Contribution of Tropical Cyclones to Rainfall at the Global Scale

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ABSTRACT

This study quantifies the relative contribution of tropical cyclones (TCs) to annual, seasonal, and extreme rainfall and examines the connection between El Niño–Southern Oscillation (ENSO) and the occurrence of extreme TC-induced rainfall across the globe. The authors use historical 6-h best-track TC datasets and daily precipitation data from 18,607 global rain gauges with at least 25 complete years of data between 1970 and 2014. The highest TC-induced rainfall totals occur in East Asia (>400 mm yr⁻¹) and northeastern Australia (>200 mm yr⁻¹), followed by the southeastern United States and along the coast of the Gulf of Mexico (100–150 mm yr⁻¹). Fractionally, TCs account for 35%–50% of the mean annual rainfall in northwestern Australia, southeastern China, the northern Philippines, and Baja California, Mexico. Seasonally, between 40% and 50% of TC-induced rain is recorded along the western coast of Australia and in islands of the south Indian Ocean in the austral summer and in East Asia and Mexico in boreal summer and fall. In terms of extremes, using annual maximum and peak-over-threshold approaches, the highest proportions of TC-induced rainfall are found in East Asia, followed by Australia and North and Central America, with fractional contributions generally decreasing farther inland from the coast. The relationship between TC-induced extreme rainfall and ENSO reveals that TC-induced extreme rainfall tends to occur more frequently in Australia and along the U.S. East Coast during La Niña and in East Asia and the northwestern Pacific islands during El Niño.

1. Introduction

Tropical cyclones (TCs) and their remnants are significant drivers of precipitation in different continental locations across the tropics and midlatitudes. While TC-induced rainfall can bring benefits to both water resources and agriculture (e.g., Abdalla and Al-Abri 2011; Kam et al. 2013), in many cases these storms lead to extensive damage for populations and infrastructure through flooding and subsequent landslides (e.g., Zhang et al. 2009; Y.-C. Chen et al. 2013; Czajkowski et al. 2013; Rappaport 2014).

To demonstrate the extent and impacts of TC-induced rainfall, we select four examples from different parts of the world (Fig. 1). Hurricane Irene (Fig. 1a) affected much of the Caribbean and U.S. East Coast during late August 2011. The hurricane induced considerable rainfall exceeding 300 mm at several stations located in Puerto Rico and along the coastal areas of North Carolina, Virginia, and Maryland, which caused an estimated 27 direct deaths (56% of the total fatalities), devastating floods, power outages for millions of people, and extensive damage to homes, roads, and bridges (Avila and Cangialosi 2011). Based on the National Flood Insurance Program Data, losses caused by Irene’s storm surge and inland flooding were estimated at $7.2 billion in the United States (Avila and Cangialosi 2011). In October 1979, Typhoon Tip brought heavy rainfall to Japan (Fig. 1b) although its strength and size weakened as it approached the Japanese coast. Over 300 mm of accumulated rain were recorded in different stations in Japan, causing 42 deaths, 283 injuries, over 22,000 flooded homes, and 600...
related landslides recorded around the country (Iacovelli and Vasquez 1998). In northeast Australia, Cyclone Yasi (Fig. 1c) produced more than 300 mm of rain from 30 January to 4 February 2011, affecting several towns in Queensland. Although the storm dissipated over land, its remnants continued to cause torrential rain, which led to flooding in several towns toward northern South Australia (BoM 2012). Yasi caused an estimated $3 billion (U.S. dollars) of damage (Y. Chen et al. 2013). The last example in Fig. 1d shows that most of the rainfall from Hurricane Kathleen (>200 mm) was recorded by rain gauges in the arid region of the Baja California Peninsula and southern California, causing historical flash floods with widespread property damage (Fors 1977).

A number of studies have examined the contribution of TCs to precipitation at the regional scale (e.g., Breña-Naranjo et al. 2015; Dare et al. 2012; Chen and Fu 2015; Ng et al. 2015). For instance, while in Mexico the total rainfall is weakly related to the amounts brought by TCs (the TC mean annual rainfall contribution typically ranges between 0% and 20%), the lower Baja California Peninsula receives up to 80% of its total annual rainfall from these storms (Breña-Naranjo et al. 2015). In Australia, the TC contribution to the November–April rainfall is the strongest along the northern coastline; however, the greatest proportional contributions are found in the northwestern region (Dare et al. 2012). In East Asia, TC rainfall can contribute to up to 60% of the monthly rainfall in the vicinity of the Philippines and the South China Sea.
during the months of May, June, November, and December (Chen and Fu 2015). Other studies have examined the connection between TCs and extremes rather than total rainfall at the regional scale, with particular emphasis on the United States (e.g., Shepherd et al. 2007; Knight and Davis 2009; Kunkel et al. 2010), North and Central America (Barlow 2011), Australia (e.g., Lavender and Abbs 2013; Villarini and Denniston 2016), and East Asia (e.g., Ren et al. 2006; Yin et al. 2010; Chang et al. 2012).

While most of the above-mentioned works focused on regional analyses, few studies have been performed at the global scale with satellite data (e.g., Prat and Nelson 2013; Jiang and Zipser 2010; Jiang et al. 2011; Skok et al. 2013). The advantage of using satellite-based estimates of rainfall is that they are available at the global scale, or at least within the 50°N–S belt. However, there are also a number of weaknesses such as (i) satellite records are generally short (i.e., post 1998), (ii) the rainfall estimates are affected by large uncertainties (e.g., Vila et al. 2009; AghaKouchak et al. 2011; Villarini et al. 2011; Derin and Yilmaz 2014; Prat and Nelson 2015), and (iii) their relatively coarse resolution (generally 0.25° × 0.25°, which is roughly 25 km × 25 km) leads to a smoothing of the extreme rainfall signature associated with TCs. For example, rainfall estimates from the Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA; Huffman et al. 2007) have been found to underestimate TC-induced rainfall extremes (e.g., Villarini et al. 2011). Breña-Naranjo et al. (2015) examined the errors associated with TMPA and other remote sensing products to quantify the contribution of TCs to total rainfall in Mexico over the 1998–2013 period. They found that satellite products underestimated rain rates by up to 50% (using maximum daily rainfall intensity during 102 TCs) compared to rain gauges.

Based on this brief overview, it is clear that different studies have examined the relationship between TCs and either total or extreme rainfall. However, global studies have generally suffered from short records, measurement errors, and smoothing of extremes, while longer-term studies have mostly been performed at the regional scale. Here we will provide a consistent long-term analysis of the contribution of TCs to total and extreme rainfall at the global scale. Moreover, we will provide insight into the spatial changes in TC rainfall contribution as the storms move inland.

While some studies related TCs and rainfall, much less is known about the role played by climate in controlling the occurrence and frequency of extreme rainfall events associated with these storms. Given the strong connection between El Niño–Southern Oscillation (ENSO) and the genesis and development of TCs at the global scale (e.g., Camargo and Sobel 2005; Camargo et al. 2007; Bove et al. 1998; Klotzbach 2011; Bell et al. 2014), it is reasonable to expect that this relationship should manifest itself in the TC rainfall records. Recently, Villarini and Denniston (2016) showed that there was a higher probability of TC-induced annual maximum rainfall events in Australia during La Niña. Yin et al. (2010) pointed out that the number of TC-heavy rain days is higher during El Niño years in eastern China. Villarini et al. (2014a) highlighted the role of North Atlantic TCs in causing flooding across the United States, with regional differences during the different ENSO phases.

Therefore, the main research questions we will address are as follows:

- What is the fractional contribution of TCs to extreme rainfall? Which areas of the world are the most susceptible to these storms in terms of TC rainfall? Analyses are performed globally to highlight regional differences.
- How does TC-induced extreme rainfall change with distance inland from the coast?
- Is there a climate connection between ENSO and TC-driven extreme rainfall, and if so, how does this connection vary spatially at the global scale?

The manuscript is organized as follows. Section 2 presents the data and the methodology. Section 3 describes the results across different regions of the world in terms of TC contributions to annual and seasonal rainfall as well as extremes. Section 4 investigates the relationship between ENSO and TC-induced extreme rainfall, while section 5 summarizes and concludes the article.

2. Data and methodology

We use daily precipitation data obtained from the Global Historical Climatology Network (GHCN; Menne et al. 2012a,b). We select 18 607 rain gauge stations from around the world with complete data and measurements ranging from 1846 to 2014. A year of daily data is considered complete if there are measurements for more than 330 days in the year. We retain only the stations with at least 25 complete years between 1970 and 2014; the year 1970 is selected because it marks the beginning of the satellite monitoring of TCs. Selected rain gauge records cover most of the TC active regions, with the exception of those surrounding the north Indian Ocean. Figure 2 shows the number of stations available globally that satisfy these requirements, and the peak in data availability between the 1970s and 1990s. To facilitate the discussion, we define three continental regions...
that correspond to the three main TC basins as follows: North and Central America (NCA), East Asia (EA), and Oceania and southeast Africa (OSA). Note that the continental area related to the north Indian TC region is not included in this analysis given the lack of complete rain gauge measurements in the area over our study period.

The TC data are derived from the International Best Track Archive for Climate Stewardship (IBTrACS; Knapp et al. 2010). Complete global IBTrACS storm data during the period 1842–2014 are used. The historical TC records provide information on the position of the center of circulation of the recorded storm, maximum sustained winds, minimum central pressure, TC track name, and radius of maximum winds every 6 h (0000, 0600, 1200, and 1800 UTC). (A summary of the time periods used in the analyses is provided in Table S1 in the supplemental material.)

We examine the connection between TCs and rainfall both in terms of total annual and seasonal contributions. Additionally, we consider the contribution of TCs to extreme rainfall using annual maximum (AM) and peak-over-threshold (POT) methods. For the AM analyses, we compute the annual maximum daily rainfall in every year and examine whether it occurred during the passage of the storm. For the POT analyses, for each site we calculate the 95th percentile of the rainfall distribution for the rainy days across the study period as our threshold, and compute the number of days exceeding this threshold every year. We consider daily rainfall to be TC induced if the center of circulation of the storm is located within a 500-km radius from the rain gauge during a time window of \( \pm 1 \) day. The choice of a 500-km radius is consistent with other studies in the literature (e.g., Jiang and Zipser 2010; Lee et al. 2010; Chavas and Emanuel 2010; Dare et al. 2012; Prat and Nelson 2013; Villarini et al. 2014b), as it represents the typical radius of a primary TC wind circulation (80–400-km radius).
from the TC center) and the extent of a curved TC cloud shield (550–600-km radius; Prat and Nelson 2013). Villarini et al. (2014b), for instance, showed that the composite mean rainfall associated with the top 10% of rainiest TCs in different TC basins is concentrated within a 5° radius (i.e., approximately 500-km radius). Furthermore, the 500-km radius accounts for the rainfall that falls directly from the inner core of the TC and the adjacent rainbands (e.g., Dare et al. 2012). We perform the analyses separately for the Northern and Southern Hemispheres, using the calendar year for the North Hemisphere, and the period ranging from September to August of the following year for the South Hemisphere because of different TC seasonality.

The examination of the role played by ENSO in controlling the occurrence and frequency of TC-induced rainfall extremes is based on logistic and Poisson regression. Logistic regression is used to estimate the probability that an annual maximum is associated with a TC during different seasons of ENSO (e.g., El Niño vs La Niña). The dependent variable is binary (1 or 0 depending on whether or not the annual rainfall maximum is associated with a TC), and therefore we model the relationship between the binary response variable and covariates as follows:

\[
\log\left(\frac{\pi}{1 - \pi}\right) = \beta_0 + \beta_1 x,
\]

where \(\pi\) is the probability of occurrence of a TC-induced annual maximum; \(\beta_0\) and \(\beta_1\) are the intercept and slope coefficients estimated via maximum likelihood, respectively; and \(x\) is the independent variable representing the Niño-3.4 index averaged for different seasons (winter, spring, summer, and fall). We use logistic regression only for rain gauges that have at least five annual maxima associated with TCs.

To examine the dependence of extreme TC rainfall days (i.e., number of days exceeding the 95th percentile of the rainfall distribution and associated with the passage of a TC) on ENSO states, we use Poisson regression, in which the rate of occurrence \(\lambda\) is a function of the ENSO index. Let \(N_i\) be the number of days exceeding a given threshold in the \(i\)th year at a given site. We model \(N_i\) with a conditional Poisson distribution as follows:

\[
P(N_i|\lambda_i) = \frac{e^{-\lambda_i} \lambda_i^k}{k!} \quad (k = 0, 1, 2 \ldots),
\]

where the rate of occurrence \(\lambda_i\) is a nonnegative random variable. We model \(\lambda_i\) as a linear function of the predictor via a logarithmic link function:

\[
\lambda_i = \exp[\beta_0 + \beta_1 x_i],
\]

where \(\beta_0\) and \(\beta_1\) are two parameters used to estimate via maximum likelihood, and the predictor is the Niño-3.4 index for the \(i\)th year and averaged for every season (winter, spring, summer, and fall). The Niño-3.4 index time series is available since 1950 from the Climate Prediction Center (CPC 2016).

3. Results

a. TC rainfall contribution

Figure 3 displays the average annual rainfall associated with TCs, and the relative contribution of TCs to the annual and seasonal rainfall totals. The largest contributions are found in areas that experience the largest TC activity, with average TC-driven rainfall in excess of 150 mm yr\(^{-1}\) and up to 1000 mm yr\(^{-1}\) in East Asia, which is the most affected region (Fig. 3a). Australia, Central America, areas in the Gulf of Mexico, and the coastal regions of the eastern United States also show relatively large TC rainfall amounts. In the EA region, the highest TC-induced annual rainfall (>400 mm yr\(^{-1}\)) is found at gauges located in the northern islands of the Philippines, southeast China, southeast Japan, and islands of the Philippine Sea (Fig. 3a). In terms of relative contribution (i.e., ratio of TC-induced rainfall to total annual rainfall; Fig. 3b), the largest proportions (from 30% to +40%) are found at stations located in the northern Philippines, Hainan, and Guam Islands. Significant fractions (20%–30%) are also found at rain gauges located in southeast Japan, along the southern coast of China, and in the central part of the Philippines. Our computed annual fractions are overall slightly higher than those detected in other global studies (e.g., Prat and Nelson 2013; Jiang andZipser 2010; Skok et al. 2013), likely because of the differences between data types (i.e., satellite vs rain gauges), spatial resolution (i.e., areal-averaged estimates vs point measurements), and/or record length (much longer here). However, fractions close to ours (around 20%–40% of total annual rainfall) were found by Ren et al. (2006) for southeastern China using rain gauges. At the seasonal scale (Fig. 3c), we ﬁnd that up to 45% of the boreal summer and fall rainfall is TC driven at stations located in southeast China, the Philippines, and the southern islands of Japan.

In the OSA region, the highest TC-induced annual rainfall is found at stations located along the coast of Northern Territory, Queensland, and northwestern Australia with values exceeding 200 mm yr\(^{-1}\). However, the largest contributions of TC rainfall to total annual rainfall (Fig. 3b) occur at stations located along the
northwestern coast of Australia (between 30% and 50%); in northern Australia the TC contribution is lower (~20%), suggesting that other mechanisms (e.g., closed lows; Lavender and Abbs 2013) are responsible for the large rainfall accumulations over that area. These fractions are generally similar to those found by Jiang and Zipser (2010), Dare (2013), Skok et al. (2013), and Ng et al. (2015) for the Western Australian coast. Substantial amounts of TC rain are also found at stations located in the south Indian Ocean islands, with the highest values ranging from 100 to 300 mm yr$^{-1}$ and accounting for up to 25% of the total annual rainfall. At the seasonal level, during the austral summer TCs are responsible for over 50% of the rain that falls along the western coast of Australia; in the northeastern coast, ~20%–30% of March–May rain originates from TCs. Nearly half of the December–January rainfall is triggered by TCs in some islands of the south Indian Ocean.

In NCA, the highest annual average TC rainfall amounts (100–150 mm yr$^{-1}$) are measured at rain gauges along the coastal areas of the southeastern United States and along the Gulf of Mexico, the Florida Peninsula, Puerto Rico, and the southern Baja California Peninsula.
coast (Fig. 3a). The proportion of TC-induced rain is about 10%–15% at stations located along the coastal regions of the eastern United States, the Florida Peninsula region, around the Mexican Gulf Coast, and in the northern Caribbean islands. Significant contributions from TCs to the annual rainfall (up to 45%) are found in the arid region of the southern Baja California Peninsula, highlighting the role of eastern Pacific TCs in the annual precipitation budget of this area. These results are consistent with Prat and Nelson (2013) and Breña-Naranjo et al. (2015), although our maximum fractions remain slightly higher than previously reported. The seasonal proportions also indicate that around 20%–25% of the September–November rainfall is TC driven in Florida, along the coastal regions of Georgia and in the Carolinas. On the Pacific side, around 25%–40% of the June–August rainfall is TC driven in the southern coast of California and in the Baja California Peninsula.

b. TCs and extreme rainfall

The estimation of the TC contribution to extreme rainfall using AM and POT approaches indicates that East Asia is the most affected region by TC-induced heavy rainfall, followed by the OSA and NCA regions (Fig. 4). The fraction of AMs associated with TCs is large in the EA region (Fig. 4a), with values ranging from 35% to more than 60% at rain gauges located along the southeastern coast of China (Hangzhou, Fuzhou, Huli District, and Guangzhou) and in the Hainan Island (over 60% of the AMs are TCs driven). In southeastern Japan, TCs are responsible for 40%–65% of the annual maxima. The station of Appari in the northern part of Luzon Island of the Philippines exhibits over 70% of TC-driven annual rainfall maxima. Large fractions are also found at stations in the south of Luzon Island (~60%) and Guam (~70%). These results are broadly in agreement with Chang et al. (2012), who found that 50%–70% of extreme rainfall along the southeastern coast of China was associated with TCs. Yin et al. (2010) found that more than 50% of the annual heavy rain days can be explained by TCs in the Fujian province of China, and the ratio reaches 85% in the northern part bordering Zhejiang Province.

In Australia (Fig. 4b), several northwestern stations exhibit from 40% to over 50% of TC-derived annual rainfall maxima, suggesting that the most extreme rainfall is driven by TCs. In contrast with the previous analyses on the fractional contribution of TCs to the mean annual rainfall, we found higher fractions (exceeding 35%) of annual rainfall maxima driven by TCs along the coast of the Northern Territory and Queensland coast, suggesting that these storms play a large role in controlling the upper tail of the precipitation distribution.

The highest proportions of TC-induced maxima in the NCA region (>30%) (Fig. 4c) are found at stations located along the U.S. East Coast (i.e., New Jersey, Maryland, Virginia, the Carolinas, and Florida), Puerto Rico, and the southern part of the Baja California Peninsula. Substantial fractions (20%–30%) are found in the Gulf Coast and southwestern Mexico. The contribution of TCs to the annual maximum rainfall is higher than their contribution to the mean total annual rainfall over these same areas (Fig. 3), implying that the role of TCs is particularly significant at the upper tail of the rainfall distribution.

Figures 4d–f display the contribution of TCs to the POTs. The overall patterns are similar to those discussed for the AM results, even though the fractional contributions tend to be lower, mainly in East Asia and along the U.S. East Coast and the Gulf of Mexico. These results suggest that extreme rainfall at these locations is also associated with other physical mechanisms besides TCs. In Australia, the fractions remain generally high particularly in the northwestern coastal area, suggesting that most of rainfall extremes are triggered by TCs in this region.

Sensitivity analysis is performed to assess the influence of varying time windows (i.e., rainfall associated with a TC only on the day of its passage, rather than ±1 day) on the fractions of TC-induced extreme rainfall (AM and POT). Results show similar patterns to those previously discussed, with a slight decrease in fractional contributions (see Fig. S1 in the supplemental material).

c. TC rainfall and distance from the shoreline

Coastal areas generally receive the majority of TC rainfall as these storms tend to weaken after making landfall. However, TC remnants may also produce heavy rainfall much farther inland from the coast (e.g., Villarini et al. 2011). Here we investigate the dependence of the TC contribution to total annual and extreme rainfall on distance inland from the shoreline by calculating the nearest distance of each station to the coastline (Fig. 5). In North America, the TC contributions to both total annual and extreme rainfall (AM and POT) are gradually decreasing as we move inland from the shore. The highest contribution of TCs to annual rainfall maxima (from 10% to over 30%) can be found at rain gauges located approximately within 400 km inland from the shore. This implies that heavy rainfall coming from TCs can penetrate hundreds of kilometers inland, affecting areas situated far from the coast. In Australia, on the other hand, there is a weaker dependence of TC influence on distance from the shore (Fig. 5b). Although high TC contributions are found along the immediate coastal areas, TC-induced rainfall remains notable and
on the same order of magnitude as coastal locations even up to 500 km inland from the Australian shoreline. The TC-induced rainfall tends to penetrate less over eastern Australia than over Western Australia due to the presence of steep slopes acting as physical barriers to TC rain (Dare et al. 2012). In East Asia, the largest contributions of TCs to mean annual and extreme rainfall are found within 150 km from the coast (Fig. 5c). The fractions decline considerably beyond 400 km. These results are in agreement with Prat and Nelson

FIG. 4. Relative contribution of TCs to extreme rainfall using (left) AM and (right) POT approaches. Results focus on (a),(d) East Asia; (b),(e) Australia; and (c),(f) Central and North America. Gray circles indicate locations at which TCs have no contribution to extreme rainfall.
who showed that the TC contribution decreased inland from the coast in North and Central America and East Asia but remained relatively constant in Australia. The rapid decrease of the TC contribution to rainfall with respect to the coast in the NCA and EA is likely related to the influence of orographic landscape features (i.e., large mountain ranges) and the presence of islands, in contrast with the wide continental expanse found in Australia (Prat and Nelson 2013).

**d. Extreme TC rainfall and ENSO**

Here we focus on the examination of the relationship between ENSO and TC-induced heavy rainfall. Because of differences in TC seasonality among our study regions, analyses are performed using 3-month averages of the Niño-3.4 index of JJA and SON for stations located in North and Central America and East Asia, and DJF and MAM for Australia.

Figure 6 summarizes the outcomes from logistic regression, in which we focus on the annual maxima. The significance and the sign of the estimated $\beta_1$ coefficient are used in interpreting the results. Negative (or positive) values of this coefficient indicate a greater probability that an annual maximum is caused by TCs during La Niña (or El Niño) years. For NCA, the results in Fig. 6 (top) highlight spatial geographical differences in the relationship between TC-induced annual maximum rainfall and ENSO, with TC AMs occurring during different ENSO phases. However, a spatially coherent negative signal (with results significant at the 5% and 10% levels) is found along the eastern coast of the United States, the Gulf of Mexico, and Puerto Rico, suggesting that TC-driven AMs are more likely during La Niña years. In East Asia on the contrary, we find a positive relationship with ENSO in most of the stations (Fig. 6, middle), indicating a higher likelihood of TC AMs during the El Niño phase. In Australia, overall, we find a higher number of stations with negative coefficients, indicating that TCs are more likely to cause annual rainfall maxima during La Niña years (Fig. 6, bottom).

The connection between ENSO and extreme TC rainfall is even stronger when we consider POT events (Fig. 7). While the results and conclusions are largely consistent with what we discussed for AMs in terms of major drivers, the overall strength of the relationship is generally much stronger. Over NCA (Fig. 7, top), the frequency of POTs caused by TCs is larger (smaller) during La Niña (El Niño) years over much of Puerto Rico, the Texas coast, and the eastern United States. This connection is not just limited to the coastal areas, but is felt farther inland in the southern Great Plains and in the northeastern United States. Between these two areas, there are indications suggesting that we would generally expect more POTs during El Niño. These regional differences can be related to differences in TC tracking during the different ENSO phases. The impact of El Niño is also felt in the southwestern United States, where POTs are generally tied to the occurrence of eastern North Pacific TCs. In East Asia (Fig. 7, middle), on average we expect a larger (smaller) number of POTs associated with western North Pacific TCs during El Niño (La Niña) years.
Niña) years, in particular in the Pacific Islands and Japan. The opposite is generally true in Australia, where the average frequency of TC-driven heavy rainfall days tend to increase during La Niña years over much of the eastern and western regions (Fig. 7, bottom).

4. Summary and conclusions

In this study, we used 18 607 rain gauges with at least 25 complete years (defined as 90% of daily measurements) of data between 1970 and 2014 to (i) characterize
TC rainfall across the globe at annual and seasonal scales, (ii) examine the contribution of TCs to heavy rainfall at each of the rain gauges, and (iii) estimate the connection between a major climate mode, ENSO, and the occurrence of TC-induced extreme rainfall.

The spatial distribution of the mean annual TC-induced rainfall indicates that the highest totals—sometimes exceeding 400 mm yr\(^{-1}\)—are found in the Philippines, coastal areas of South China, southeast Japan, and islands in the Philippine Sea. In Australia, TCs contribute to large rainfall totals in excess of 200 mm yr\(^{-1}\), particularly along the northeast coast of Queensland and north/northwestern Australia. Values in NCA are generally smaller than those observed in the other two regions, with the largest contributions (100–150 mm yr\(^{-1}\)) along the coastal areas of the Gulf of Mexico, Florida, the southeastern United States, and Puerto Rico. In relative terms, TCs play a major role (30%–50%) in determining the annual rainfall budget in western North Australia, the Baja California Peninsula, the northern Philippines, and

FIG. 7. As in Fig. 6, but for POTs and using Poisson regression.
Hainan and Guam Islands. Seasonally, the highest TC-induced rainfall proportions (~30%–50%) are recorded in northwestern Australia and the south Indian Ocean during the austral summer, and at stations in East Asia (southeast China, the Philippines, and southern islands of Japan) and western Mexico during the boreal summer and fall. We found similar relative TC-induced contributions to previous studies (e.g., Ren et al. 2006; Skok et al. 2013; Ng et al. 2015) in some specific areas (e.g., east China and northwest of Australia) but overall, our fractions tend to be slightly higher in comparison with global studies that used satellite data (Prat and Nelson 2013; Jiang and Zipser 2010; Skok et al. 2013) likely because of the spatial resolution of the datasets (i.e., areal-averaged estimates vs point measurements) or the difference in length of studied periods.

In addition to seasonal and annual totals, we also quantified the TC impacts on extreme rainfall using annual maxima (AM) and peak-over-threshold (POT) approaches. Overall, TCs produce more than 50% of the annual maxima at stations located in Northwestern Australia and EA (China coast, eastern Japan, the Philippines). Large fractions (20%–40%) are also found along the U.S. East Coast, the Gulf of Mexico, and Puerto Rico. When compared with the TC contribution to total and seasonal rainfall, these fractions suggest that TCs have a stronger effect on the upper tail of the rainfall distribution than on the total rainfall in the United States and NCA more generally. TC POT contributions are generally smaller than TC AM contributions, in particular in East Asia and North and Central America.

The fraction of TC-driven rainfall generally decreases as one moves inland. This is particularly visible in East Asia, and to a lesser extent in North and Central America, but far less so in Australia, where fractional values found along the coastal areas persist up to 500–600 km inland. Most of the differences among these regions are tied to the presence or absence of significant orographic barriers in the proximity of the coastline as previously highlighted by Dare et al. (2012) and Prat and Nelson (2013).

Given the strong connection between TC genesis/tracking and ENSO, and between TCs and extreme rainfall, we examined the relationship between ENSO and TC-induced extreme rainfall. We found that La Niña years witness an increased probability of TC-induced extreme rainfall in the United States and Australia; on the other hand, we would expect more extreme rainfall associated with TCs in East Asia during El Niño years. While analyses based on AM or POT series generally lead to the same conclusions, we found a much stronger signal for the POTs. That is, ENSO exerts a stronger control on the number of TC-induced heavy rainfall days, likely because of its connection with the frequency, genesis, and tracking of these storms. Overall, our findings on the relationship between ENSO and TC heavy rainfall reflect the large-scale response of TC tracks to ENSO (e.g., Camargo and Sobel 2005; Kim et al. 2014). In Japan, however, we find an increased probability of TC rainfall during El Niño despite a relatively low frequency of TCs. To examine this, we assessed the relationship between ENSO and the length of the tracks of AM-rainfall-inducing TCs from genesis to landfall at every rain gauge station in Japan. Tracks were significantly (at the 5% level by means of a t-test) longer during El Niño than La Niña years at several stations (Fig. S2 in the supplemental material). These findings are comparable to others (e.g., Wang and Chan 2002; Camargo and Sobel 2005), suggesting that TCs tend to be more intense, longer lived, and have more northward recurved trajectories during El Niño years in the western North Pacific. Thus, it is likely that in Japan the effect of ENSO on TC extreme rainfall is not tied to a larger frequency of TCs, but to the proximity of TC genesis to the date line, which produces longer TC tracks over areas with high sea surface temperature, providing more time for the TCs to intensify, leading to larger TC rainfall amounts during El Niño.

Our results indicate that TCs play a prominent role in generating extreme rainfall in different parts of the world, which often induce devastating consequences. Damages resulting from TC rainfall will likely escalate, as future projections point to up to a 20% increase in TC-induced heavy rainfall in a warmer climate (e.g., Knutson et al. 2010, 2015) and as populations living in TC-affected regions continue to grow (e.g., Peduzzi et al. 2012; Mendelsohn et al. 2012). However, the connection that has been found here between TC-induced extreme rainfall and ENSO suggests that improved ENSO forecasts may help predict the occurrence of TC-driven extreme rainfall in the regions where the strongest relationship between ENSO and TC extreme rainfall has been found.

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