The impact of tropical cyclones on drought alleviation in the Atlantic and Gulf Coasts

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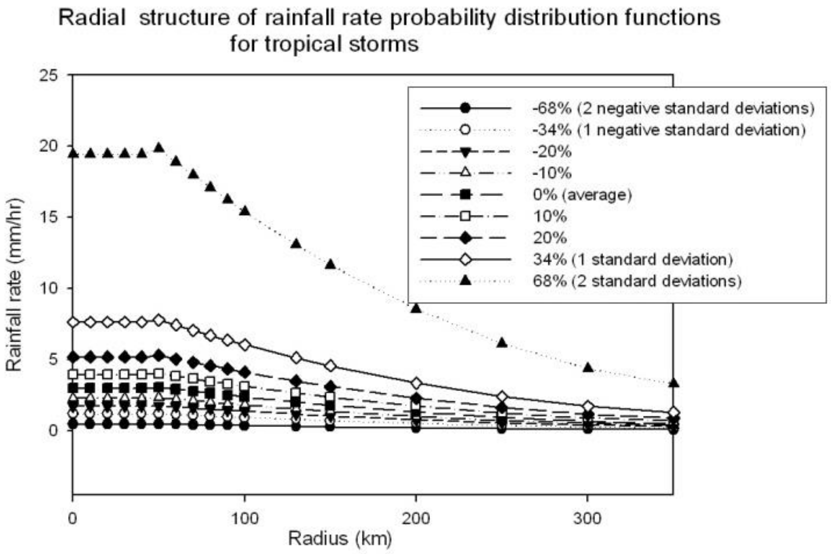
- *Background on hurricane rainfall*
- *Research results*

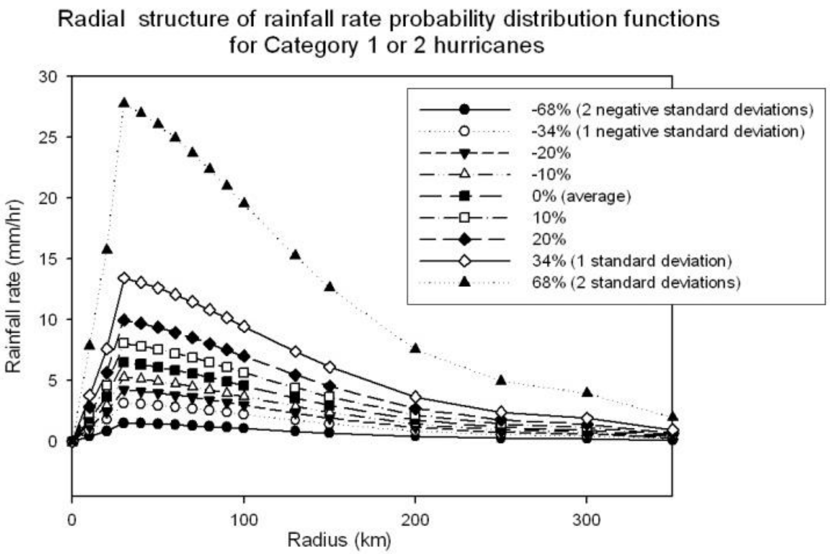
Background on hurricane rainfall

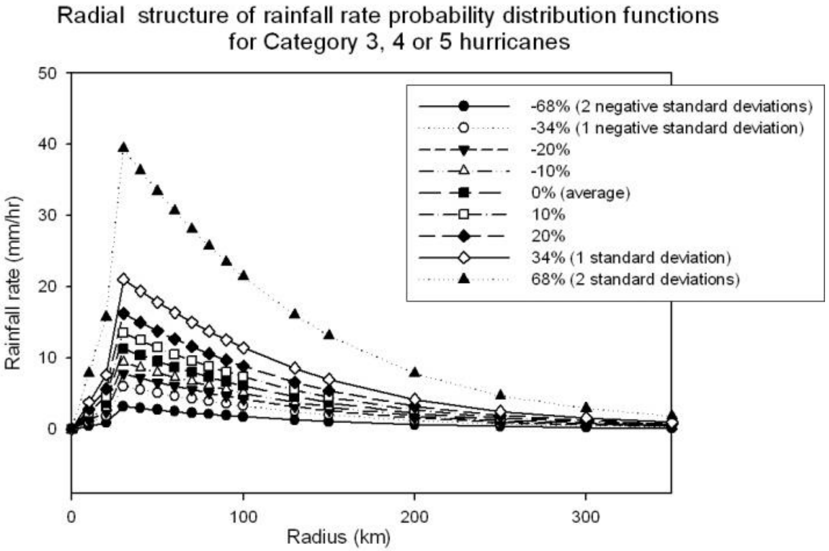
Monthly and seasonal rainfall contributions from hurricanes

- Landfalling hurricanes contribute 15-20% of rainfall along Gulf Coast coast (Larson et al. 2005)
- Wide yearly contributions along East Coast of 3-16% (Nogueira and Keim 2010)
- Atlantic hurricanes contribute 8-9% of seasonal rainfall in that basin (Jiang and Zipser 2010)
- However, during the peak season, Atlantic hurricanes contribute 20% to that basin, suggesting they can end droughts at opportune times (no other ocean basin has a higher percentage)

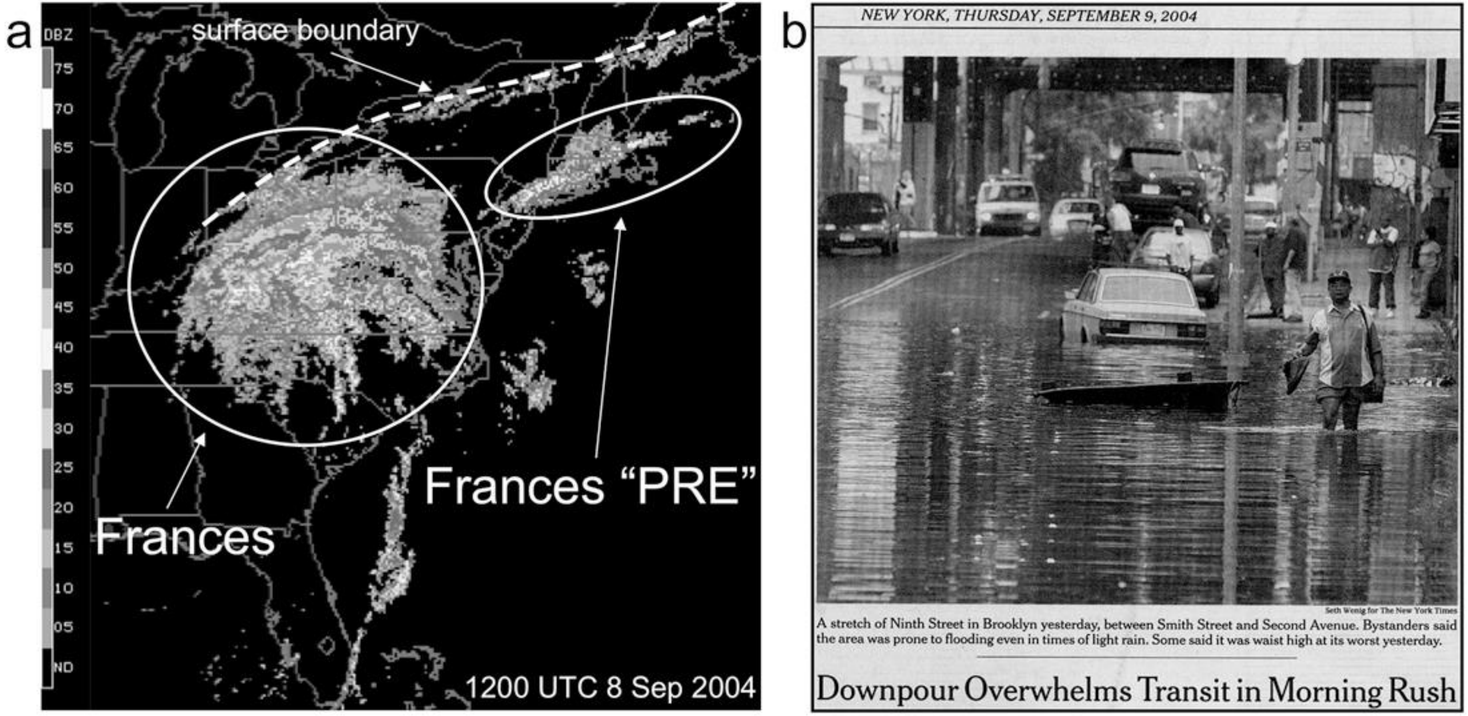
Average rainfall is 3, 6, and 11 mm/hr for TS, Min Hurr, and Major Hurr – but large spread!







From Fitzpatrick and Lau (2011) Based on Lonfat et al. (2007)

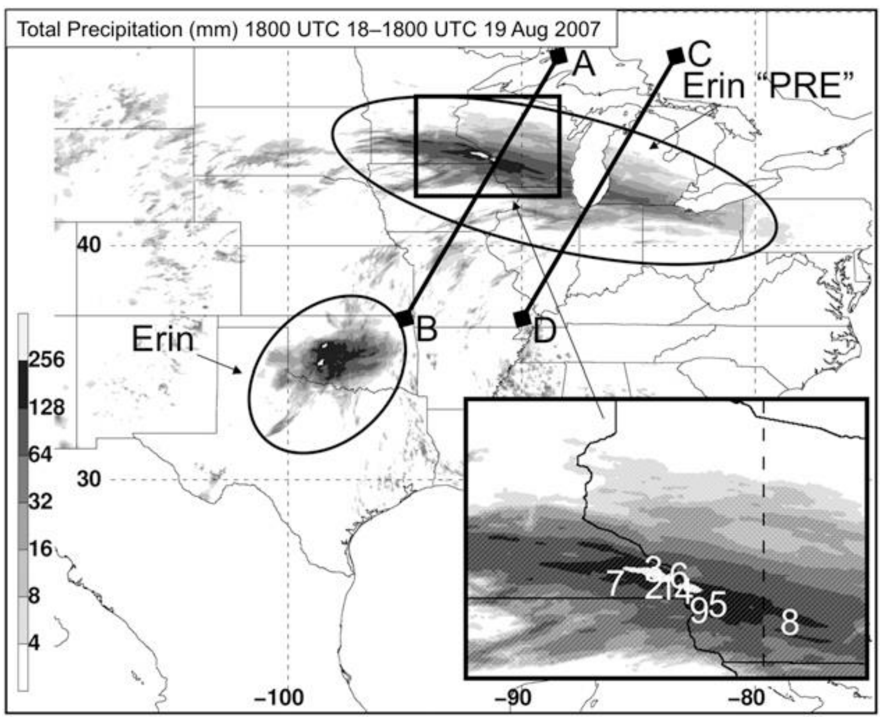


NEW YORK, THURSDAY, SEPTEMBER 9, 2004

Seth Wenig for The New York Times

A stretch of Ninth Street in Brooklyn yesterday, between Smith Street and Second Avenue. Bystanders said the area was prone to flooding even in times of light rain. Some said it was waist high at its worst yesterday.

Downpour Overwhelms Transit in Morning Rush



Can also have precursor rain events (Galarneau et al. 2010)

Drought busting hurricane results

Hill and Fitzpatrick (2012)

Maxwell et al. (2012)

Sugg (1968)

Palmer Drought Severity Index (PDSI)

Function of:

- Rainfall totals
- Potential moisture balance (evapotranspiration, soil water recharge, runoff)
- Recursive (influence by previous monthly PDI)
- Adjusted using a “climatic characteristic” coefficient to account for regional and seasonal variations for relatively homogenous regions

Assuming large monthly changes of PDSI are due to rainfall totals

What constitutes drought alleviation?

Palmer Drought Severity Index (Palmer 1965)

$PDSI \leq -4.0$	extreme
$-4.0 < PDSI \leq -3.0$	severe
$-3.0 < PDSI \leq -2.0$	moderate
$-2.0 < PDSI \leq -1.0$	mild
$-1.0 < PDSI \leq -0.5$	incipient
$PDSI \geq -0.5$	normal or wet conditions

PDSI is calculated monthly at each state climate division

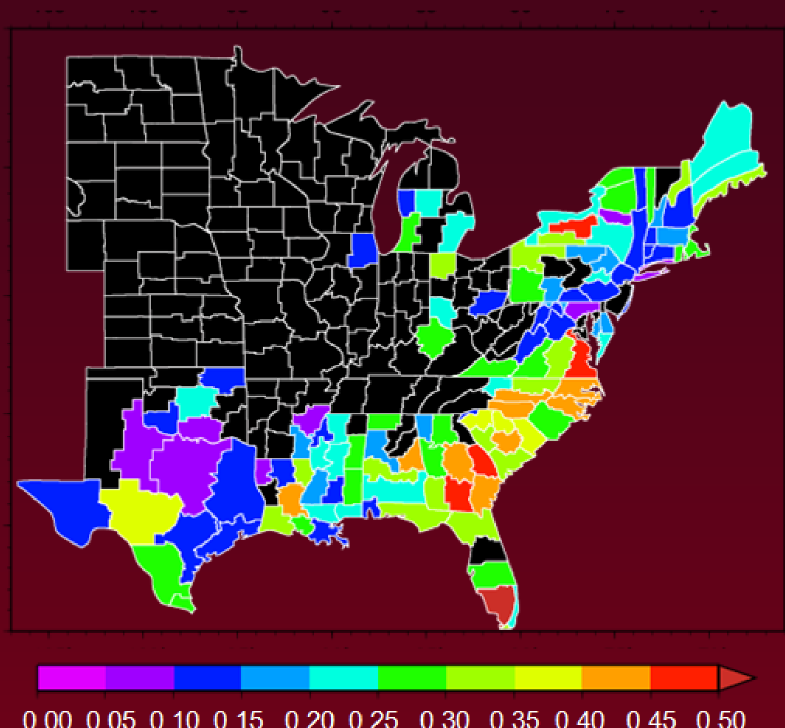
An alleviated drought event (ADE) is defined <u>here</u> as:

initial PDSI < -2.0 (moderate drought or worse)
increasing by +1.0 or more (one or more categories)
over the course of one month

Based loosely on Suggs, who identified 9 drought-busting hurricanes from 1928-1963.

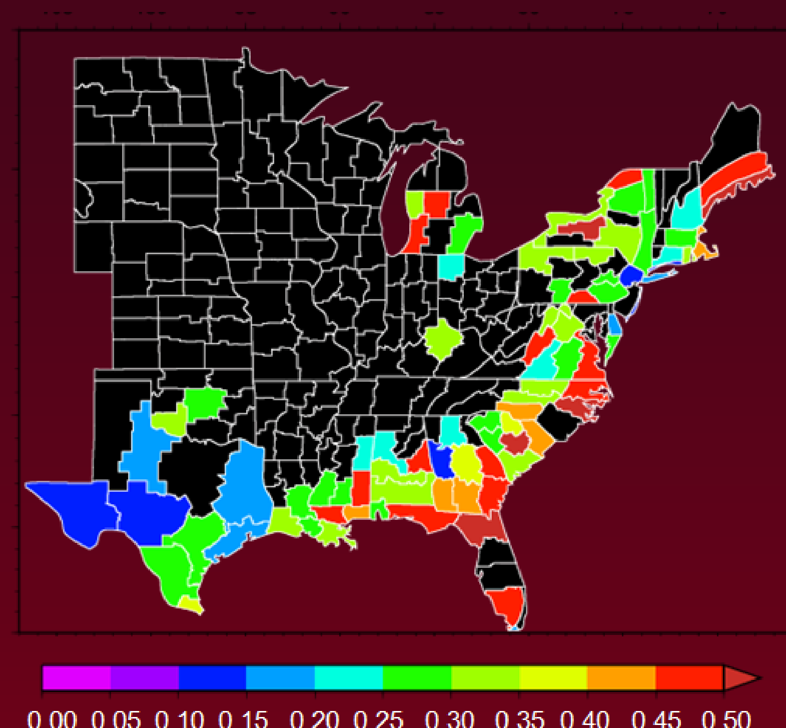
Percentage of droughts ended by tropical storms or hurricanes

TC-affected ADE frequency (150 km range) 1960 - 2010



The frequency of ADEs contained within the {R = 150 km} circulation area of TC.

TC-affected ADE frequency (R34 range) 1988 - 2010



The frequency of ADEs contained within the R34 circulation area of TCs.

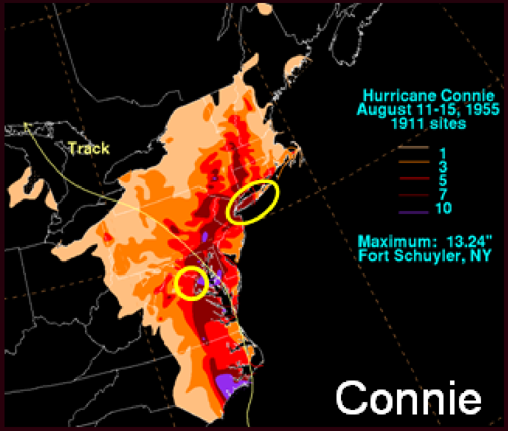
Examples of significant drought alleviation by tropical cyclones

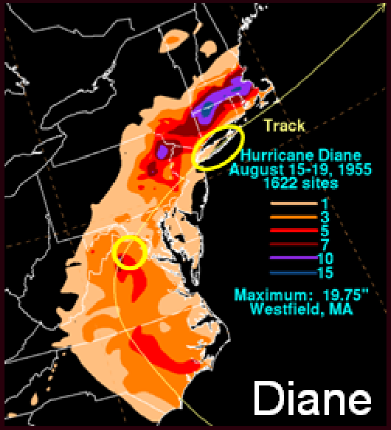
Connie was followed one week later by Diane during August 1955.

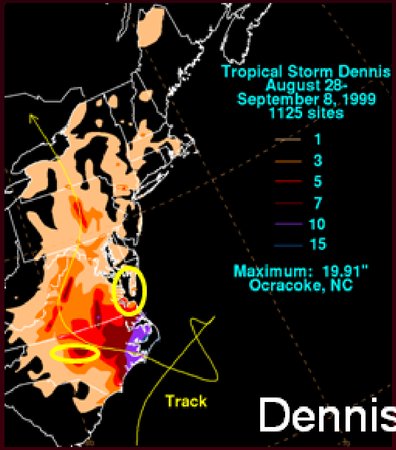
PDSI	VA-04	NY-04
July	-2.53	-3.27
August	2.69	2.06
change	**+5.22**	**+5.33**

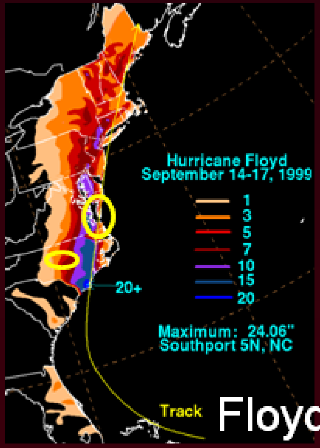
Dennis was followed within two weeks by Floyd during September 1999.

PDSI	VA-01	NC-04
August	-2.34	-3.77
September	3.95	2.24
change	**+6.29**	**+6.01**









tropical cyclone rainfall data compiled by NOAA/NCEP/HPC

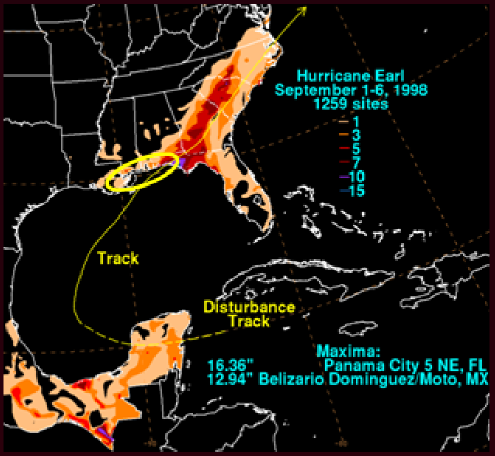
Examples of signficant drought alleviation by tropical cyclones

September 1998

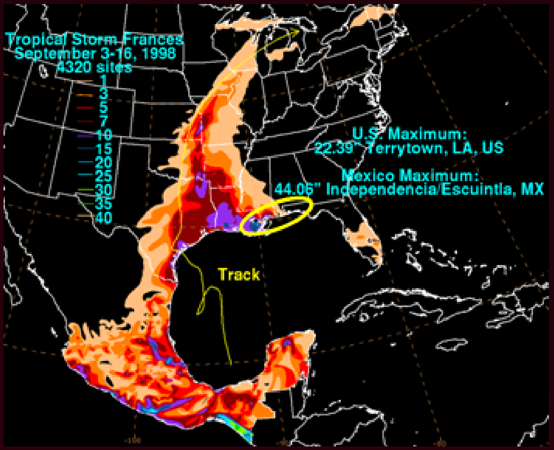
Four tropical cyclones contributed to the alleviation of a wide ranging drought along the Gulf Coast.

PDSI	LA-09	MS-10
August	-2.42	-2.17
September	2.51	2.81
change	**+4.93**	**+4.98**

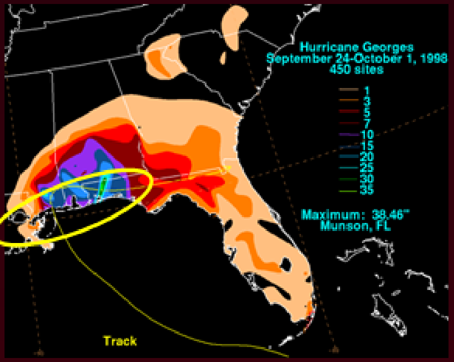
PDSI	FL-01	AL-08
August	-3.38	-2.14
September	2.94	2.61
change	**+6.32**	**+4.75**



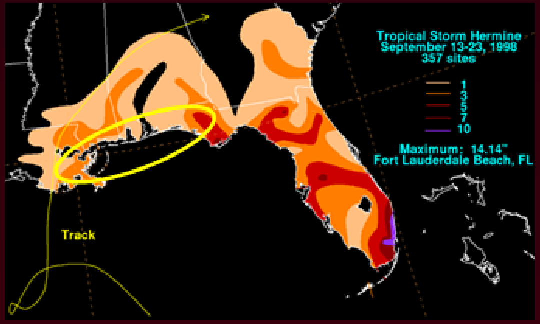
Earl



Frances



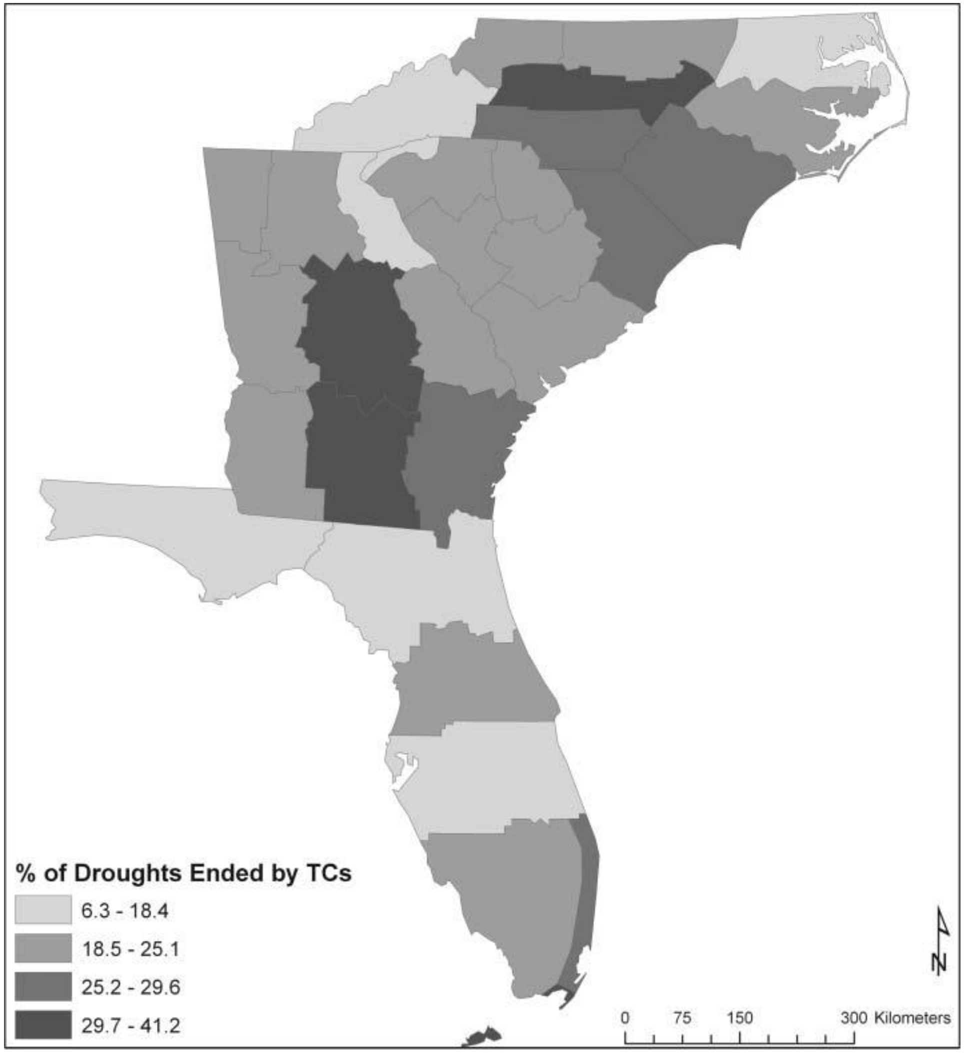
Georges



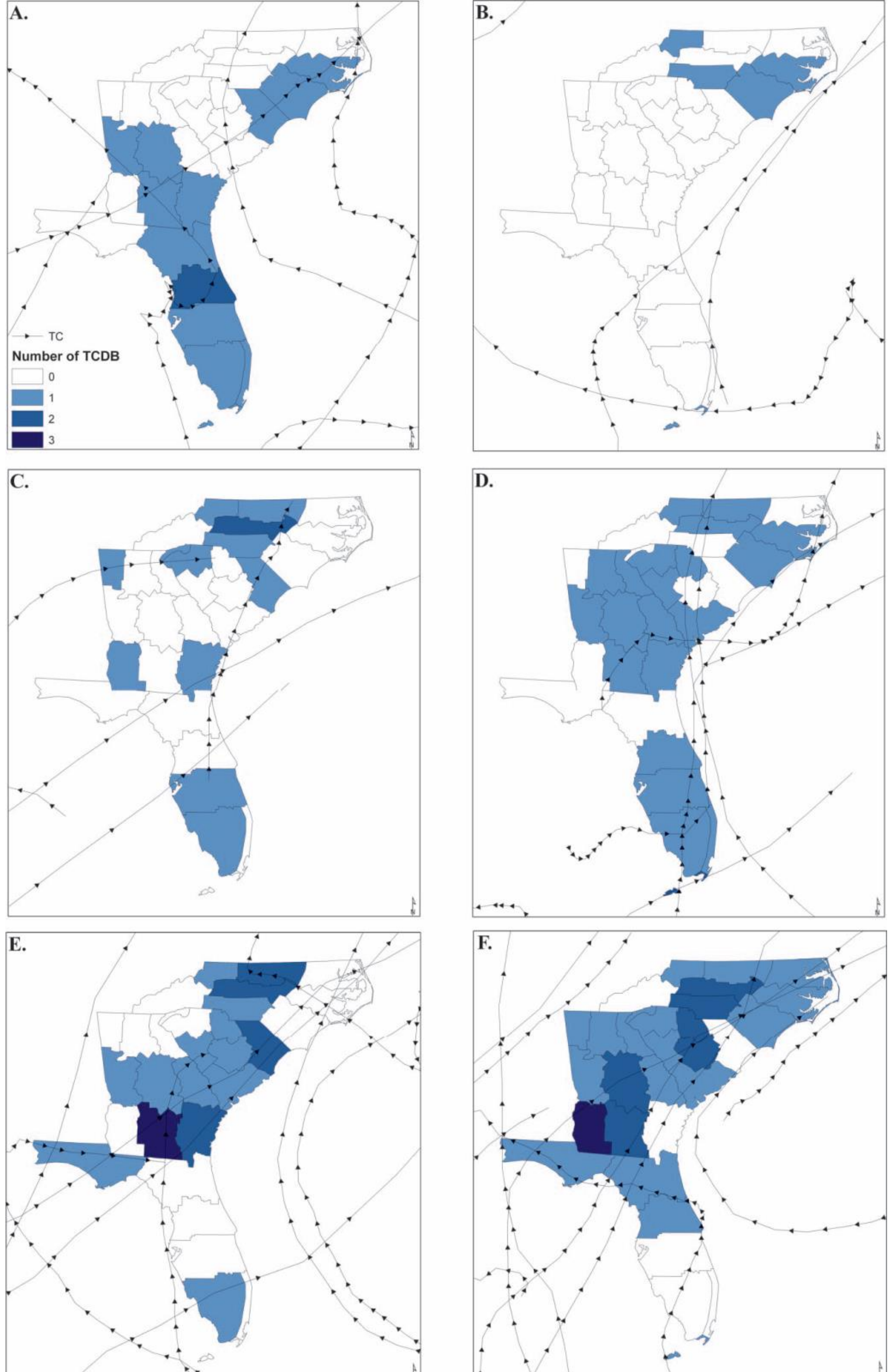
Hermine

tropical cyclone rainfall data compiled by NOAA/NCEP/HPC

Percentage of droughts ended by tropical storms or hurricanes in SE U.S. (Maxwell et al. 2012)



Note: they use a PDSI change to > -0.5 (near normal) .


A.
B.
C.
D.
E.
F.
TC
Number of TCDB
0
1
2
3

Summary

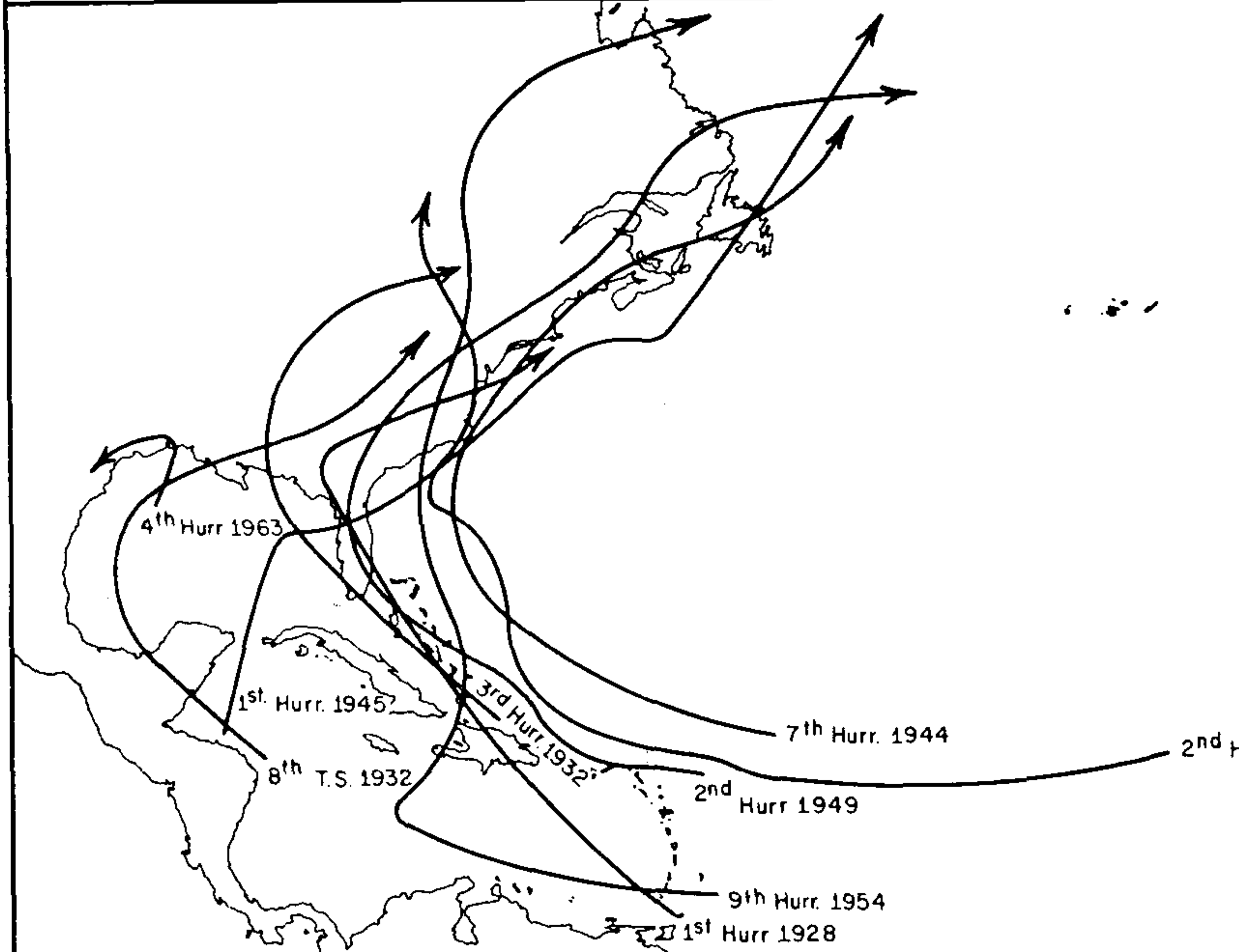
- Geographic patterns exist for hurricanes ending drought
    - Highest percentage (20-50%) in southeast US and NC
    - Fewer in Texas
    - Northeast is unclear
    - Interior U.S. apparently rarely have droughts ended by hurricanes

- Length of drought did not influence the ability of tropical cyclones to end drought. Long (> twelve months), medium (three–twelve months), and short (< three months) droughts were ended by tropical cyclones during the last sixty years (Maxwell et al. 2012)

- Seasonal forecast skill of drought-busting hurricanes may be possible. Proposal submitted.

Additional slides

TROPICAL CYCLONES WHICH HAVE TERMINATED DROUGHT CONDITIONS



Penman-Monteith PE (PE_pm, based on equation (4.1.14) of *Shuttleworth* [1993]), referred to as PDSI_pm and sc_PDSI_pm hereafter, additional data for surface net radiation, humidity, wind speed, and air pressure are needed. There are no station-data-based analysis products for these variables, except for surface humidity for which CRU has created a 0.5° product from 1901 to 2002 for surface vapor pressure [*Mitchell and Jones*, 2005]. However, many land areas in the CRU product had no observations and were filled with long-term mean values. Furthermore, the station data used for the 0.5° CRU product were not as vigorously checked for temporal inhomogeneity as for the CRUTEM3 data set. For these reasons, I simply used the gridded data from 1948 to 2008 for surface-specific humidity, wind speed, and air pressure from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis [*Kalnay et al.*, 1996]. In addition, we used surface net solar radiation from the Community Land Model version 3 (CLM3) simulation [*Qian et al.*, 2006], in which observed cloud cover [from *Qian et al.*, 2006] was used to estimate surface downward solar radiation. Surface net longwave radiation was estimated using surface air temperature, vapor pressure, and observed cloud fraction [*Dai et al.*, 2006] based on equation (4.2.14) of *Shuttleworth* [1993]. Since data before 1948 for these additional surface variables are not readily available over most land areas, I simply used the long-term mean values for years before 1948. Thus, the PDSI_pm and sc_PDSI_pm before 1948 contain no additional variations compared to PDSI_th and sc_PDSI_th, respectively. I realize that large uncertainties likely exist in these surface data, especially for surface wind speed and radiation, as high-quality data for these fields are unavailable over the global land. Because of this, the PDSI_pm and sc_PDSI_pm results may not fully reflect the impact of the actual changes in wind speed [*Roderick et al.*, 2007] and radiation on aridity [*Donohue et al.*, 2010] since 1950.

[17] As in the studies by *Dai et al.* [1998, 2004], I used the soil texture-based estimate of the water-holding capacity map from *Webb et al.* [1993]. Tests showed [*Dai et al.*, 1998] that the PDSI is not sensitive to the holding capacity values, presumably due to the normalization used in the Palmer model.

[18] Drought is often associated with dry soils and below-normal streamflow [*Dai*, 2011]. Thus, I evaluate the performance of the PDSI and sc_PDSI as a measure of drought by correlating area-averaged PDSI and sc_PDSI values with

[19] Here I briefly describe the relevant aspects of the PDSI and sc_PDSI formulations. More details can be found in the studies by *Palmer* [1965], *Alley* [1984], *Karl* [1986], and *Wells et al.* [2004].

[20] Besides P, *Palmer* [1965] considered four other surface water fluxes: E, recharge to soils (R), runoff (RO), and water loss to the soil layers (L), and their potential values PE, PR, PRO, and PL, respectively. Then Palmer introduced the concept of the climatically appropriate for existing conditions (CAFEC) values. To do that, he first defined the following water-balance coefficients calculated using local climate (often over a calibration period, which is 1950–1979 in this study) for each month *i*:

$$\alpha_i = \frac{\overline{E_i}}{\overline{PE_i}} \qquad \beta_i = \frac{\overline{R_i}}{\overline{PR_i}} \qquad \gamma_i = \frac{\overline{RO_i}}{\overline{PRO_i}} \qquad \delta_i = \frac{\overline{L_i}}{\overline{PL_i}}, \qquad (1)$$

where the overbar indicates averaging over the calibration period. Thus, these coefficients represent the ratio of the long-term mean values between a water flux and its potential value. The CAFEC values are simply the product of the potential value of a water flux times its coefficient, e.g., $\alpha_i\, PE$ for CAFEC evapotranspiration. In particular, the CAFEC precipitation ($\hat{P}$), which represents the amount of precipitation needed to maintain a normal soil moisture level for a given time, is defined as

$$\hat{P} = \alpha_i\, PE + \beta_i\, PR + \lambda_i\, PRO - \delta_i\, PL. \qquad (2)$$

The difference between the actual precipitation in a given month and the computed $\hat{P}$ for the same month is the moisture departure ($D = P - \hat{P}$) for the month. Obviously, a given value of D can have different meanings for the surface water balance at different locations and different times of the year. To correct that, Palmer multiplied D by a climatic characteristic coefficient K to derive the moisture anomaly index or the Z index ($Z = D\,K$), where K for month i is defined by Palmer using data from the central United States as follows:

$$K_i = K_o\, K_i' = \frac{17.67}{\sum_{i=1}^{12} \overline{D_i}\, K_i'} K_i' \qquad \text{and}$$

$$K_i' = 1.5 \log_{10}\left(\frac{\frac{\overline{PE_i}+\overline{R_i}+\overline{RO_i}}{\overline{P_i}+\overline{L_i}} + 2.8}{\overline{D_i}}\right) + 0.5. \qquad (3)$$

1998] that the PDSI is not sensitive to the holding capacity values, presumably due to the normalization used in the Palmer model.

[18] Drought is often associated with dry soils and below-normal streamflow [*Dai*, 2011]. Thus, I evaluate the performance of the PDSI and sc_PDSI as a measure of drought by correlating area-averaged PDSI and sc_PDSI values with

$$\sum_{i=1}^{12} \overline{D}_i\, K_i'$$

$$K_i' = 1.5 \log_{10}\left(\frac{\frac{\overline{PE}_i+\overline{R}_i+\overline{RO}_i}{\overline{P}_i+\overline{L}_i}+2.8}{\overline{D}_i}\right)+0.5. \quad (3)$$

The Z index is then used to compute the PDSI value for time t (X_t):

$$X_t = p\,X_{t-1} + q\,Z_t = 0.897\,X_{t-1} + Z_t/3, \quad (4)$$

where X_{t-1} is the PDSI for the previous month. The use of K_i is to allow comparisons of PDSI values over different time and space. The p and q coefficients in (4) are called duration factors, which determine how sensitive the PDSI is to the monthly moisture anomaly Z_t and how much autocorrelation the PDSI has. *Palmer* [1965] derived the values of $p = 0.897$ and $q = 1/3$ using the linear slope between the length and severity of the most extreme droughts that he studied in Kansas and Iowa.

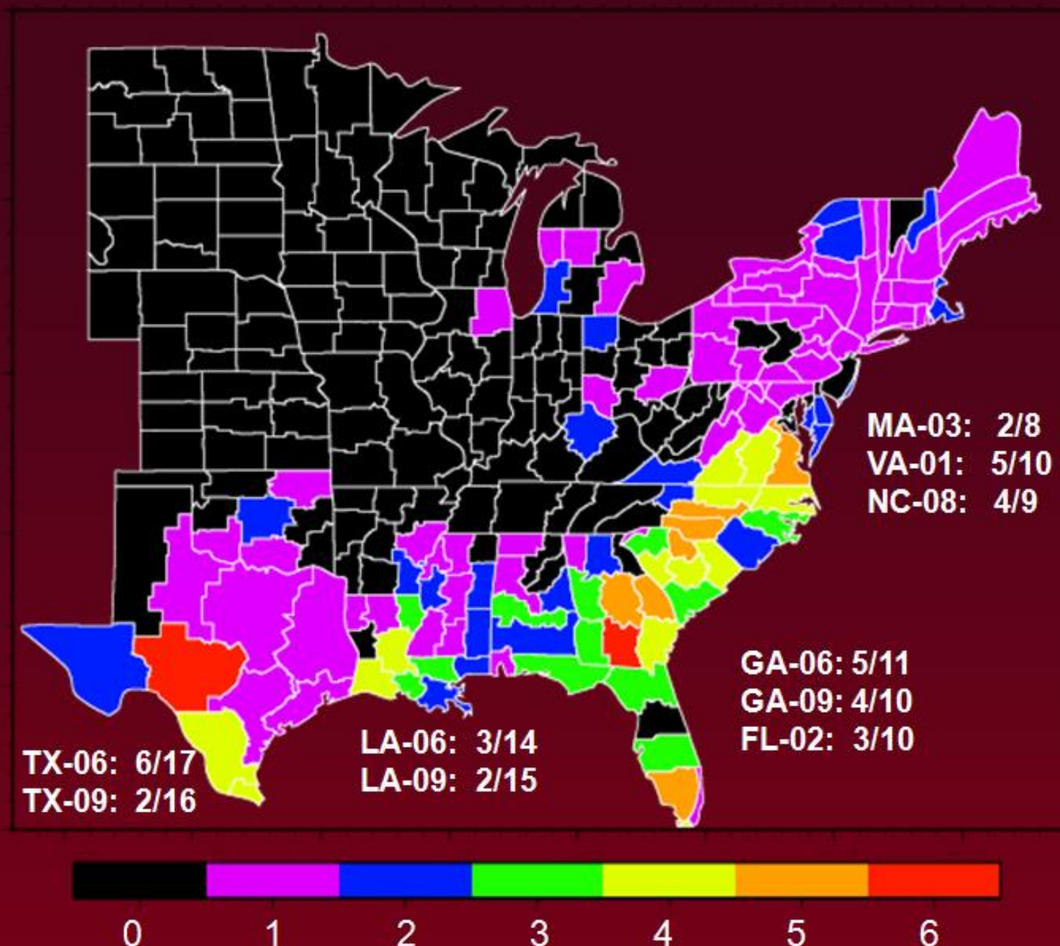
[21] To make the PDSI more comparable spatially, *Wells et al.* [2004] proposed a new method to calculate K (more specifically, K_o in (3)), p, and q using local climate conditions, so that the PDSI has more comparable histograms across different locations and the duration factors p and q reflect the local slope between the length and severity of the most extreme droughts. However, one still needs to make certain choices regarding the exact length over which the regression for the slope is done and how the extreme drought spells are selected. *Wells et al.* [2004] did not discuss these issues. I tested three different methods for doing the length versus severity regression that determines the p and q values and found that the results are not very sen-

with conclusions of *Burke et al.* [2006] and *van der Schrier et al.* [2011], who also found that the PDSI of the 20th century was similar when either PE_th or PE_pm was used.

3.3. Histograms of the PDSI

[24] Figures 2 and 3 compare the histograms of the monthly PDSI_pm and sc_PDSI_pm, respectively, at nine grid boxes around the world during 1900–1979. Some boxes may not have data for the earlier decades of the period, and years after 1979 are not included because of the recent drying trend. Histograms for PDSI_th (sc_PDSI_th) are not very different from those for PDSI_pm (sc_PDSI_pm) at most of the locations. It can be seen that the PDSI and sc_PDSI ranges vary from location to location, and the shape of the distributions can differ substantially from Gaussian at some locations such as the Amazonian and southern Indian boxes. The normalization to local climate in sc_PDSI improves the symmetry of the distributions, but it is still not Gaussian at some locations (e.g., the Amazon), and this problem exists even for the histograms of the calibration period (1950–1979). The value range of the sc_PDSI becomes more comparable among the different locations, generally within −6 to +6, whereas the range for the original PDSI varies considerably from one location to another, making it less comparable spatially. Thus, the sc_PDSI is indeed improved over the original PDSI in terms of spatial comparability, but it is still not symmetrically distributed around the neutral (i.e., zero) line at some locations.

ADEs with tropical cyclone within 150 km
1960 - 2010



tropical cyclone center distance determined from HURDAT

CD-00: # / #

# of TC-affected ADEs / # of total ADEs

Y	M	CD	TCprcp	Mprcp	TC-eff	dPDSI
1988	8	GA06	17	182	0.104	2.83
1988	8	NC04	37	183	0.217	2.78
1988	9	MI05	14	137	0.099	3.98
1988	9	MI08	10	156	0.073	3.68
1988	9	OK05	40	162	0.223	3.10
1990	10	GA05	19	208	0.113	4.79
1990	10	GA06	46	376	0.139	6.29
1990	10	GA08	34	134	0.312	4.89
1990	10	GA09	49	196	0.257	5.55
1990	10	SC03	34	349	0.115	5.46
1990	10	SC05	37	272	0.128	4.15
1990	10	SC06	14	343	0.040	5.78
1990	10	SC07	1	310	0.005	5.28
1991	8	MA03	16	140	0.112	2.40
1995	10	AL05	120	259	0.462	4.65
1995	10	AL06	111	264	0.404	4.06
1995	10	NY09	25	164	0.153	3.60
1995	10	NY10	8	165	0.051	3.98
1995	10	PA10	30	130	0.232	3.49
1996	10	GA08	108	180	0.620	2.65
1996	10	GA09	55	170	0.366	2.94
1998	8	TX06	134	327	0.355	5.31
1998	8	TX07	39	167	0.204	3.94
1998	8	TX08	42	145	0.296	3.02
1998	8	TX09	24	166	0.117	4.34
1998	9	AL07	153	482	0.297	5.70
1998	9	AL08	411	630	0.642	4.75
1998	9	FL02	98	440	0.225	1.21
1998	9	GA05	57	257	0.219	1.52
1998	9	GA06	31	158	0.201	1.03
1998	9	GA08	109	278	0.339	4.63
1998	9	LA05	46	253	0.166	4.56
1998	9	LA06	29	283	0.130	1.67
1998	9	LA07	102	339	0.304	4.05
1998	9	LA08	94	295	0.333	1.35
1998	9	LA09	24	450	0.049	4.93
1998	9	MS09	130	317	0.371	1.36
1998	9	MS10	272	561	0.402	4.98

Y	M	CD	TCprcp	Mprcp	TC-eff	dPDSI
1998	10	FL01	99	532	0.160	6.32
1998	11	FL05	114	168	0.608	3.86
1999	9	CT02	65	288	0.232	4.52
1999	9	CT03	13	243	0.039	4.80
1999	9	ME02	16	254	0.063	4.54
1999	9	ME03	20	227	0.085	4.59
1999	9	MD01	55	217	0.259	4.94
1999	9	MA02	76	243	0.317	4.02
1999	9	MA03	20	187	0.105	3.24
1999	9	NH02	38	239	0.169	4.16
1999	9	NJ01	168	324	0.502	5.68
1999	9	NY03	10	178	0.054	4.31
1999	9	NY04	23	196	0.110	4.80
1999	9	NY08	12	167	0.082	3.12
1999	9	NC03	114	375	0.249	5.29
1999	9	NC04	143	318	0.361	6.01
1999	9	NC05	56	320	0.171	1.48
1999	9	PA03	53	293	0.174	5.76
1999	9	PA04	16	185	0.086	4.62
1999	9	PA06	36	201	0.158	3.94
1999	9	RI01	5	188	0.035	3.70
1999	9	SC04	140	336	0.358	4.42
1999	9	SC07	96	221	0.365	2.75
1999	9	VA01	138	412	0.336	6.29
1999	9	VA02	34	322	0.088	6.08
1999	9	VA03	30	298	0.104	5.74
1999	9	VA04	14	258	0.056	6.43
1999	9	VA05	12	197	0.065	5.44
1999	9	WV06	11	147	0.076	1.44
2000	9	FL01	25	238	0.091	5.39
2000	9	FL02	40	281	0.155	1.47
2000	9	GA05	21	153	0.136	5.62
2000	9	GA06	33	185	0.169	1.37
2000	9	GA08	4	256	0.014	5.22
2000	9	NC05	26	188	0.142	1.19
2000	9	SC05	70	190	0.387	1.43
2000	9	SC06	51	182	0.288	1.21

Y	M	CD	TCprcp	Mprcp	TC-eff	dPDSI
2001	6	LA06	71	513	0.134	7.50
2001	6	LA09	103	524	0.202	6.77
2001	6	MS10	65	358	0.186	5.16
2001	6	NC08	69	224	0.263	1.61
2002	9	AL07	84	197	0.351	2.92
2002	9	GA04	8	134	0.071	4.32
2002	9	NC07	27	205	0.108	2.32
2002	9	PA08	15	93	0.161	3.65
2002	10	GA09	9	121	0.081	2.99
2002	10	NC08	47	137	0.345	3.78
2004	10	LA08	7	267	0.028	3.50
2005	7	MI10	21	155	0.135	1.14
2005	7	OH01	9	139	0.059	2.88
2005	7	TX10	49	125	0.419	1.44
2005	9	LA07	198	219	0.749	1.22
2006	6	SC03	26	241	0.118	3.93
2006	6	SC06	43	205	0.191	3.03
2008	7	TX05	20	101	0.219	4.04
2008	7	TX09	56	171	0.269	4.98
2008	7	TX10	159	325	0.483	8.08
2008	8	AL03	25	171	0.146	3.37
2008	8	AL06	41	239	0.167	4.67
2008	8	FL02	155	357	0.432	4.05
2008	8	FL07	66	201	0.330	1.17
2008	8	MS06	18	228	0.075	4.69
2008	8	MS07	20	289	0.070	5.31
2008	8	MS08	29	196	0.146	3.09
2008	8	MS09	43	217	0.196	3.58
2008	9	NJ03	34	159	0.218	2.76
2010	9	NC07	25	335	0.085	2.08
2010	9	NC08	26	329	0.083	4.25
2010	9	VA01	15	234	0.056	1.53