Recent increases in U.S. heavy precipitation associated with tropical cyclones

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Received 19 August 2010; revised 29 October 2010; accepted 3 November 2010; published 23 December 2010.

[1] Precipitation time series for 935 long-term U.S. climate stations were analyzed to identify daily extreme events associated with tropical cyclones (TCs). Extremes were defined as daily amounts exceeding a threshold for a 1 in 5-yr occurrence. TCs account for 30% or more of all such extreme events at a number of stations and about 6% of the national annual total. During 1994–2008, the number of TC-associated events was more than double the long-term average while the total annual national number of events was about 25% above the long-term (1895–2008) average. Despite the limited spatial area and portion of the annual cycle affected by TCs, the anomalous number of events associated with TCs accounted for over one-third of the overall national anomaly for 1994–2008. While there has been a recent increase in the number of landfalling U.S. hurricanes, the increase in TC-associated heavy events is much higher than would be expected from the pre-1994 association between the two. **Citation:** Kunkel, K. E. D. R. Easterling, D. A. R. Kristovich, B. Gleason, L. Stoecker, and R. Smith (2010), Recent increases in U.S. heavy precipitation associated with tropical cyclones, *Geophys. Res. Lett.*, *37*, L24706, doi:10.1029/2010GL045164.

1. Introduction

[2] Numerous studies have documented increases in U.S. heavy precipitation during the latter part of the 20th Century [*Kunkel et al.*, 2003; *Groisman et al.*, 2004, 2005; *Kunkel et al.*, 2007]. The meteorological factors that have caused such trends have not been identified. This paper examines the potential contribution of tropical cyclones (TCs) to the observed trends. There is no evidence for a long-term increase in North American mainland land-falling tropical cyclones [*Landsea*, 2005]. Also, the total number of daily rainfall events exceeding 50.8 mm and associated with TCs along the southeastern coast of the United States on a century time scale has not changed significantly [*Groisman et al.*, 2004]. This paper examines trends in heavy precipitation events due to TCs, and how they have contributed to the previously-observed national increases.

2. Data and Methods

[3] A set of 935 long-term COOP stations used for a series of recent studies [e.g., *Kunkel et al.*, 2005] was employed in this project. Daily heavy precipitation events were identified for each station based on exceedance of the threshold amount for a 1 in 5-yr recurrence interval over the period of 1895–2008. These events were determined empirically by ranking daily precipitation amounts by magnitude and selecting the top N/5 events, where N is the number of years of available data for a particular station.

[4] Using the 1895–2008 portion of the HURDAT dataset [*Jarvinen et al.*, 1984] of TC tracks and other characteristics, a heavy precipitation event was considered to be associated with a TC if the track of a cyclone passed within a 5° (latitude and/or longitude; approximately 500 km) radius of the location of the event on the same day. In this situation, it is likely that the heavy rains were associated with the tropical system's circulation. The vast majority of TCs are smaller than 500 km as measured by the extent of gale-force winds [*Kimball and Mulekar*, 2004] and a 5° search radius should be large enough to identify events associated with them. The ability to associate heavy events with TCs is aided by the usual pattern of rainfall. Subsiding air outside of the TC, an integral feature of the overall dynamics of these systems, typically creates an area of little or no precipitation and a separation with other precipitation-producing systems until it dissipates or merges with mid-latitude systems. There were 1305 heavy precipitation events (out of a total of 20,242 events) that were determined to be associated with TCs. These 1305 events were used to compute a time series of the frequency of events associated with TCs. Heavy events identified as associated with TCs occurred, as expected, mainly in the south and southeast regions, accounting for 13% of the national number of heavy precipitation events between June and October and 6% of all events.

[5] Because of the variations in spatial density of long-term stations, the station data were used to create a gridded data set of heavy precipitation events. Grid "events" were weighted. If all stations in a grid box experienced precipitation amounts qualifying as a "heavy event" on a particular day, the assigned weight was 1.0. Otherwise, the weight is the fraction of stations experiencing an event. The gridded data set was used for the following analyses. In order to place the TC results in perspective, an analysis of seasonal and regional variations in the frequency of heavy precipitation was performed, using the gridded data set. Events were segregated by month and region of occurrence; the nine regions [*Karl*

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0094-8276/10/2010GL045164

Table 1. Heavy Precipitation Event Trends for the Nine NCDC Climate Regions Using the Mann-Kendall Slope Estimator[a]

	North-east	East North Central	Central	South-east	West North Central	South	South-west	North-west	West
MAM	NS	NS	NS	NS	***−44*** (−36)	**NS**	NS	NS	NS
JJA	NS	**28** (31)	***39*** (33)	NS	***35*** (32)	NS	***45*** (38)	NS	NS
SON	NS	NS	***40*** (45)	NS	NS	***53*** (78)	NS	NS	NS
DJF	NS	NS	NS	NS	NS	NS	NS	NS	NS
ASO	NS	***36*** (50)	***47*** (48)	NS	**32** (31)	***55*** (73)	NS	NS	NS
Annual	NS	***36*** (38)	***33*** (34)	NS	NS	***38*** (40)	NS	NS	NS

[a]Trends calculated using linear least squares regression are also shown (in parantheses). Statistical significance is shown for the Mann-Kendall slopes is noted at p = **0.10**, ***0.05***, and ***0.01***. Percent of change in number of events per station per century.

and Knight, 1998] defined by the National Climatic Data Center (NCDC) were used for the regional analysis (http://www.ncdc.noaa.gov/img/climate/research/usrgns_pg.gif). Then, monthly and seasonal time series of regional and national event counts were computed. These time series were scaled such that the sum of the 12 monthly or 4 seasonal national time series equals the annual national time series which has an average value of 1. These scaled time series of heavy event frequency will be referred to as the heavy precipitation event index, or HPEI.

3. Results

[6] Most of the time series analyzed herein were found to be non-normal using the Shapiro-Wilk W test [*Shapiro and Wilk*, 1965]. Thus, the non-parametric Mann-Kendall test [*Kendall*, 1938; *Mann*, 1945; *Hirsch et al.*, 1982] was primarily used to determine significance and to estimate trends for each HPEI, although linear least squares regression trends were also calculated to shed light on the sensitivity of the trend magnitudes to the slope estimator used. Possible persistence in the time series that would reduce the number of statistically independent samples was accounted for in the statistical tests following *Santer et al*. [2008]. Table 1 shows the results of the trend analysis for the annual and each season and for each region. Statistically significant upward trends in the annual time series are found in three regions, all located in central or eastern areas. Of 7 statistically significant seasonal trends, 6 are positive. All of the statistically significant upward trends occur in the summer or fall. Regionally, statistically significant trends are most frequent in the central and eastern part of the U.S. The only statistically significant negative trend is found in the West North Central region in spring. When TC events are excluded from the time series, the SON and ASO trends in the Central region are no longer statistically significant while the other trends remain statistically significant, indicating a substantial contribution from non-TC causes.

[7] The concentration of positive trends in summer and fall and east of the Rocky Mountains suggests the possibility that TCs may be contributing to the observed trends. The monthly HPEI were aggregated into the core TC season of August-October. Figure 1 displays the HPEI time series for this time periods, as well as for the annual and the TC-associated events. The annual HPEI is an update of the results presented in previous studies [e.g., *Kunkel et al*., 2007] and exhibits familiar behavior. There is an overall statistically-significant ($p<0.01$) upward trend of +0.17 (or 17%) per century. This is not a monotonic increase. Event frequencies are relatively high early in the record before 1920, but are exceeded by values after 1990. The August-October HPEI shows a statistically significant ($p<0.01$) upward trend of +0.14 per century, only slightly below the annual trend of +0.17 per century. Thus, the dominant contribution to the overall trend is in the late summer and early fall, the period of peak TC activity. The time series of heavy precipitation counts associated with TCs also shows an upward trend, concentrated in the latter part of the record, although not quite significant at the 95% level of confidence ($p=0.056$). Regionally, there are statistically significant upward trends for August-October in 5 of the 9 regions (Table 1), all located in central or eastern areas.

[8] For the last 15 years of the analyzed record (1994–2008), the national HPEI averages 1.25, or 25% above the long-term normal while the tropical cyclone HPEI is 0.18, more than double its long-term average of 0.08. In fact, the positive TC HPEI anomaly for this period accounts for more than one-third of the overall national annual anomaly. Regionally, there are positive 1994–2008 anomalies in all nine regions, suggesting a multitude of meteorological causes for the overall national anomaly, with TCs making a substantial contribution in four regions. Those four along with the percentage HPEI anomaly and TC contribution are the Northeast (73% HPEI anomaly, 32% TC contribution), Central (26%, 51%), South (25%, 48%), and Southeast (40%, 100%). In the northeast, central, and south regions, factors other than TCs make at least an equal contribution to the recent anomalies. However, the southeast anomaly is solely a result of anomalous TC contributions.

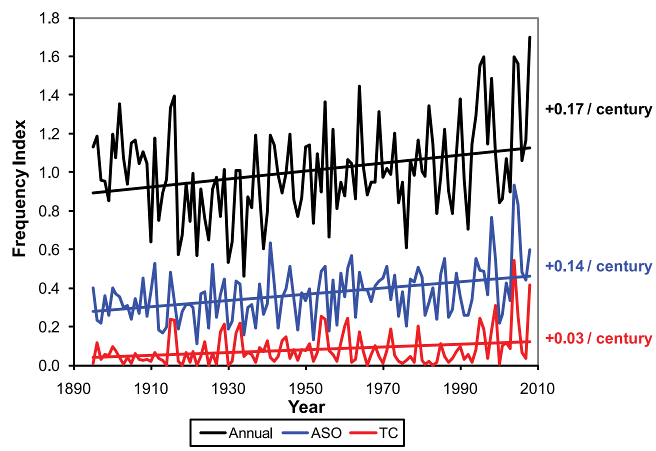

Figure 1. Time series (1895–2008) of national average heavy precipitation event index (HPEI) for the entire year (annual, black), for August through October (ASO, blue), and for heavy events associated with tropical cyclones (TC, red). The HPEI is normalized such that the annual time series averages 1.0. The values for other periods indicate the fractional contribution of that season to the total.

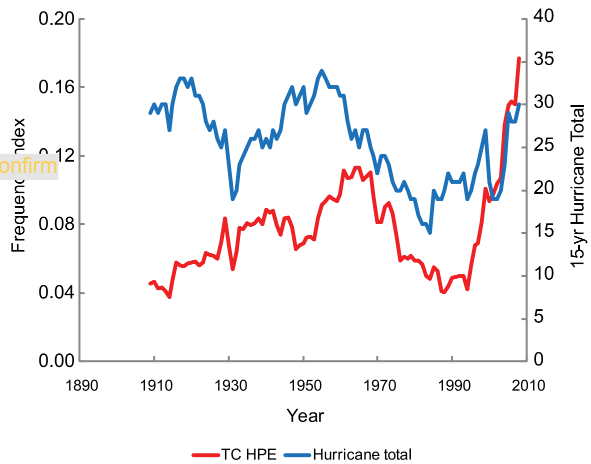

Figure 2. Time series of the 15-yr running average (plotted at the end point of the 15-yr blocks) of the TC HPEI (red) and the associated 15-yr total of U.S. landfalling hurricanes from HURDAT (blue).

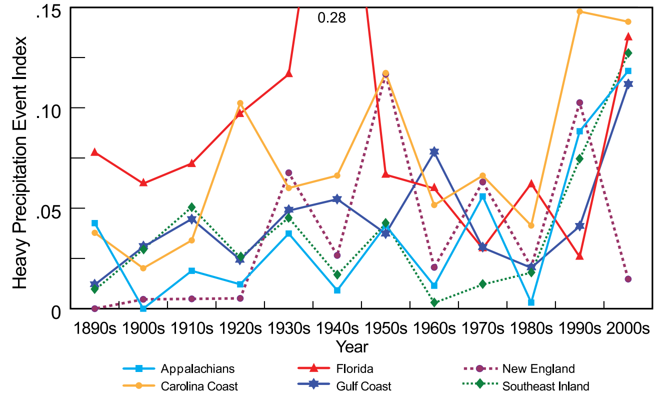

Figure 4. Time series (1895–2008) of decadal-averaged frequencies of the frequency of extreme events associated with tropical cyclones for the 6 groups shown in Figure 3. The event index is the number of extreme events per available station per year.

[9] The Mann-Whitney 2-sample U test [*Mann and Whitney*, 1947] was used to test the significance of mean differences between the most recent 15-yr block (1994–2008) and the earlier portion of the record. The mean value of the TC HPEI for 1994–2008 (0.18) is the highest 15-yr mean in the time series and the difference with every other 15-yr block is statistically significant with one exception. The second highest 15-yr mean is 0.11 during 1947–1961. While this is substantially smaller than the 1994–2008 mean, the difference is not statistically significant. At the regional scale, the difference of the 1994–2008 TC HPEI from the earlier portion of the record is statistically significant for the Northeast, Central, South, and Southeast regions.

[10] A comparison of the 15-yr running average of the TC HPEI and the associated total of U.S. landfalling hurricanes (Figure 2) shows a rough correspondence. However, using a linear relationship between TC HPEI and landfalling hurricanes derived from the pre-1994 data, the estimated value of the TC HPEI for 1994–2008 (0.08) is less than half of the observed value (0.17).

[11] Since there has not been an overall trend in landfalling systems [*Kunkel et al.*, 2008] (Figure 3), the upward trend in heavy precipitation events may be due to an increase in the number of heavy precipitation events per system. To investigate this possibility, the number of heavy precipitation events occurring on the same day within 5 degrees of a TC center was counted. Histograms for consecutive 10-yr periods showed the frequency of occurrence for different values of events per storm. One feature is supportive of the above expectation. Since 1895, there have been eight TCs that were each associated with 30 or more heavy precipitation events in the 935-station network; three occurred since 1995.

[12] The impact of events associated with TCs was investigated for each individual station. The percentage of extreme events from TCs at individual stations (Figure 3) is 30% or more at many stations near the Gulf and Atlantic coasts. At least one TC-associated event has occurred at a

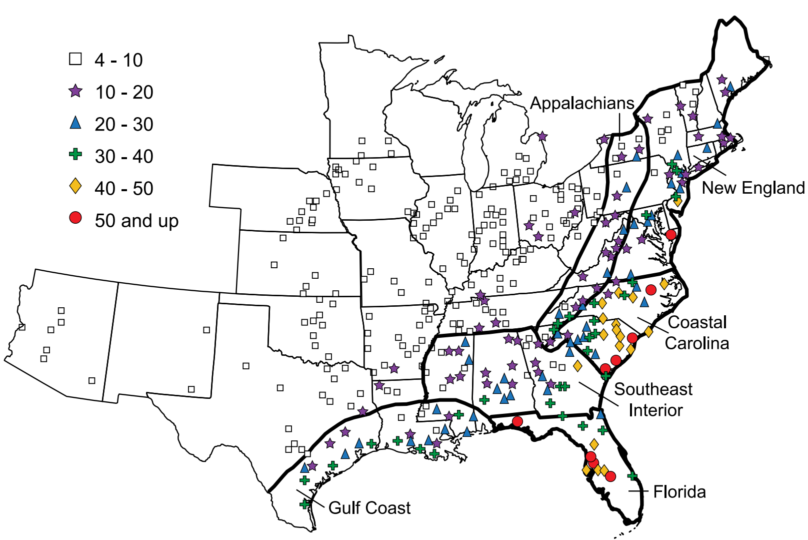

Figure 3. Percent of heavy events associated with tropical cyclones (TC) at individual stations (delineated by color and symbol type) and regional groupings (delineated by thick black lines). Only stations with at least 1 TC-associated event are plotted.

number of stations in the central and southwest U.S. Station time series of TC-associated events were examined and subjectively clustered into six groups (Figure 3). Time series of extreme event frequencies for these groups (Figure 4) by decade show relatively high values in the 1990s and 2000s. Values in the 2000s are the highest in the record for every group except Florida and New England, for which the 1940s and 1950s, respectively, are highest. The upward trends for the Coastal Carolina and Appalachians are statistically significant at p=0.05 while the upward trends for the New England and Southeast Inland groups are significant at the p=0.10 level of confidence. The trends for the Florida and Gulf Coast groups are not statistically significant.

4. Conclusions

[13] Heavy precipitation events associated with TCs represent about 6% of the coterminous U.S. total. There has been a recent dramatic increase in this number. During 1994–2008, this number was more than double the long-term average. The total annual national number of events was about 25% above the long-term (1895–2008) average during this same time period. Despite the limited spatial area and portion of the annual cycle affected by TCs, the anomalous number of events associated with TCs accounted for over one-third of the overall national annual anomaly. While there has been a recent increase in the number of landfalling U.S. hurricanes, the increase in TC-associated heavy events is much higher than would be expected from the pre-1994 association between the two. Much of the Gulf and Atlantic coastal areas have experienced an increase in the frequency of such events associated with TCs.

[14] With respect to future changes arising from anthropogenic forcing of the climate system, models generally show an increase in precipitation intensity for all types of systems [*Gutowski et al*., 2008]. Specifically for hurricanes, model simulations suggest an increase in precipitation rates of 20% in the cores of such systems by 2100 [*Knutson et al*., 2010]. The historical results described herein are generally consistent with these climate model projections of future trends, but this study simply documents the observed behavior. It does not address attribution and specifically whether an anthropogenic signal should currently be detectable.

[15] **Acknowledgments.** This work was partially supported by National Oceanic and Atmospheric Administration Climate Program Office award NA07OAR4310063. We thank James Angel and Alan Black for their constructive comments. Any opinions, findings, and conclusions are those of the authors and do not necessarily reflect the views of NOAA or the institutions for which they work.

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