eastern seaboard of US over the Carolinas region. Furthermore Knight and Davis (2009) indicate that the contribution of rainfall from tropical cyclone to extreme precipitation in the SeUS has increased significantly since 1972.

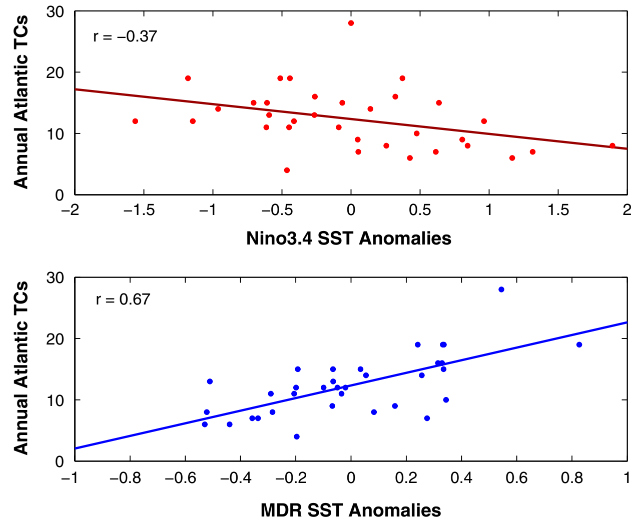

Fig. 1 Scatter plot of named Atlantic tropical cyclone counts (June–November) with corresponding Niño3.4 SSTA (*top*) and MDR SSTA (*bottom*) for the period 1979–2012

From the above discussions it is apparent that understanding and unraveling any existing synergy between the landfalling TCs and droughts in SeUS is important given their contrasting responses to large-scale SST variations in the Atlantic and in the Pacific Oceans. SeUS seems to be special in this regard as there are more landfalling TCs in this region than in other parts of the continental US (Knight and Davis 2009).

There are however a few studies that have specifically looked at the role of the landfalling TCs in mitigating SeUS droughts (Maxwell et al. 2012, 2013; Ortegren and Maxwell 2014). These studies variously conclude that there are "tropical cyclone drought busters" which mitigate prevailing droughts in the SeUS. Furthermore, Maxwell et al. (2013) found that a combination of positive Atlantic multidecadal oscillation and negative North Atlantic Oscillation led to higher frequency of these tropical cyclone drought busters as the former increased the likelihood of the intense cyclones and the latter increased the likelihood of steering the TCs towards the SeUS. These studies however examined the drought anomalies over the US climate division scale (Guttman and Quayle 1996), which is unlike this study that examines the impact on drought over 28 relatively small watersheds across the SeUS. The earlier studies have considered the ability of the TCs to ameliorate either multi-year or shorter term droughts, while in this study we will specifically be examining the impact on the monthly drought anomalies coinciding with the Atlantic tropical cyclone season (June–November).

2 Methodology

The differences of the drought index (DI) of this study from existing PDSI (https://climatedataguide.ucar.edu/climate-data/palmer-drought-severity-index-pdsi) is that a more complex hydrological model, generally suitable in modeling the rainfall runoff relationship at daily time scale is used instead of simple two layer bucket model used in the derivation of the original PDSI (Dai et al. 2004). The simple two-layer bucket model as used currently in the calculation of PDSI uses a very simple concept of a moisture availability parameter for computing evaporation that avoids the complexity of the surface resistance (Pitman 2003). The water balance model used in PDSI relies on reliable value of soil moisture capacity, which is a key soil parameter. Direct measurements of soil moisture capacity are expensive and time consuming. Therefore, psuedo-transfer function, based on available soil data such as particle size distribution, soil texture, and density, are used for the estimation of the soil moisture capacity. Therefore, estimation of PDSI is affected both by the uncertainty in model parameter i.e., soil moisture capacity, and oversimplification used for the representation of a complex hydrological process (Vicente-Serrano et al. 2011). Vicente-Serrano et al. (2011) argue that use of more complex hydrological models is suitable for simulating water balance, which is a key variable of PDSI index. However, different model structure result in different soil moisture dynamics (Mo 2008). Therefore, for this study, multiple, conceptual semi distributed lumped hydrological models are run, which have multiple soil moisture storage tanks at a temporal resolution of daily time step. This means that the meteorological forcing is allowed to vary in space, while the parameters of the hydrological model are lumped (and fixed) for a given watershed. This allows the inclusion of some spatial heterogeneity of meteorological inputs in the modeling framework. The model parameters will be estimated based on the model parameter estimation experiment (MOPEX) dataset (Schaake et al. 2006). Based on the model simulation with calibrated parameters, the climatically appropriate rainfall for each month (Eq. 1), defined in Palmer (1965) is estimated as:

$$
\begin{aligned}
&d = R_i - (\alpha PET_i + \beta PR_i + \gamma PRO_i + \delta PL_i) \\
&\alpha_j = (ETP/PET)_j, \quad \beta_j = (R/PR), \quad \gamma_j\,(RO/PRO)_j, \\
&\delta_j = (L/PL)_j,
\end{aligned}
\tag{1}
$$

where d is the departure of rainfall from climatologically appropriate value (Palmer 1965; and also serves as a soil moisture anomaly index), α, β, γ and δ are the climatic coefficient, ETP and PET are the actual and potential evapotranspiration, R and PR are recharge and potential recharge, RO and PRO are runoff and potential runoff, L and PL are loss and potential loss.

Hydrological models use a set of interrelated mathematical equations to aggregate spatially complex hydrological processes. The aggregation of processes, simplifications, lack of knowledge (with empirically determined parameters), and the stochasticity in hydrological models often result in hydrological prediction uncertainties (Beven et al. 2012; Clark et al. 2012). Owing to such uncertainty in model structure and parameters in hydrological models, it is a common practice to use multi-model hydrological simulations to obtain robust estimates of streamflow (Tingsanchali and Gautam 2000; Wagener et al. 2001; Bastola et al. 2011, 2013; Bastola and Misra 2014; Nag et al. 2014). The generalized likelihood uncertainty estimation (GLUE) method (Beven and Binley 1992) has been widely used in hydrological literature to quantify hydrological model uncertainty from multi-model simulations (Beven and Binley 1992; Freer et al. 1996; Bastola et al. 2011, 2013). GLUE is based on Monte Carlo simulation where a hydrological model is run with large number of model parameters sampled from its prior distribution. Contrary to optimization based approach, it embraces the fact that a range of values of model parameters can result in acceptable simulation and rejects the notion of existence of single best value of model parameter. The GLUE framework not only allows for quantifying uncertainty in model parameters but also allows combining multiple models.

This study uses the following three lumped conceptual rainfall runoff models: hydrologic model (HyMOD; Boyle 2001), Nedbør–Afstrømnings-model (NAM; Madsen 2000) and Tank model (TANK; Sugawara 1995). The three models have been widely used to simulate hydrological responses in watersheds located in various climatic regions (e.g., Tingsanchali and Gautam 2000; Wagener et al. 2001; Bastola et al. 2014; Bastola and Misra 2014). All three models quantify different components of hydrological cycle by accounting for moisture content in different but mutually interrelated storage.

HyMOD model is based on the probability distribution model of Moore (1985). The model has two sets of conceptual stores, one that partitions total precipitation into runoff and the other set of the store routes the flow from the point in watershed to the basin outlet. The routing component comprises of three identical reservoirs in series, which release the runoff quickly and is referred as quick reservoir. In parallel to these quick reservoirs there is a single reservoir, which releases the water to the stream slowly and is referred as slow reservoir. HyMOD assumes that watershed is composed of large number of points with varying stores in order to account for the variation of the soil moisture stores within the watershed.

NAM model is a conceptual rainfall runoff model where different components of the hydrological cycle are conceptually represented through four interrelated water storages namely snow storage, surface storage, lower zone storage and groundwater storage. The surface storage characterizes the water stored in vegetation, ground depression, and top soil. The lower zone storage represents water stored in root zone. The moisture content in lower zone plays a central role in NAM model as it controls the recharge and production of different flow components e.g., interflow, overland flow. The maximum size of surface and lower zone storage are the process based parameter for a watershed. In NAM model, the evapotranspiration occurs at potential rate from surface storage whereas the evapotranspiration from lower zone storage is proportional to the relative soil moisture content of lower zone storage.

TANK Model conceptualizes watershed using a number of linear and nonlinear tanks arranged vertically in series to model different components of the hydrological cycle. In this study, the TANK model with four vertical tanks is used. The top tank which represents the surface store is modeled as nonlinear tank i.e., tank with three side outlet positioned at three different levels. The bottom most vertical tank that represents the groundwater reservoir is modeled as a linear reservoir. The remaining two intermediate tanks partly discharge water to the tank immediately underneath them through bottom outlet and partly discharge water to the stream flow through side outlet. The level of each of the outlet, and coefficients are the process based parameters of tank model for a given watershed.

These models are applied on 28 watersheds spread across the SeUS (Fig. 2). These three models have been calibrated for these 28 SeUS watersheds (Bastola and Misra 2014). These watersheds are chosen for their minimal anthropogenic influence in terms of their water management and

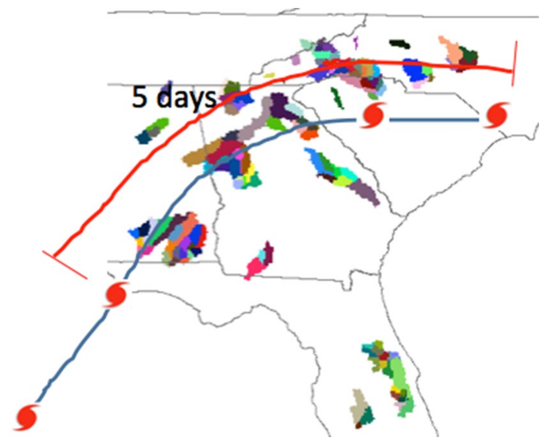

Fig. 2 The Southeastern United States (SeUS) domain used in the study with the outline of the 28 SeUS watersheds. A sample track of a landfalling tropical cyclone with the period of 5 days when rainfall in computing the Expt drought index is zeroed out is indicated for illustration purposes

are based on the MOPEX dataset (Schaake et al. 2006). Such pristine watersheds allow for better calibration of the hydrological models and are easier to interpret for impact assessments from meteorological events on hydrology as intended in this study. The MOPEX dataset excluded watersheds that were subject to diversion, transfer of water and significant change in land cover. The hydrological models are forced with the observed daily precipitation analysis of the Climate Prediction Center available at 0.25° resolution (Higgins et al. 2000). This dataset is available from 1948 to 2006 and was also used for the model calibration.

$$DI = C_i d \tag{2}$$

$$C_i = \frac{17.67\hat{C}_i}{\sum_{i=1}^{12} \bar{D}_i C_i}, \quad i = 1\ldots12 \tag{3}$$

$\bar{D}_i$ is the average absolute value of C and $\hat{C}_i$ is calculated using Eq. (4)

$$\hat{C}_i = 1.5Log10\left(\frac{X_i + 2.8}{\bar{D}}\right) + 0.5 \tag{4}$$

and X_i is calculated as a ratio of moisture demand to supply (Eq. 5)

$$X_i = \frac{(PET_i + R_i + RO_i)}{(P_i + L_i)} \tag{5}$$

The DI, which is a measure of the moisture level in the watershed is defined as a daily index of moisture anomaly estimated by scaling the departure of available moisture from climatically appropriate soil moisture value (d; see Eq. 1). The derivation of DI is similar to that of PDSI except that DI is based on daily hydrological simulation. So we expect that the monthly aggregated DI and PDSI value have similar range i.e., −10 to +10. Since, we only focus on SEUS and have not expanded the work to different regions, we expect that the daily DI range may exceed the typical range of PDSI. In this study the definition adopted in original Palmer DI is adopted i.e., a soil moisture anomaly index (DI; Eq. 2) is calculated by weighting d of Eq. (1) with a weighting factor (Eq. 3) so that results across the different region are comparable. For spatial comparability among different region (e.g., at global scale) of the index, it is appropriate to re-calibrate the coefficient of Eq. (3) for different climatic region (e.g., Wells et al. 2004). However, as we only focus on SeUS, we used the original coefficient used by Palmer (1965).

3 Experiment design

To understand the impact of rainfall from landfalling TCs on the DI, we computed control (Cont) and experimental (Expt) drought indices. The Cont DI followed the methodology explained in the previous section. The Expt DI was computed exactly in the same manner as Cont DI but with precipitation removed for 5 days from the time a tropical cyclone made landfall in the SeUS (anywhere from the Gulf coast of Alabama to the Atlantic coast of North Carolina). Here the assumption being made is that the tropical cyclone will traverse the inland SeUS watersheds at most within 5 days after landfall. We make the assumption that 5 days after landfall the tropical cyclone would either move out of the domain or lose its organization and status of a tropical cyclone. This is a very conservative estimate, as majority of the 71 identified TCs between 1948 and 2006 (listed in Table 1) traversed the region well under 5 days within the domain shown in Fig. 2. The density of the TCs expressed as the number of TCs per $1^\circ \times 1^\circ$ grid cell is shown in Fig. 3 for the time period of 1948–2006 using the 71 TCs (Table 1).

By way of selecting these landfalling TCs that made landfall anywhere in the domain shown in Fig. 2, we are supposedly neglecting TCs that skirt the coastline (especially along the Atlantic coast) whose center remains offshore but its rain bands are well within the coastal SeUS and we are ignoring day(s) before landfall when the outer rainbands of the tropical cyclone could be raining over the watershed. But of the 28 watersheds analyzed in this study only 6 are regarded as coastal watersheds (Table 2), which are most vulnerable to such events and the rest of the 22 are inland watersheds (Fig. 2). Furthermore a small minority of

Table 1 The list of coastal watersheds

S. no.	Basin (USGS ID)	Lon.	Lat.	Area (sq. mile)	River system
1	2296750	−81.9	27.2	1367	Peace River at Arcadia, FL
2	2329000	−84.4	30.6	1140	Ochlockonee River near Havana, FL
3	2365500	−85.8	30.8	3499	Choctawhatchee River at Caryville, FL
4	2375500	−87.2	31.0	3817	Escambia River near Century, FL
5	2236000	−81.4	29.0	3066	St. Johns River near Deland, FL
6	2202500	−81.4	32.2	2650	Ogeechee River near Eden, GA

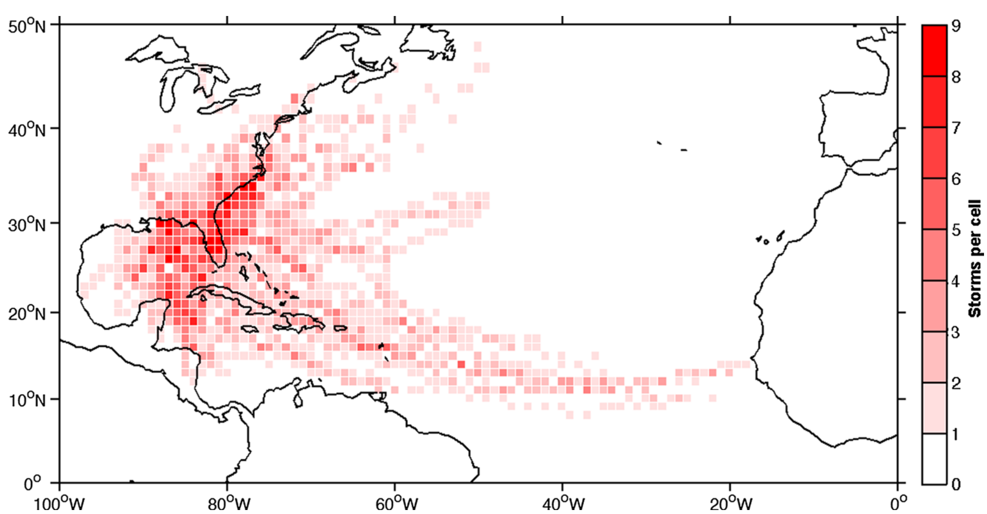

Fig. 3 The density of 71 named tropical cyclones that made landfall the SeUS between 1948 and 2006 expressed as number per $1^\circ \times 1^\circ$ cell

Table 2 The 71 Atlantic tropical cyclones that made landfall in the SeUS domain between 1948 and 2006

S. no.	Date	Name	S. no.	Date	Name	S. no.	Date	Name
1	8/31/1950	Baker	24	6/9/1966	Alma	48	8/16/1994	Chris
2	9/6/1950	Easy	25	9/17/1967	Doria	49	6/5/1995	Allison
3	10/18/1950	King	26	6/4/1968	Abby	50	8/2/1995	Erin
4	10/21/1950	Love	27	10/19/1968	Gladys	51	10/4/1995	Opal
5	10/2/1951	How	28	10/3/1969	Jenny	52	10/8/1996	Josephine
6	8/2/1952	Able	29	8/27/1971	Doria	53	7/19/1997	Claudette
7	6/6/1953	Alice	30	10/1/1971	Ginger	54	9/3/1998	Danielle
8	9/26/1953	Florence	31	6/19/1972	Agnes	55	9/22/2000	Helene
9	10/9/1953	Hazel	32	9/23/1975	Eloise	56	8/6/2001	Barry
10	10/15/1953	Hazel	33	8/19/1976	Dottie	57	9/14/2001	Gabrielle
11	8/12/1955	Connie	34	9/3/1979	David	58	9/5/2002	Edouard
12	8/17/1955	Diane	35	8/17/1981	Dennis	59	10/11/2002	Kyle
13	9/25/1956	Flossy	36	9/13/1984	Diana	60	9/6/2003	Henri
14	9/8/1957	Debbie	37	9/27/1984	Isidore	61	8/12/2004	Bonnie
15	7/9/1959	Cindy	38	6/23/1985	Bob	62	8/14/2004	Charley
16	9/29/1959	Gracie	39	10/10/1985	Isabel	63	9/6/2004	Frances
17	10/8/1959	Irene	40	10/31/1985	Juan	64	8/29/2004	Gaston
18	10/18/1959	Judith	41	11/22/1985	Kate	65	9/16/2004	IVAN
19	7/29/1960	Brenda	42	8/17/1986	Charley	66	9/26/2004	Jeanne
20	9/10/1960	Donna	43	8/29/1988	Chris	67	6/11/2005	Arlene
21	8/27/1964	Cleo	44	11/23/1988	Keith	68	7/10/2005	Dennis
22	9/10/1964	Dora	45	9/22/1989	Hugo	69	10/5/2005	Tammy
23	10/14/1964	Isbell	46	7/3/1994	Alberto	70	6/13/2006	Alberto
			47	7/20/1994	Unnamed	71	9/1/2006	Ernesto

TCs (~4) that skirt the Atlantic coasts of Florida, Georgia, and the Carolina's have been ignored during the period of study (1948–2006).

A severe constraint than intended to assess the sensitivity of the tropical cyclone rainfall on SeUS droughts is imposed by removing the precipitation for all watersheds of the SeUS (shown in Fig. 2) for the 5 days succeeding the time of the landfall of a tropical cyclone. In other words, this assumption implies that the tracks of all 71 TCs are alike, which affects all of the 28 SeUS watersheds simultaneously. If the differences between Cont and Expt are found to be negligible despite this rather severe (and unrealistic) assumption then the conclusion of negligible impact of landfalling TCs on seasonal droughts of the SeUS is going to be far more persuasive or sustainable. From Table 2 we find that there are 8, 6, 16, 21, 17, and 2 landfalling TCs in June, July, August, September, October, and November from 1948 to 2006 in the SeUS domain respectively. This follows the well known seasonal cycle of the Atlantic tropical cyclone activity. Figure 3 shows the storm density on $1^\circ \times 1^\circ$ cell (or grid) in units of storms per cell. It is apparent from the figure that most landfalling TCs are in Florida and the Carolinas. Furthermore the density is far more along the coasts than further inland, which relates to the rapid dissipation of these cyclones.

4 Results

4.1 Sensitivity of drought to landfalling tropical cyclones

Figure 4a shows the annual climatological mean DI from Cont and Expt for the each of the 28 SeUS watersheds. It is apparent from the figure that the differences of DI between Cont and Expt are marginal (~5 %). In other words, the drought mitigating impact of the landfalling TCs in the 28 watersheds of the SeUS over the period of 1948–2006 is rather minimal. However, one has to be cautious to make a general conclusion from this result because this insensitivity of DI to rainfall from landfalling tropical cyclone can be attributed to the timing of the transient meteorological event relative to the soil moisture conditions present in the watershed. For example, in Fig. 4b we show the drought indices computed in the months of landfalling TCs in SeUS domain between 1948 and 2006 averaged over all watersheds from Cont and Expt. Figure 4b shows large differences in DI between Cont and Expt. This difference is especially apparent in months when there are multiple landfalling TCs (e.g., August 2004, September 2004, August 1955). In the short term (in days), rain from

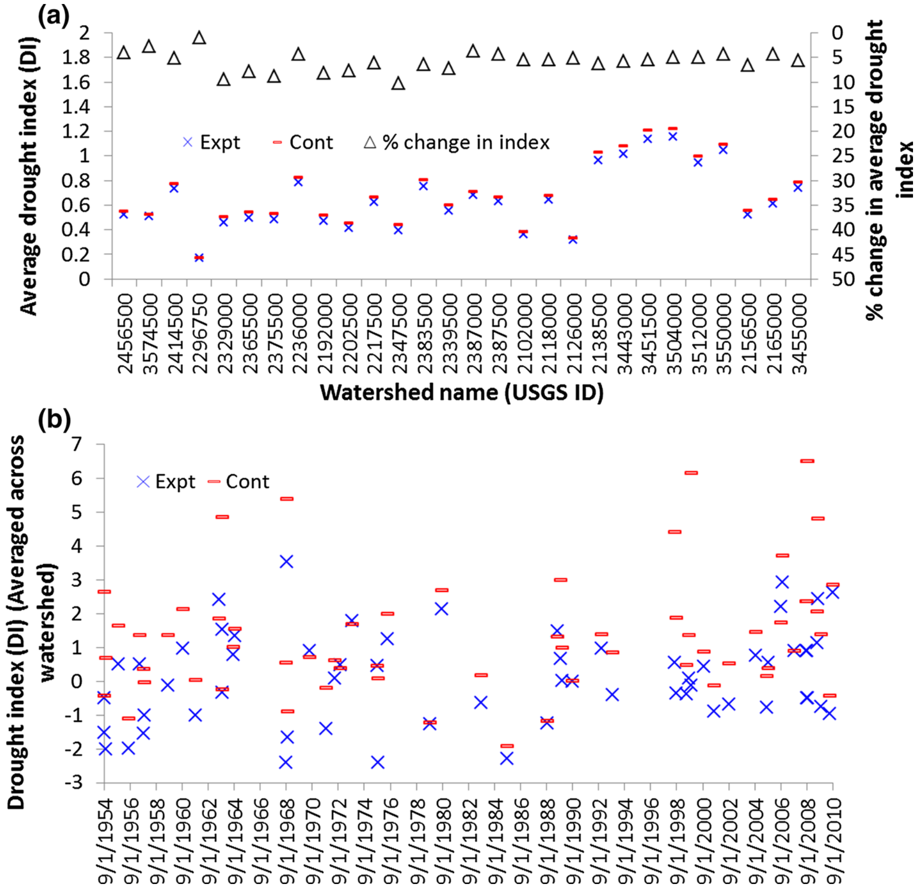

Fig. 4 **a** Time averaged Cont and Expt drought index over the period 1948–2006 and percent change in drought index between them. **b** Cont and Expt drought index for each year averaged over all 28 SeUS watersheds

landfalling tropical cyclone does increase the soil moisture. But in none of these 28 SeUS watersheds the rainfall from landfalling TCs seems to have a significant impact on the DI in the long term (as in monthly or seasonal mean; Fig. 4b).

In order to further assess the role of landfalling TCs in the SeUS from 1948 to 2006 we classified droughts as mild and moderate based on the following criterion:

$$\text{Mild drought:} \; -1 < \mathrm{DI} \leq 0.49 \tag{6}$$

$$\text{Moderate drought:} \; -2 < \mathrm{DI} \leq -1 \tag{7}$$

We then define a drought mitigation fraction of such mild (or moderate) drought events defined by monthly values as the ratio of the number of wet events (over the period of 1948–2006) that raise DI to levels above which they will not be classified as mild (or moderate) drought event to the total number of such drought events in the same period. Therefore a type of drought is considered mitigated if the DI changes from -1 (-2) to 0.49 or higher (-1 or higher) for mild (moderate) drought events by the subsequent month. In Fig. 5a, b we show the drought mitigation fraction for mild and moderate drought events respectively. We observe from the figures that many of the SeUS watersheds display significant recoveries (~50 %) across all the watersheds from both mild and moderate droughts. However this recovery for either of the two droughts in the 28 SeUS watersheds is marginally (~5 %) attributable to landfalling TCs (obtained as the difference between Cont and Expt; Fig. 5) in majority of the SeUS watersheds. In other words the majority of the drought recovery in the SeUS happens to arise from other wet meteorological events outside of the landfalling TCs.

4.2 The sensitivity of drought index to hydrological model

In Fig. 6, we show the annual climatological mean DI for each of the 28 SeUS watersheds from each of the three conceptual rainfall-runoff models along with the multi-model mean. Here we observe that the three models are reasonably consistent with each other across all the 28 watersheds in the SeUS (Fig. 6a) and over time (Fig. 6b). Interestingly, for many of the SeUS watersheds the percent change in the annual climatological mean DI from each of the hydrological models with respect to the multi-model mean is around 8 % (Fig. 6a) which is larger than the sensitivity to rainfall associated

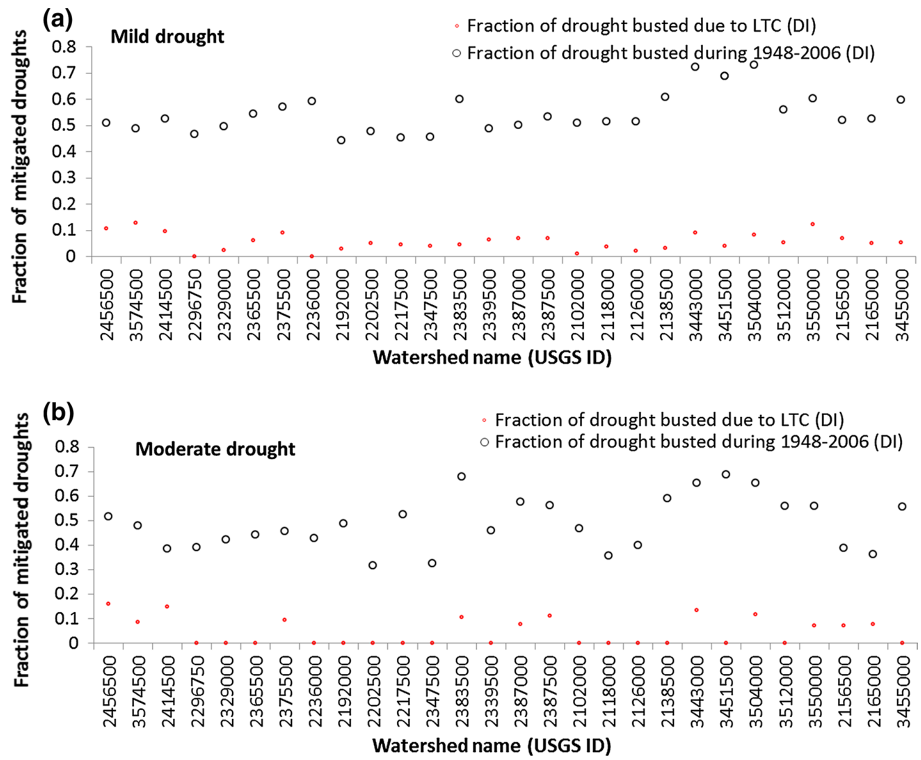

Fig. 5 Fraction of **a** mild and **b** moderate droughts mitigated during the period from 1948 to 2006 across the 28 SeUS watersheds. The *red filled circles* are computed as the difference between Cont and Expt. *LTC* landfalling tropical cyclones

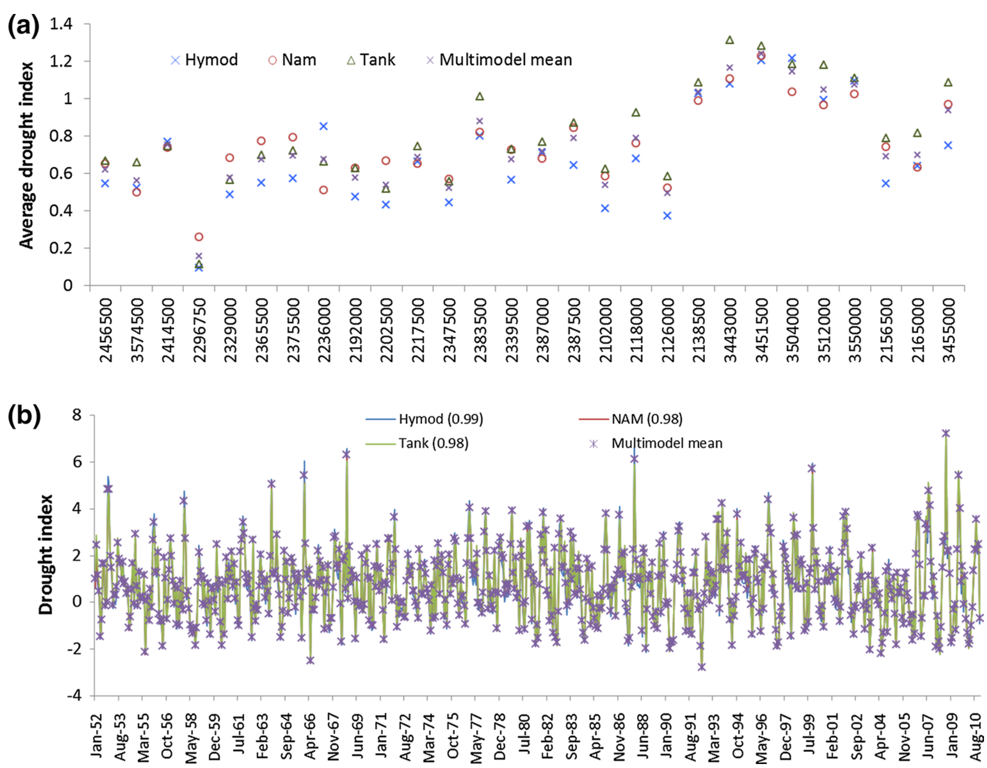

Fig. 6 Drought index from each of the three hydrological models and multi-model mean. **a** Averaged over time for each of the 28 SeUS watersheds and **b** averaged across all 28 watersheds

with landfalling tropical cyclone (~5 %). Similarly the monthly DI averaged over all 28 SeUS watersheds in Fig. 6b shows significant variations but are yet comparable across the three hydrological models. The correlations of the variations of DI with the multi-model mean ranges from 0.98 to 0.99.

5 Discussion and conclusion

This paper was motivated by intriguing paradigms on the influence of large-scale SST variations on continental US droughts including that over the SeUS and that on the seasonal Atlantic tropical cyclone activity. From earlier studies, it is understood that warm (cold) eastern tropical Pacific and cold (warm) Atlantic Ocean Sea Surface Temperature Anomaly (SSTA) increases the likelihood of wetter (drier) conditions over the continental US including the SeUS. Juxtaposing this understanding with the fact that landfalling TCs contribute significantly to the annual mean total rainfall in the SeUS and in El Niño (La Niña) years with cold (warm) tropical Atlantic SSTA lead to reduced (increased) Atlantic tropical cyclone activity raises an intriguing question on the potential synergy between landfalling TCs and seasonal droughts in the SeUS. There could be several arguments put forth to explain this apparent dichotomous role of large-scale SST variations on the hydrology of the SeUS. First many of these earlier studies (Hoerling and Kumar 2003; Schubert et al. 2009; Seager et al. 2009; Nigam et al. 2011) were conducted with coarse resolution climate models that were insufficient to resolve any of the Atlantic tropical cyclone events. Furthermore, majority of these studies including observational studies such as that of McCabe et al. (2004) alluded to annual mean rain deficits or surplus and ignored the seasonality. In addition, many of these modeling studies were focusing on the forced signal from the SST anomalies, which are most dominant in the winter hydrology over the continental US. But given that the summer wet season contributes the most to the annual mean total rainfall we feel it is important to reconciling this somewhat conflicting paradigms on large-scale SST variations on hydrology of the SeUS.

To study this problem, we specifically defined the equivalent of a Palmer DI which is based on using multiple conceptual rainfall-runoff models to capture the complexity of the soil hydrology better than the two-layer bucket model which is otherwise used in more commonly used Palmer drought severity index (PDSI; Dai et al. 2004). We conducted this study over 28 watersheds that were spread across the SeUS that were most pristine and least managed.

The climatological mean DI computed with and without the rainfall associated with landfalling tropical cyclone for the each of the 28 SeUS watersheds are significantly similar to one other, indicating that the DI across the watersheds of SeUS are rather insensitive to the rainfall from landfalling TCs. The total count of drought events (1948–2006) increased by 5 % when the rainfall corresponding to landfalling TCs is disregarded. We find that the sensitivity of DI to the selection of hydrological model is larger than the sensitivity of rainfall associated with landfalling tropical cyclone.

On average, the Cont simulation (which included all landfalling tropical cyclone events in the SeUS) showed nearly 123 mild and 39 moderate droughts spread over the 28 SeUS watersheds. Nearly half of the droughts recovered in the subsequent months. However, only 5 % of these droughts between 1948 and 2006 actually recovered during the period of landfalling tropical cyclone in the SeUS. The insensitivity of rainfall from landfalling tropical cyclone on the DI can be attributed to the timing of the event in relation to the overall moisture condition of the watershed and weakening of the impact of landfalling tropical cyclone as it moves inland. It is interesting to note that in the study period of 59 years from 1948 to 2006, an insignificant minority of landfalling TCs in the SeUS has affected the monthly DI between June and November.

The result of this study is however not surprising following Chan and Misra (2010), who showed that there were no landfalling TCs during the SeUS summer seasonal droughts between 1979 and 2001. This was largely because the large-scale pattern of circulation during the summer droughts in the SeUS seemed to favor the steering of the TCs away from the SeUS (Colbert and Soden 2012). In years of anomalously wet summers in the SeUS, Chan and Misra (2010) showed that there was an excess of moisture drawn from the tropical waters of the Caribbean Sea and northwestern tropical Atlantic Ocean, which was similar to the moisture trajectories of the extreme wet events (e.g., landfalling TCs) in the SeUS. Even Maxwell et al. (2012) in their observational study of using over 100 years of data found that only about 17.5 % of the "drought busting" events at the climate division scale in the SeUS were a result of landfalling TCs while the remaining 72.5 % were other "drought busting" wet events.

Our study used a very conservative approach to test the hypothesis of the landfalling TCs affecting the summer droughts in the SeUS by assuming that all 71 landfalling TCs between 1948 and 2006 had identical tracks after making landfall in the SeUS. Despite this approach we found insignificant impact of the tropical cyclone rainfall on droughts over the 28 relatively small watersheds in the SeUS. Therefore this study suggests that the irregular tracks of landfalling TCs in the SeUS are going to further diminish their potential influence on the monthly drought anomalies over the relatively small 28 SeUS watersheds despite a comparatively dense population of landfalls in the SeUS coast.

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