"Tropical Cyclones Feed More Heavy Rain in a Warmer Climate"

by K. M. Lau , Y. Zhou and H. T. Wu

Popular Summary

The possible linkage of tropical cyclones (TC) to global warming is a hotly debated scientific topic, with immense societal impacts. Most of the debate has been focused on the issue of uncertainty in the use of non-research quality data for long-term trend analyses, especially with regard to TC intensity provided by TC forecasting centers. On the other hand, it is well known that TCs are associated with heavy rain during the processes of genesis and intensification, and that there are growing evidences that rainfall characteristics (not total rainfall) are most likely to be affected by global warming. Yet, satellite rainfall data have not been exploited in any recent studies of linkage between tropical cyclones (TC) and global warming. This is mostly due to the large uncertainties associated with detection of long-term trend in satellite rainfall estimates over the ocean. This problem, as we demonstrate in this paper, can be alleviated by examining rainfall distribution, rather than rainfall total.

This paper is the first to use research-quality, satellite-derived rainfall from TRMM and GPCP over the tropical oceans to estimate shift in rainfall distribution during the TC season, and its relationships with TCs, and sea surface temperature (SST) in the two major ocean basins, the northern Atlantic and the northern Pacific for 1979-2005. From the rainfall distribution, we derive the TC contributions to rainfall in various extreme rainfall categories as a function to time. Our results show a definitive trend indicating that TCs are contributing increasingly to heavier rain events, i.e., intense TC's are more frequent in the last 27 years. The TC contribution to top 5% heavy rain has nearly doubled in the last two decades in the North Atlantic, and has increased by about 10% in the North Pacific. The different rate of increase in TC contribution to heavy rain may be related to the different rates of different rate of expansion of the warm pool (SST >28^{o} C) area in the two oceans.

Tropical Cyclones Feed More Heavy Rain in a Warmer Climate

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Hurricanes and typhoons, collectively referred to as tropical cyclones (TC), are driven by condensation heating associated with heavy precipitation during TC genesis and intensification. Changes in precipitation characteristics have been associated with global warming. Yet rainfall data have not been exploited in recent studies linking TCs and global warming. In this paper, we focus on trends in tropical rainfall characteristics and contribution of TC to rainfall extremes. We find that climatologically TCs in the North Atlantic contribute less to total rain, and sustain lower rain rates compared to those in the North Pacific. TCs have been feeding more heavy rain since 1979 to present, with a near doubling in contribution to extreme heavy rain in the North Atlantic, but a modest increase of about 10% in the North Pacific. The difference may be related to the greater rate of expansion of the warm pool area in the North Atlantic compared to the North Pacific.

Recent high impacts weather events such as Hurricane Katrina in 2005 have fueled debates of a possible link between global warming and increased intense tropical cyclone (TC) activity[1-5]. Up to now most studies on linkages between intense TC and global warming have relied on definitions of TC intensity based on sustained maximum wind and subjective satellite imagery interpretation provided by operational centers[6,3]. These definitions suffered from uncertainties stemming from changes in definition of TC intensity by different operational centers based on forecast rather than research requirements. More recent studies have attempted to use unified definitions globally based on objective satellite classifications[7].

On the other hand, studies have shown that precipitation characteristics are more likely to change in response to global warming than total precipitation amount[8,9]. A recent study[10] based on satellite rainfall data found a significant shift in the tropical rainfall distribution that indicates positive trends in extreme heavy and light rains, and a negative trend in moderate rain during the last 25 years since 1979. In the tropics, heavy rainfall events can arise from a variety of severe weather systems such as squall lines, meso-scale convective complexes, tropical supercloud clusters, TCs and others. Given the increasing evidences on the connection between extreme weather events and climate change, it may be instructive to understand the linkage between hurricane activity and climate change through the perspective of extreme rain events. Here, we combine historical storm track data with state-of-the-art satellite rainfall data, to examine possible trends in TC contributions to tropical rainfall extremes, based on a consistent and universal measure of extreme rain events defined from percentile ranked rain distribution.

This study is focused on rainfall statistics during the hurricane season July through November (JASON) over two oceanic domains of comparable size at [20 °W-90 °W, 10 °N-40 °N] in the North Atlantic (NAT) and [120°E-180°E, 10°N-40°N] in the western North Pacific (WNP). Cumulative probability distribution function (CPDF) for rain amount and for rain occurrence (see Supplement A for description of CPDF). Rainfall extremes are defined with respect to ranked rain rates, as top 20% (T20), top 10% (T10), and top 5% (T5) extreme rain, from the CPDF of rain amount in each ocean domain. The results described here are independent of the exact percentile ranks, which are only chosen as representative quantifier for extreme rainfall events. We further define TC-rain as the rainfall associated with TC, by computing the rainfall accumulation when a storm passes within the 5-day window, and within a radius of 500 km around the storm center[11,12] based on the best track records from the National Hurricane Center and from the Joint Typhoon Center. The TC-rain for each of the three extreme category is then defined by applying the same procedure, but only for accumulated rain in that category. Note that because of the coarse resolution of the GPCP data, the TC-rain is an integral measure of rainfall associated with TC over a five day period, and not the instantaneous rain, for which the higher resolution (3-hourly, $0.25^{\circ} \times 0.25^{\circ}$) rainfall data from Tropical Rainfall Measuring Mission (TRMM) is a much better approximation. Comparing the statistics of rainfall extreme and TC-rain from TRMM and GPCP has found that the CPDFs from the two data sets have consistent characteristics for the overlapping period (1998–2005) (see Supplement A for comparison of TRMM and GPCP rainfall statistics), ensuring the coarse resolution GPCP data set can be used for the longer data period (1979–2005). For more details on data and definitions, see the Data and Methodology section at the end of this article.

Table 1 shows the GPCP extreme rainfall statistics extracted from the rainfall CPDF for the two ocean domains respectively. For NAT, TC-rain accounts for 9.7% of total rain occurrence, and about 19.6% total rain amount, consistent with the observations that TC events occur rather infrequently and are typically associated with heavier rain compared with other rain-bearing tropical weather disturbances. This is evident also in the monotonic increase in TC-rain for more extreme rain categories. At T5, the TC contributed rain event and rain amount is more than 50% of total rain. For WNP, the statistics are similar, including the monotonic increase in the percentage of TC contributions for more extreme rains, but with higher rain thresholds, and higher TC-rain fractions for the same ranked rain rates. For WNP, TCs account for 12.2% and 27.2% of total rain events and rain amount, respectively. At T5, the corresponding TC contributions rise to 77.1% and 78.3%. These suggest that overall, TCs in WNP are stronger than those in NAT, producing more rain and sustaining higher rain intensity.

The domain averaged total GPCP rainfall over NAT and WNP for JASON show no discernible trends during the last 27 years (see Supplement B, Fig. S3). However, this does not preclude trends in different portions of the rain spectrum, manifested as a shift in the rainfall distribution[10] . Such a shift is apparent in the rainfall distribution from the first half (1979–1991) of the data record to the second half (1993–2005) for both domains (Figs. 1a and c), with the latter period showing increasing heavy rains and decreasing moderate rains in both oceans. The increase in extreme rainfall becomes very pronounced in the normalized deviations by rain bin (Figs. 1b and d), which show clearly positive increments for heavy rain events with some very large (> 50%) normalized deviation for very extreme events (T5 or above). The relative changes appear to be more pronounced in NAT compared to WNP. A compensating negative trend in moderate-to-light rains (2-15 mm day^{-1}) is noted in both domains[10].

To examine the long-term variations of extreme rains and associated TC contributions, we have computed the seasonal accumulated frequency of occurrence (FOC) and rain amount for all three extreme categories, T20, T10, and T5 respectively. Since all three extreme categories have similar variability, only those for T10 are shown. In the following discussion, a trend is defined as a monotonic increase or decrease within the data period. A time series is considered to possess a trend when its regressed linear trend exceeds the 95% confidence level (c.l.), computed based on the R^2 statistical test[13]. Additionally, we define a measure called the average TC rain intensity (TC-RI) as the rainfall amount per unit FOC for TC-rain. For NAT, the T10 total, and corresponding TC-rain amount (Fig. 2a) each shows an obvious upward trend (>99% c.l.). Superimposed on the trend are large interannual and decadal variations with peaks in the late 1980s and in the mid-1990s. The residual (figure omitted) computed as the difference between the two time-series in Fig. 2a shows no clear long-term signal. Hence, it can be inferred that TCs are feeding dominantly to the variability and trend of the T10 rain. Fig. 2b shows variations in T10 FOC with a clear trend (>99% c.l.), and decadal variations similar to T10 total rain and TC-rain amount. As evident in Fig. 2b, there is also a trend (>95% c.l.) albeit weaker in TC-RI. These imply that the observed trend in extreme rain amount (Fig. 2a) is likely to be derived primarily from more TC events (either more TCs or TCs with longer duration), and to a lesser degree from an increase in TC intensity.

For WNP, both the total rain and TC-rain show linear trends exceeding 99% c.l. However, as shown in Fig. 2c, the T10 time series for total and TC-rain are far from linearity, but dominated by large interannual and decadal variations. The T10 rain amount rises relatively steeply from 1984 to 1989, and stays nearly constant with a slight decline from 1995–2005. The TC-rain shows a similar rapid rise from the mid-1980s to the mid-1990s, followed by a more pronounced decline after the 1995. The steep rise may be related to reported rapid increase in typhoon activity in WNP since 1989[14]. Again, the results here suggest that TCs contribute strongly to the variability and trends of the extreme rain event in WPN. The FOC time series for TC events (Fig. 2d) shows long-term variations similar to the rain amount, suggesting that increase in extreme rain stems from extended periods of TC events. Similar to that in NAT, the TC-RI in WNP also shows a positive trend (>99% c.l). In terms of the increasing contributions of TCs to extreme rain, the two ocean domains are quite similar and much more pronounced compared to similar statistics for total rain, and total TC-rain in the respective domain (see Supplement B, Fig. 3S).

Previous studies have noted that NAT and WNP have been warming at a moderate rate of approximately 0.5° C or less from 1980 through 2005[2]. Because of the strong control by surface evaporation on TC intensity[15], and that TCs are seldom formed when SST is below 26° C, it is reasonable to expect that TC activity may be sensitive to the area of the warm pool[16]. Indeed, the warming signals in NAT and WNP are most pronounced at the higher SSTs as evidenced in the SST distribution constructed using a 0.5°C bin for the two ocean basins in JASON for the pre-1992 and the post-1992 periods. In NAT (Figs. 3a and b) there is a clear signal of increase in FOC of SST >28–29° C, and reduced occurrence of cooler SST (<28° C). Similar shifts in the SST distribution can be found in WNP (Figs. 3c and d). If we define the size of the warm pool as areas with SST > 28° C, the distribution shift translates into an increase in total warm pool area of approximately 20% in NAT, and only 9% in WNP respectively from pre-1992 to the pos-1992 periods (see Table 2).

Fig. 4 shows the relationship between the warm pool area and the fractional contribution of TC-rain to total rain for T10. The TC-rain fraction in NAT (Fig. 4a) shows a pronounced upward trend from the pre-1992 to the post-1992 period indicating a nearly doubling in TC contribution to extreme rain amount. The long-term variation tracks well the percentage increase in the area of the warm pool in NAT during the data period (Fig. 4a), suggesting a possible relationship between the increased TC-rain fraction and a substantially expanded warm pool in NAT. By comparison, the fractional TC-rain for T10 in WNP (Fig. 4b) increases only modestly from the pre-1992 period to the post-1992 period. This modest increase in TC-rain contribution is consistent with the smaller percentage increase in the WNP warm pool size during that period.

Table 2 summarizes the percentage TC-rain contribution to total rain and to the three extreme rain categories, including the percentage change of warm pool area from the pre- to the post-1992 period. For NAT, there is clearly an increase in the fractional rain amount contributed by TCs as a function of extreme rain threshold in both periods. In all three extreme categories, the TC contributions in the latter period are much higher, approaching a near doubling (98%) compared to the earlier period in T5. In contrast, in WNP the fractional rain contributed by TC increases by 19% for total rain, and shows only a modest increase of about 10% for all extreme rain categories. These suggest that a natural limit may have been reached for extreme rain, and that TCs are also contributing more to moderate rain events. It is noted that at T5 in WNP, the 5-day rainrate threshold from GPCP is 33 mm day^{-1}, and the daily rainfall threshold from TRMM is 136 mm day^{-1} (Table S1). It is likely that only a very small number of storms can sustain such extreme rainrates for extended periods.

Recent studies[1,2] found nearly doubling of the number of intense TCs (Categories 4 and 5 based on the Saffir-Simpson scale) in both NAT and WNP. Others[16] found a much smaller trend of about 10% globally in Category 4 and 5, and a large increase in Category 4 and 5 in NAT, but not in WNP. Kossin *et al.*[7] reported that there are no robust trends in intense TCs in all ocean basins, except for the North Atlantic since 1983. Our results are partially consistent with these authors in that for total TC rain (including all rain categories), there are significant trends in NAT, but not in WNP. However, for TC-rain in the extreme categories, we find trends in *both* oceans. Overall, NAT shows more pronounced trend signals than WNP in almost all TC-related rain statistics we examined. Most important, our results show a near doubling in the percentage rain contribution by TC to extreme rainfall in NAT but only about 10% increase in WNP during the period 1979–2005. Since we used a unified classification of rain extremes and TC-rain in both oceans with the same rainfall dataset, our definition of TC-rain is not subject to the uncertainties due to secular changes in the definition of TC intensity used by different operational centers. Our results may also be understood on the physical basis that the increase in intense TC-rain is a part of a canonical response of the rainfall distribution manifested in an increase in extreme rain events in a warmer climate[10]. The difference in the rate of increase in TC rain fraction between the two oceans may be related nonlinearly to the increase in the areas of the warm pool (SST >28°C) with NAT undergoing much larger percentage warm pool expansion (~20%) compared to WNP (~9%). This is consistent with a recent study[17] which suggests that tropical cyclone potential intensity is more sensitive to localized SST changes stemming from coupled ocean-atmosphere dynamical feedback, than to the uniform SST pattern associated with greenhouse-gas-induced warming.

Data and Methodology

Data used in this study include the pentad rainfall from the Global Precipitation Climatology Project (GPCP) for 1979–2005[18, 19], the 3-hourly Tropical Rainfall

Measurement Mission (TRMM) rainfall data (3B42, Version 6) for 1998–2005[19], the 6-hourly hurricane best track data (1979–2005) with a correction of wind speed[1] from the National Hurricane Center and Joint Typhoon Warning Center, respectively. The Hadley Center monthly data (1979–2005) is used for the SST analysis. The 3-hourly TRMM data is used to generate daily gridded precipitation data. The spatial resolution is 2.5° latitude x 2.5° longitude for GPCP, 0.25° x 0.25° for TRMM, and 1° x 1° for SST. The analyses in this study are based on a large oceanic domain (20 °W–90 °W, 10 °N–40 °N) over NAT, and a domain with comparable size (120°E–180°E, 10°N–40°N) over WNP during the hurricane season, July through November (JASON). Following the approach described in ref. 10, we construct the probability distribution function (PDF) and cumulative PDF (CPDF) of rainfall amount and rain frequency, with the data binned at the interval of 1 mm/day. Rainfall extremes will be defined with respect to ranked rain rates, as top 20% (T20), top 10% (T10), and top 5% (T5) extreme rain, from the CPDFs of rain amount in each ocean domain.

In order to examine the TC contribution to the total rain and to each rainfall category, we calculate the TC-related rainfall using the 6-hourly storm track data for both NAT and WNP. Following Larson *et al.* [11] and Rodger *et al.* [12], we define TC-rain as rain that falls within an area of 500 km radius, from the center of the TC, *i.e.,* assuming that rainfall occurs within the 500 km of storm center is all associated with the TC during the same day the TC occurs. This procedure is first applied to the TRMM daily data. Because of GPCP's coarse spatial and temporal resolution, we define the pentad rainfall as TC-rain if a TC passes through during anytime of the pentad within the 500 km of the grid box. If the pentad rainfall meets the extreme criteria defined before, it is further defined as TC-related extreme rainfall. The GPCP TC-rain defined in this way is only a crude approximation to actual TC rain, because it may overestimate the direct TC contribution, since other forms of rain may have contributed to the total rainfall in the pentad. On the other hand, it may underestimate TC-rain with high rain rates, because some heavy TC rainfall may not be counted in the extreme TC rainfall if the corresponding GPCP pentad is not qualified as an extreme event due to GPCP's coarse space-time resolution. The consistency between the TRMM-defined and GPCP-defined rainfall extremes and TC-rain statistics are examined and described in Supplement A.

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Table 1a. Statistics of rainfall extreme, and percentage contributions by TC on rain amount and events for NAT [90°–20°W, 10°–40°N], using GPCP pentad data during JASON for1998–2005.

	T5	T10	T20	Total
threshold rainrate (mm/day)	23.0	18.0	13.0	---
TC event (%)	54.6	45.4	35.8	9.7
TC-rain (%)	55.9	47.8	39.3	19.6

Table 1b. Same as Table 1a except for WNP [120°–180°E, 10°–40°N]

	T5	T10	T20	Total
threshold rainrate (mm/day)	33.0	26.0	19.0	---
TC events (%)	77.1	68.4	55.7	12.2
TC-rain (%)	78.3	70.3	59.3	27.2

Table 2. Percentages of GPCP total and extreme rainfalls (T20, T10, and T5) contributed by TC during JASON for 1979–1991 (pre-1992) and 1993–2005 (post-1992) and for (a) NAT, and (b) WNP. Also shown is the ratio of warm SST area to total area in percentage.

a. North Atlantic (90°W–20°W, 10°N–40°N)	Pre-1992	Post-1992	Percentage Change
GPCP _T100 (Total)	10.2	17.8	75%
GPCP_T20	19.6	37.0	89%
GPCP_T10	23.4	45.3	94%
GPCP_T5	27.1	53.7	98%
Area of SST > 28°C	31.8	38.1	19.9%

b. Western North Pacific (120°E–180°E, 10°N–40°N)	Pre-1992	Post-1992	Percentage Change
GPCP_T100 (Total)	27.4	32.5	19%
GPCP_T20	59.1	64.9	10%
GPCP_T10	68.1	74.9	10%
GPCP_T5	74.0	82.0	11%
Area of SST > 28°C	53.1	58.1	9.3%

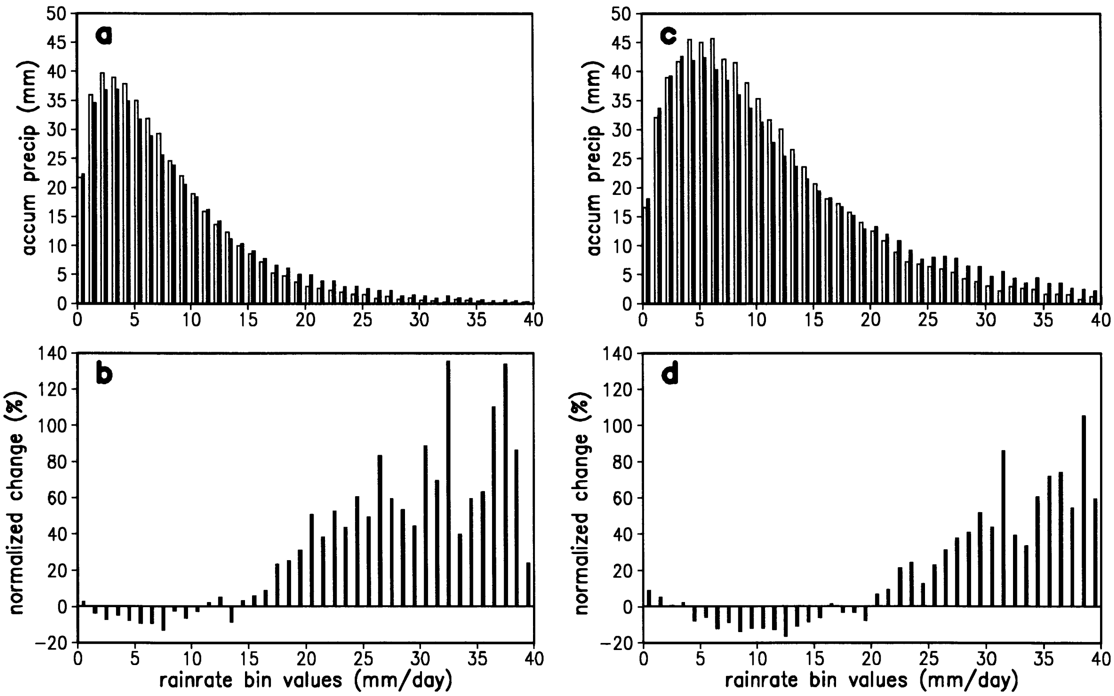

Figure 1. (a) The climatological PDF from GPCP for JASON accumulated rainfall amount at each rainfall bin (with 1 mm/day interval) of the first 13 years (1979–1991, outlined bar) and the latter 13 years (1993–2005, filled bar), and (b) shift in PDF shown as the difference between the rainfall PDF of the latter period (1993–2005) and the first period (1979–1991) normalized by the mean of these two periods for NAT. (c) and (d), are the same as in (a) and (b), except for WNP.

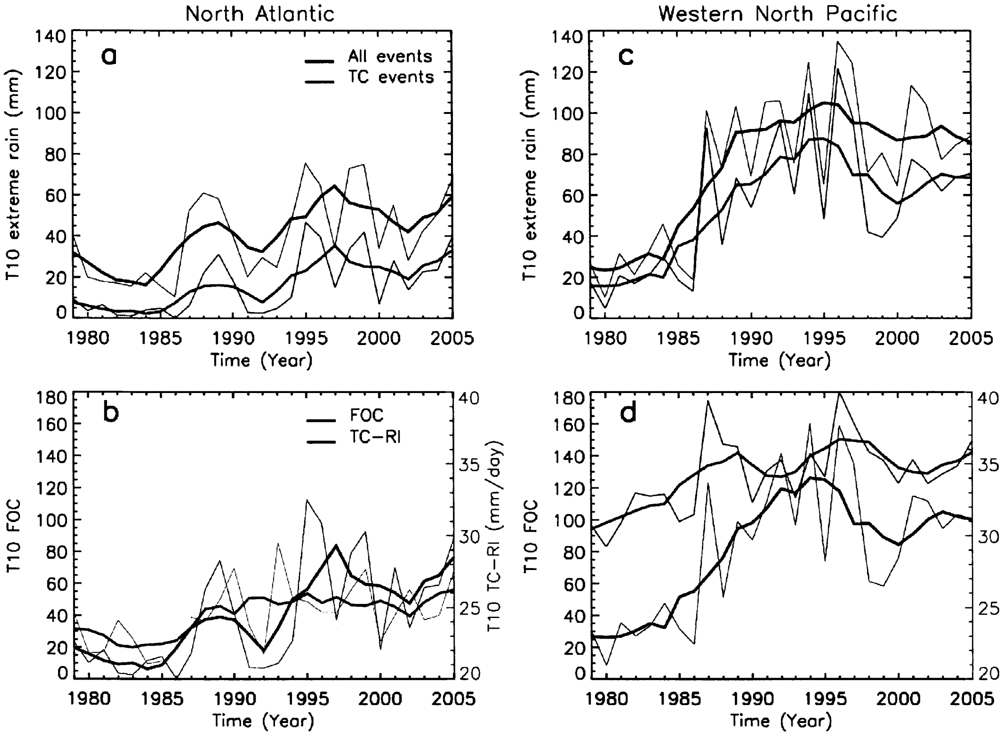

Figure 2. (a) Cumulative seasonal (JASON) GPCP rainfall amount (blue line) and TC-related rainfall (orange line) in T10 from 1979 to 2005. (b) Cumulative TC frequency of occurrence (blue line) and TC average rain intensity (orange line) in T10 for NAT. Thick lines show 5-year running averages. (c) and (d) are the same as in (a) and (b), except for WNP.

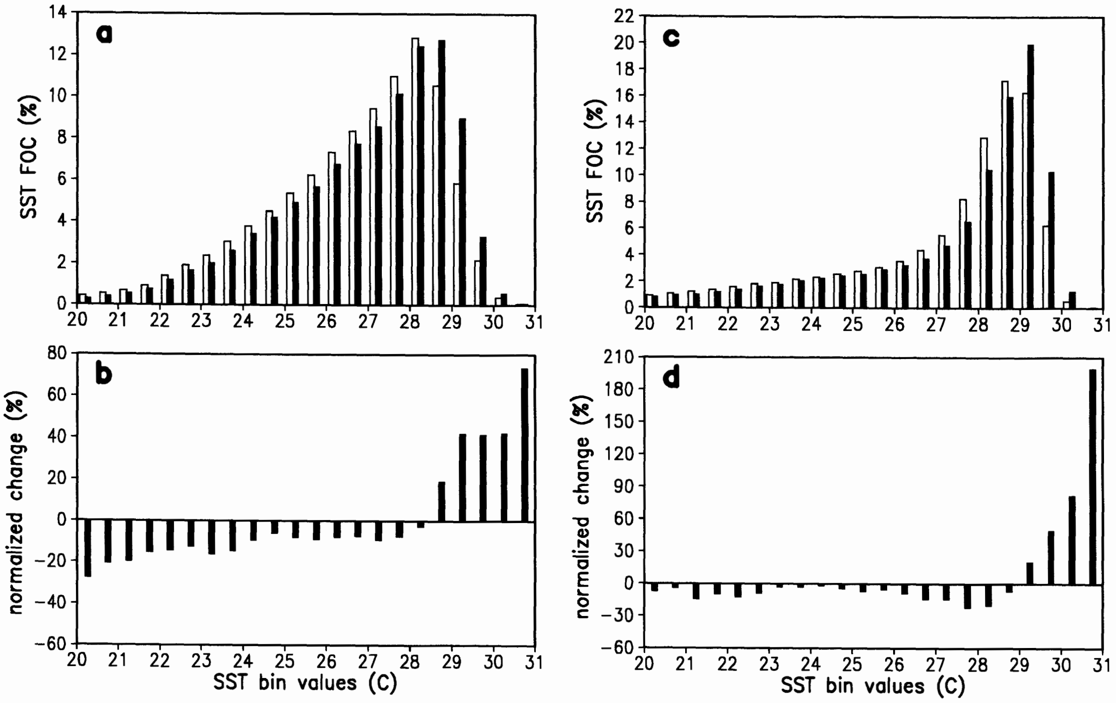

Figure 3 (a) The climatological frequency of occurrence (FOC) of SST at each SST bin (with 0.5°C interval) during JASON of the first 13 years (1979–1991, outlined bar) and the latter 13 years (1993–2005, filled bar), and (b) shift in FOC shown as the difference between the SST FOC of the latter period (1993–2005) and the first period (1979–1991) normalized by the mean of these two periods, for NAT. (c) and (d), as in (a) and (b), except for WNP.

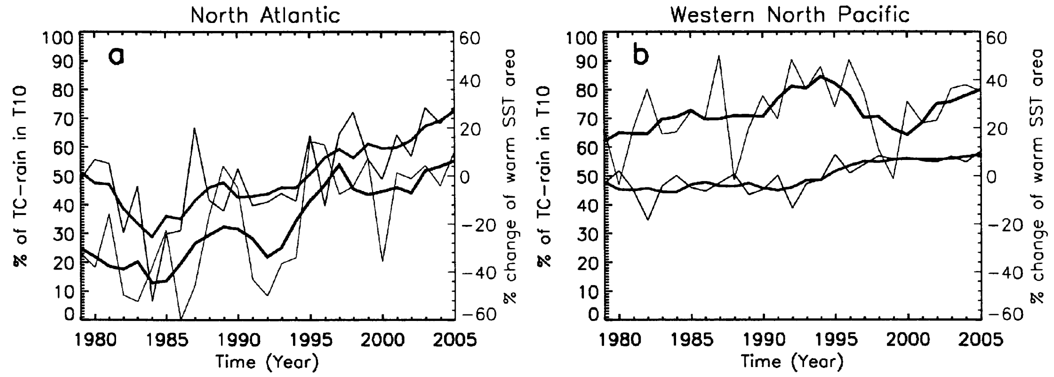

Figure 4 Percentage of cumulative extreme rainfall amount related with TC in T10 from GPCP (blue line). Orange line shows the normalized anomaly in percentage of warm pool area (defined as monthly SST>28°C) over JASON season for each year for NAT (a) and for WNP (b). Thick lines show 5-year running averages.

FIGURE CAPTIONS

Figure 1. (a) The climatological PDF from GPCP for JASON accumulated rainfall amount at each rainfall bin (with 1 mm/day interval) of the first 13 years (1979–1991, outlined bar) and the latter 13 years (1993–2005, filled bar), and (b) shift in PDF shown as the difference between the rainfall PDF of the latter period (1993–2005) and the first period (1979–1991) normalized by the mean of these two periods for NAT. (c) and (d), are the same as in (a) and (b), except for WNP.

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SUPPLEMENT MATERIALS

A. Comparison of rainfall statistics from TRMM and GPCP.

In this section of the supplement, we present the basic statistics of extreme rainfall and TC-related rainfall (TC-rain) based on the daily TRMM data, for NAT and WNP respectively, to provide background for understanding the main results shown in the paper. We also examine the consistency of TRMM-derived and the GPCP-derived rain statistics for the overlapping periods (1998–2005) to ensure that GPCP pentad data can be used for the extended period (1979–2005). Supplementary Fig. 1a shows the CPDFs for total rain, TC-rain amounts, and for the ratio of TC-rain to total rain in each category constructed from the TRMM daily data. Similar CPDFs for rain frequency have also been computed (Supplementary Fig. 1b). For low rainrates, the CPDF for total rain increases more rapidly than for TC-rain. For high rainrates, the reverse holds. These indicate that TC contributes more to heavy rain events than to light rain events. The percentage contribution of accumulated TC-rain to total rain increases almost linearly, as a function of rain rate. As shown by the intercepts at the ordinate in supplementary Fig. 1a, and also in supplementary Table 1, total TC- rain accounts for a modest 17.3% of the total amount, and occurs rather infrequently, accounting for only 7.9 % of the total occurrence as shown in supplementary Fig. 1b. For extreme rains, for example T10, 49% of rain events, and 53% of rain amount are accounted for by TC-rain. For WNP, the CPDFs (not shown) are similar including the nearly linear increase in contribution of fractional TC-rain, as a function of rainrate. The key CPDF statistics for NAT and WNP are shown in Table 1S. Comparing the two domains, TCs in WNP appear to produce more intense rain than in NAT, accounting for 9.0% of rain occurrence, but 20.3% of the total rain amount. The higher rainfall intensity for WNP TCs is also reflected in the higher rainfall thresholds in all three extreme rain categories (T5, T10, T20) (supplementary Table 1Sb). At T10, 53% of TC-rain occurrence accounts for 57% for rain amount. At T5, the corresponding ratios are 62% and 64%. These ratios appear to approach a common value (~65% for T5) for highly extreme events for both domains. Interestingly, at such highly extreme rain events, non-TC rain can still contribute up to 30% of the rain amount.

Similar CPDFs are constructed from the pentad-GPCP data for the overlapping period (1998–2005) of the two datasets, as shown in Table 1a and 1b for NAT, and WNP respectively. Since the GPCP pentad rainfall has lower spatial and temporal resolutions compared to TRMM, TC-rain can only be defined for the entire pentad, i.e., counting all rainfall within a pentad, if a TC passes over a given location during anytime of the pentad. Comparing Table 1S to Table 1, it is clear that the even though the thresholds for the GPCP extreme events are considerably lower relative to the daily TRMM data, the relative TC contributions to rainfall and frequency of occurrence are reasonably scale-invariant with respect to the extreme categories, with generally increasing TC contribution for heavier rains.

The spatial distributions of TC-rain from TRMM, and GPCP for Hurricane Katrina (Aug 24–28, 2005, Fig. S2a), for Typhoons Talim and Nabi (Aug 29 – Sep 2, 2005, Fig. S2b) show reasonably good matches in pattern and magnitude between the GPCP-pentad, and the 5-day rain constructed from the TRMM 3-hourly data, indicating that essentially the same TC related rain systems are captured by the two datasets. The above results provide reassurance that the GPCP data can be used to study the relationship between extreme rain and TC-rain, for the extended period, including the pre-TRMM era.

B. Time variation of total rain and TC-rain.

Fig. S3a shows the long-term variations of total rain and associated TC contributions, as well as seasonal accumulated FOC, and related averaged TC rain intensity (TC-RI) for all rain events for the two domains, NAT and WNP respectively. Definition of a trend is the same as described in the main text. It is first noted that there is no obvious trend in total rain for both NAT and WNP. In NAT, a weak trend (>95% c.l.) exists in TC-rain. Fig. S3b shows that the TC-rain possesses a significant trend in FOC, and a weak trend (>95% c.l.) in TC-RI. In WNP, the TC-rain amounts show large decadal scale swings, but exhibit no obvious trends (Fig. S3c). Notice also that the all-rain and TC-rain amounts in WNP are much higher than in NAT, with all events in WNP producing about 700 mm rain, compared to 450 mm in NAT. Similarly, TC-rain in WNP produces higher rain amount (~200–300 mm), compared to those in NAT (~50–100 mm). This again confirms the observation that TCs as a whole release more energy to the atmosphere in WNP compared to NAT. For TC-rain in WNP, there is no significant trend in FOC, but the TC-RI shows a significant trend (>99.9% c.l.) (Fig. S3d). As shown in the main text, the positive trends in TC-RI for both oceans can be attributed to the increasing contribution of TC to extreme rain events, with the NAT at a steeper rate compared to the WNP, possibly related to the faster rate of expansion of the warm pool in the NAT.

Table S1a. TC related extreme event rainfall statistics based on TRMM data for NAT (90°W–20°W, 10°N–40°N) during JASON 1998-2005.

	T5	T10	T20	TOTAL
TRMM-threshold (mm/day)	119.0	88.0	60.0	---
TC_event (%)	61.3	49.4	36.7	7.9
TC_rain (%)	63.9	53.2	41.6	17.3

Table S1b. Same as in Table S1a except for WNP (120°E–180°E, 10°N–40°N).

	T5	T10	T20	Total
TRMM-threshold (mm/day)	136.0	101.0	69.0	---
TC_Events (%)	61.5	53.2	42.5	9.0
TC_Precip (%)	64.2	56.7	46.9	20.6

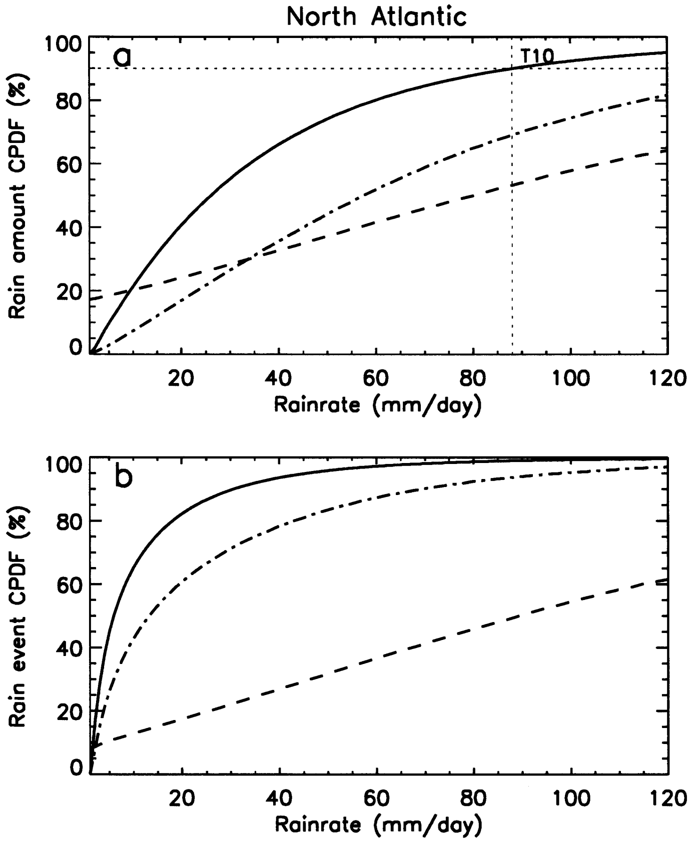

Figure S1. Cumulative PDF of daily rainfall (solid line) and TC-rain (dash-dot line) from TRMM 3B42 data for the North Atlantic (90–20°W, 10–40°N) during JASON, 1998–2005, for (a) rainfall amount and (b) frequency of occurrence. The dashed line in (a) shows the fractional TC-rain to total rain amount, and in b) the fractional TC events to total rain events.

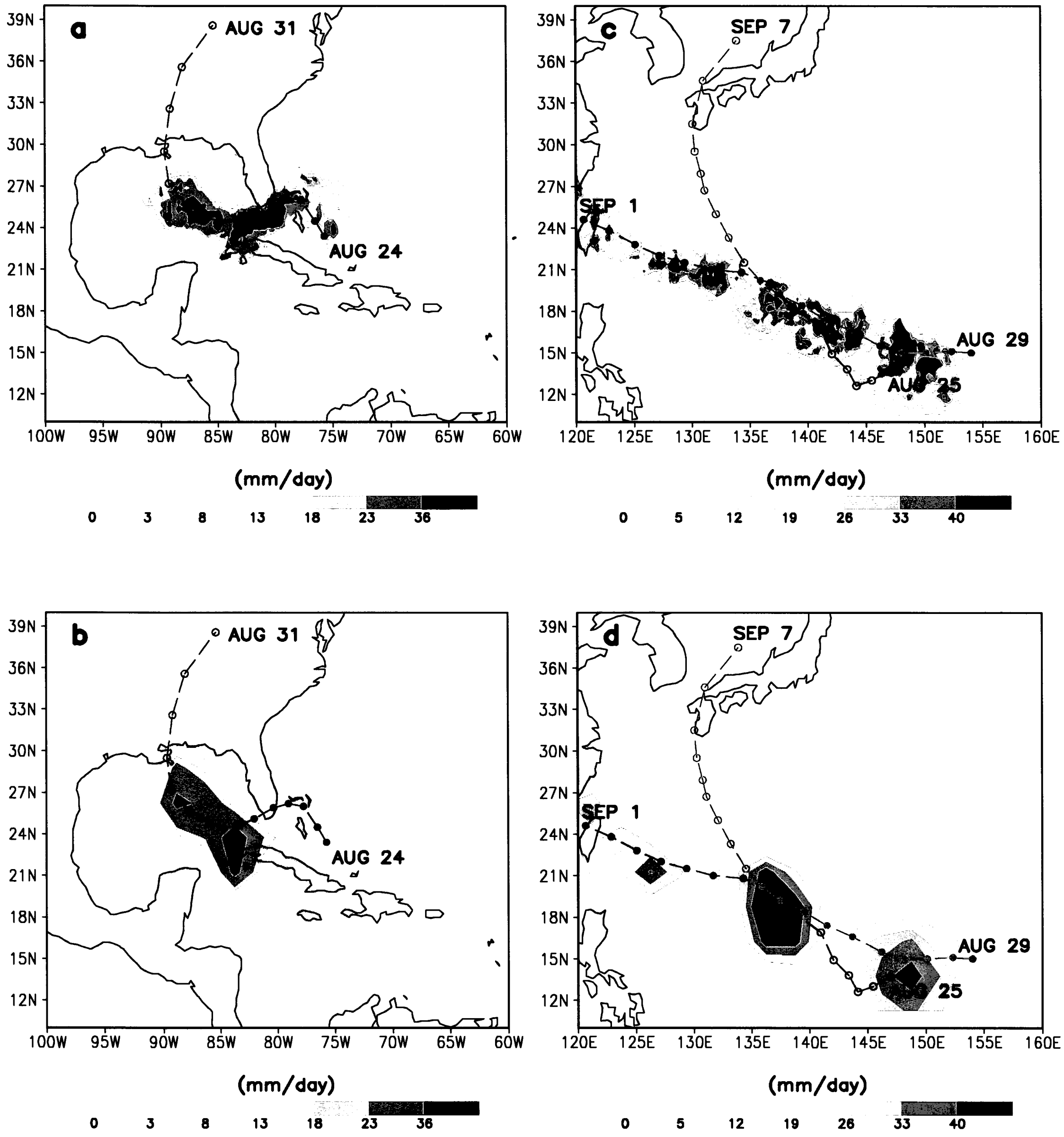

Figure S2. TC-rain from TRMM (a) and GPCP (b) during Aug 24–28, 2005 overlay with best track of Hurricane Katrina. TC-rain from TRMM (c) and GPCP (d) during Aug 29 – Sep 2, 2005 overlay with best tracks of Typhoons Nabi and Talim.

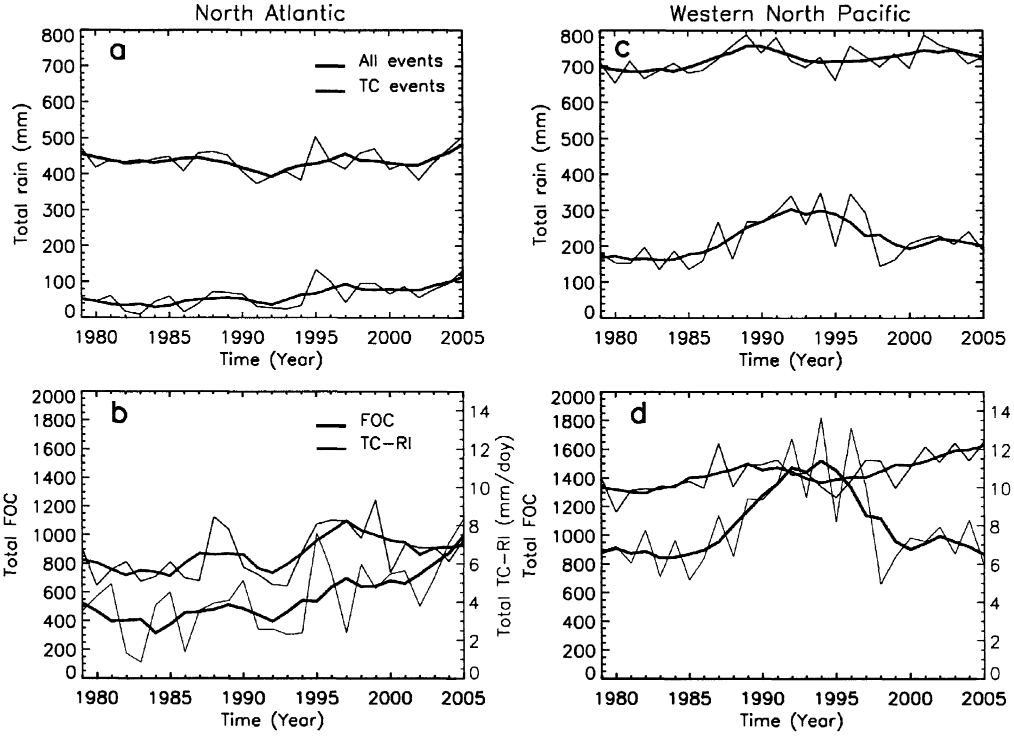

Figure S3. (a) Cumulative seasonal (JASON) GPCP total rainfall amount (blue line) and total TC-related rainfall (orange line) from 1979 to 2005. (b) Cumulative total TC frequency of occurrence (blue line) and average TC rain intensity (orange line) for NAT. Thick lines show 5-year running averages. (c) and (d) are the same as in (a) and (b), except for WNP.