Observed Changes in Extreme Precipitation Associated with U.S. Tropical Cyclones

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ABSTRACT: Numerous recent tropical cyclones have caused extreme rainfall and flooding events in the CONUS. Climate change is contributing to heavier extreme rainfall around the world. Modeling studies have suggested that tropical cyclones may be particularly efficient engines for transferring the additional water vapor in the atmosphere into extreme rainfall. This paper develops a new indicator for climate change using the enhanced rainfall metric to evaluate how the frequency and/or intensity of extreme rainfall around tropical cyclones has changed. The enhanced rainfall metric relates the amount of rain from a storm over a given location to the 5-yr return period rainfall in that location to determine the severity of the event. The annual area exposed to tropical-cyclone-related 5-yr rainfall events is increasing, which makes it a compelling climate change indicator. Quantile regression illustrates that the distribution of tropical cyclone rainfall is also changing. For tropical storms, all quantiles are increasing. However, major hurricanes show large increases in their most extreme rainfall. This study does not attempt to make any detection claims (vs natural variability) or attribution of the observed trends to anthropogenic forcing. However, the sensitivity of the results to natural variability in tropical cyclone frequency was somewhat constrained by comparing 2 decades from the previous active era (1951–70) with two from the current era (2001–20). This comparison also shows that both the mean rainfall and the maximum rainfall associated with tropical cyclones are increasing over most areas of the eastern CONUS with the most significant increases from northern Alabama to the southern Appalachians.

SIGNIFICANCE STATEMENT: The purpose of this study is to analyze the changes in frequency and magnitude of extreme precipitation events associated with tropical cyclones with the goal of developing a new indicator for climate change. This is important because heavy rainfall and associated flooding is one of the primary causes of tropical cyclone destruction and fatalities, especially in inland locations away from where storms initially make landfall. Our results show that both the frequency and magnitude of extreme rainfall events from tropical cyclones have increased over the CONUS. The strongest storms (major hurricanes) also show more of an increase in extreme rainfall than storms of weaker intensities.

KEYWORDS: Extreme events; Tropical cyclones; Climatology

1. Introduction

Tropical cyclones are one of the most destructive and lethal forms of severe weather, and they have become even more devastating over the last several decades (Emanuel 2005; Nogueira and Keim 2011; Weinkle et al. 2018). A significant risk associated with tropical cyclones is the extreme rainfall that they often produce. Most of the fatalities associated with tropical cyclones are not directly caused by the wind, but instead by water hazards (Rappaport 2014). The top two causes of death from U.S. tropical cyclones between 1963 and 2012 were storm surge (49%) followed by rain (27%) (Rappaport 2014). Tropical cyclones account for up to half of the daily 100-mm events (Prat and Nelson 2016) and up to 20% of the annual precipitation in portions of the southeast (Prat and Nelson 2013) in the Tropical Rainfall Measuring Mission (TRMM) precipitation estimates. Tropical cyclone quantitative precipitation estimates can change markedly depending on the source of the data (Mazza and Chen 2023). Rainfall estimates from stage IV radar data, which are a combination of radar and gauge data, exceeded precipitation estimates from IMERG, CMORPH, TRMM, and ERA5, with consistent underestimations from the satellite-based estimates.

Recent tropical cyclones have highlighted the threats posed specifically from the extreme rainfall caused by tropical cyclones. In 2017, Hurricane Harvey became the wettest tropical cyclone in U.S. history, dropping over 1500 mm of rain in Nederland, Texas (Blake and Zelinsky 2018; Landsea 2018; Kunkel and Champion 2019; Bosma et al. 2020). In 2018, Hurricane Florence set the all-time tropical cyclone rainfall record for North Carolina with over 900 mm of rain occurring over Elizabethtown, North Carolina (Bosma et al. 2020). Multiple rivers set new flood stage records across the region, several of which had just previously been set during the passage of Hurricane Matthew in 2016 (Stewart and Berg 2019).

Kunkel and Champion (2019) ranked the top 100 precipitation events in the CONUS for a 4-day duration and 50 000 km^2 area. Harvey was the wettest such event, and Florence was the seventh wettest event. Tropical cyclones accounted for 25% of

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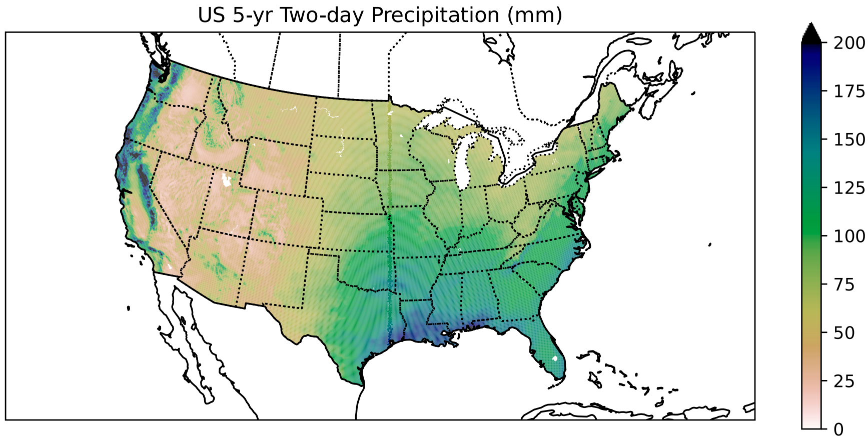

FIG. 1. Map of 5-yr return levels of 2-day accumulated precipitation (mm) for the CONUS.

the top 100, and the frequency of tropical cyclone extreme rainfall has been increasing with time. In fact, the likelihood of a precipitation event of the magnitude of Hurricane Harvey may have increased by a factor of at least 3.5 over the Houston area as a result of anthropogenic forcing (Risser and Wehner 2017). Models suggest that the recurrence period of a rainfall event of the magnitude of Hurricane Harvey will increase from a 1 in 100-yr event at the end of the twentieth century to a 1 in 5.5-yr event at the end of the twenty-first century as a result of anthropogenic forcing using the representative concentration pathway (RCP) 8.5 (Emanuel 2017).

Simple Clausius–Clapeyron scaling would suggest that tropical-cyclone-related rainfall would increase by about 7% per 1°C of global warming (Knutson et al. 2020). Modeling studies generally suggest that tropical cyclones are particularly efficient at tapping the excess moisture and may exceed that rate (Knutson et al. 2015; Wright et al. 2015; Liu et al. 2019; Patricola and Wehner 2018; Reed et al. 2022, 2021). However, the details are sensitive to the regions and methodologies. The modeling studies are particularly uncertain with regard to how the increasing rainfall rates will vary between the inner core and outer rainbands of tropical cyclones (Knutson et al. 2020).

Precipitation has already increased in association with tropical cyclones. For example, Maxwell et al. (2021) reconstructed tropical cyclone rainfall data over coastal North and South Carolina using tree ring data, which showed that precipitation amounts have been increasing over the past 300 years. Kunkel et al. (2010) examined daily heavy precipitation events at 935 COOP stations in 1895–2008. They attributed these events to tropical cyclones when they occurred within a 5° radius (~500 km) of a tropical cyclone. The precipitation associated with tropical cyclones was increasing, with most of the increase being concentrated in the most recent few decades (Kunkel et al. 2010).

Shearer et al. (2022) performed a similar analysis with high-resolution, continuous cloud-top temperatures from satellites that are bias-corrected on a monthly scale using GPCP gauge data. They also showed increases in overall precipitation rates over the last 4 decades. All tropical basins globally have shown increasing rates of tropical cyclone precipitation. Total precipitation increases from tropical cyclones globally are around 7%–15% over 40 years, with the largest increases in the North Atlantic, South Indian, and South Pacific basins (maximum 59%–64% over 40 years).

Increased rainfall rates are not the only contributor to these increasing trends. The translational speed of tropical cyclones over land and while near the coast is slowing down, which prolongs the extreme rainfall over a given location (Kossin 2018; Hall and Kossin 2019; Kossin 2019). Additionally, intensification rates of tropical cyclones as they approach landfall have been increasing (Klotzbach et al. 2018; Bhatia et al. 2019; Balaguru et al. 2022). Tropical cyclones with higher lifetime maximum intensities tend to produce more rainfall than weaker tropical cyclones (Cerveny and Newman 2000; Touma et al. 2019; Lavender and McBride 2021), and thus, increasing landfall intensity could produce a corresponding increase in precipitation as well (Xi et al. 2023).

This paper builds on the existing studies of trends in tropical cyclone precipitation (Kunkel et al. 2010; Guzman and Jiang 2021; Tu et al. 2021; Shearer et al. 2022). It leverages the recently released nClimGrid-Daily (Durre et al. 2022) dataset, which interpolates gauge data onto a 5-km grid over CONUS for 1951–present. These data provide a substantially longer record than is possible with satellite studies (e.g., Jiang and Zipser 2010; Shearer et al. 2022; Prat and Nelson 2013, 2016), which is important given the multidecadal variability of tropical cyclones in the Atlantic (Goldenberg et al. 2001; Schreck et al. 2021). It also provides greater spatial continuity than is possible with raw gauge data (e.g., Kunkel et al. 2010). The current study also provides two significant methodological innovations over previous observational studies. First, we use the extreme rainfall metric (ERM; Bosma et al. 2020) to categorize and standardize extreme rainfall relative to 5-yr extreme events. Second, we use quantile regression to examine how the full distribution of tropical cyclone rainfall rates is changing. One of the goals of this study is to develop a new climate change indicator (Stevens et al. 2023) for monitoring changes in tropical-cyclone-related rainfall over CONUS. In the context of this paper, climate change refers to the IPCC Sixth Assessment Report (AR6) definition, which is a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions, and persistent anthropogenic changes in the composition of the atmosphere or in land use (IPCC 2023).

2. Datasets

Rainfall data were obtained from nClimGrid-Daily, which covers 1951–present with a 5-km grid over the CONUS. The nClimGrid-Daily gridded rainfall data were generated from the Global Historical Climatology Network (GHCN) daily dataset (Menne et al. 2012). Most of the observations come from the morning cooperative network and ASOS stations. Unlike PRISM (Daly and National Center for Atmospheric Research Staff 2023), nClimGrid-Daily does not include radar or CoCoRaHS stations, which reduces its spatial coverage but improves temporal homogeneity. The gauge data are interpolated to a grid using thin-plate smoothing splines. The spline interpolation may also smooth some of the extreme values. However, this study is focused on the relative amplitudes of extreme events related to one another, not their absolute values. Since the smoothing would have similar effects on all extremes, the conclusions should be insensitive to those effects.

The tropical cyclone intensity and location data that were used originated from the hurricane database (HURDAT), which is maintained by NOAA. The HURDAT contains all Atlantic tropical cyclone observations from 1851 to present and was used to gather the location and intensity data for all storms in this study (Jarvinen et al. 1984; Landsea and Franklin 2013). This study uses data from the 1951–2021 hurricane seasons. All tracks are included in the analysis, including those portions marked subtropical or extratropical.

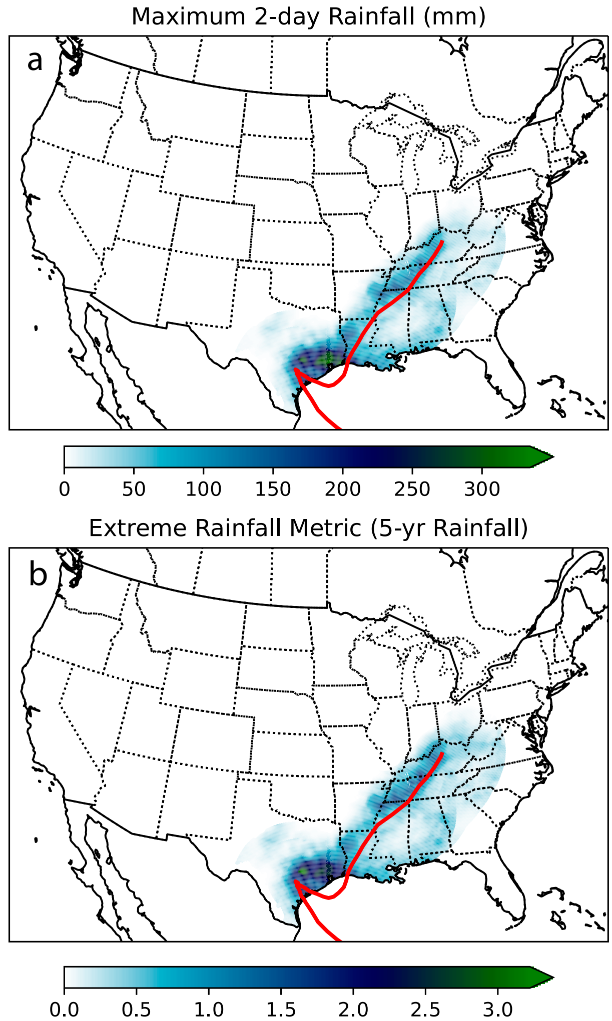

FIG. 2. Map of the 2-day precipitation (mm) associated with (a) Hurricane Harvey (2017) and (b) ERM associated with Harvey.

3. Methodology

Extreme rainfall events will be identified in part using the extreme rainfall multiplier (Bosma et al. 2020), which was defined for a given storm (s), location (χ), and duration of the rainfall event (t) as

$$\mathrm{ERM}_{s,\chi,t} = \frac{R_{s,\chi,t}}{R_{\chi,t}^{T\text{-yr}}},$$

where ERM is the extreme rainfall multiplier, $R_{s,\chi,t}$ is the rainfall depth from the given storm event, and $R_{\chi,t}^{T\text{-yr}}$ is the "T-year" return period for a rainfall event at that location and duration of rainfall event (Bosma et al. 2020). Originally, the extreme rainfall multiplier used a denominator of a 2-yr rainfall event to define an extreme event (Bosma et al. 2020). They argued that a 2-yr event was common enough to provide a frame of reference but significant enough to have societal impacts (Leopold 1968). We use the term "enhanced rainfall metric" for ERM as we believe it more accurately conveys the meaning of the metric used instead of "extreme rainfall multiplier" as defined originally by Bosma et al. (2020). It also happened to map to a range of roughly 0–6, which made for easier comparison with the Saffir–Simpson hurricane wind scale (SSHWS).

In this study, we will use a 5-yr return period. Similar to the 2-yr events in Bosma et al. (2020), a 5-yr event will be common enough to provide context and to be robustly calculated without the need for an extreme value model. However, we believe this higher threshold will have a stronger connection to societal impacts and is consistent with other studies of extreme rainfall (e.g., Kunkel et al. 2010). We also use 2-day rainfall events to account for the likelihood for even a short event to extend across nClimGrid-Daily's arbitrary reporting time of ~0700 LT.

To calculate the ERM for all rainfall events from tropical cyclones impacting the CONUS, the 5-yr 2-day rainfall was calculated for each grid point in the nClimGrid-Daily dataset for the entire CONUS. For each grid point, the annual maximum 2-day rainfall total, including nontropical events, was

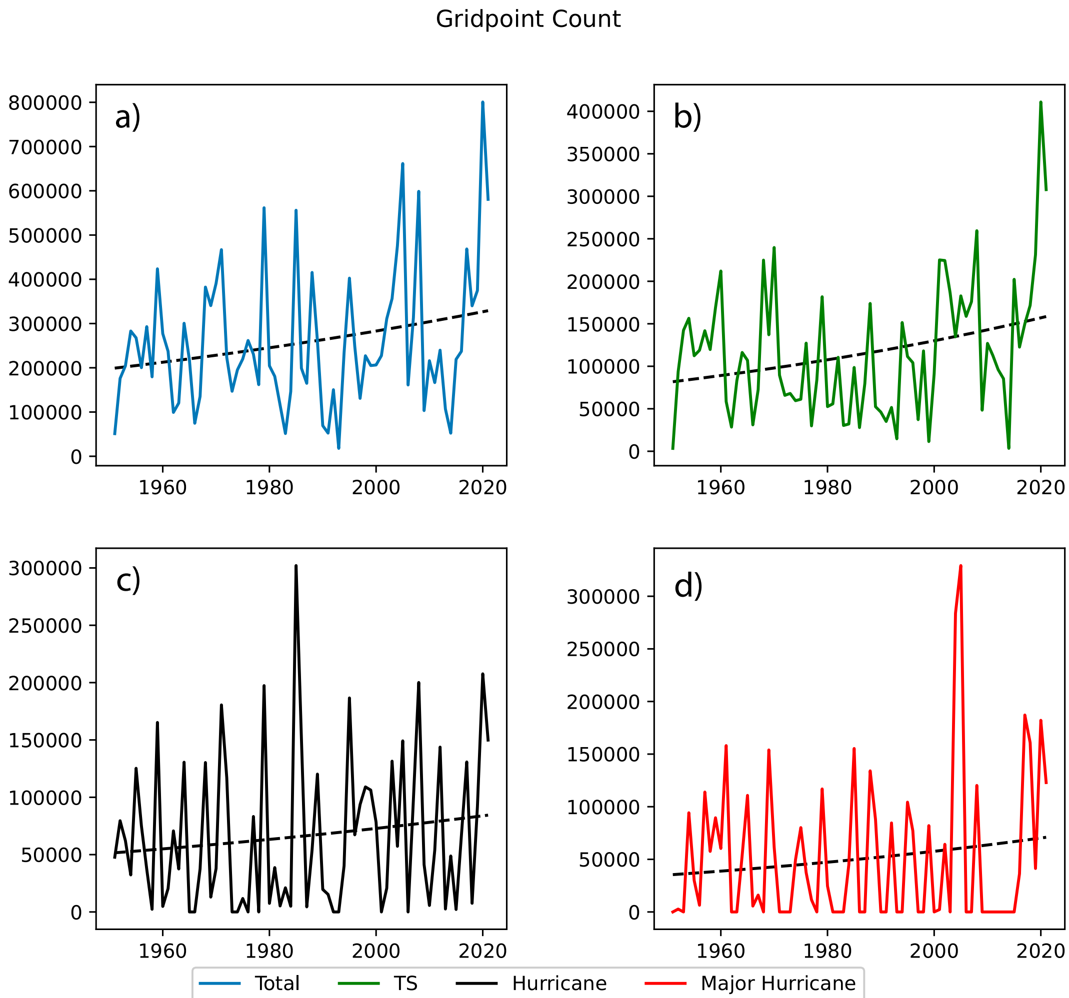

FIG. 3. Annual counts of the number of grid points where rainfall associated with a tropical cyclone occurred over the CONUS. The counts are broken down by (a) all storms, (b) tropical storm strength systems, (c) hurricane strength systems (categories 1 and 2), and (d) major hurricane strength systems (categories 3–5). The Poisson regression curve is shown by the black dashed line.

found for each year 1951–2021. The 5-yr 2-day rainfall was calculated as the 80th percentile of those annual maxima. Figure 1 shows the magnitude of 5-yr 2-day rainfall for the entire CONUS. The major advantage of using the ERM to determine whether or not an event is considered "extreme" is that it accounts for the geographic distribution of typical rainfall magnitudes. For example, Fig. 1 shows that a 5-yr 2-day rainfall event over the Gulf Coast has much higher magnitudes (>150 mm in most locations) than most East Coast locations (~75–125 mm). The denominator of ERM remains the same throughout the analysis, even when looking at separate storm intensities and time periods. Due to societal adaptations, areas that are prone to higher-magnitude rainfall events would be more resistant to their impacts; thus, the ERM values help adjust for the potential discrepancies in impact based on location for a given rainfall amount.

For each 6-hourly tropical cyclone position in HURDAT, all rainfall within 500 km is attributed to that storm following previous studies (Kunkel et al. 2010; Chalise et al. 2021; Prat and Nelson 2013). At each point for a given storm, only the greatest 2-day rain total is retained [either (day −1 and day 0) or (day 0 and day +1)], where day 0 is the day of the best track time step. In the event that a slow-moving storm results in overlapping 500-km radii, the overall storm maximum is taken for each grid point. Figure 2a shows an example of the rainfall associated with Hurricane Harvey in 2017 overlaid with the track of the hurricane. Figure 2b shows how the rainfall data are converted to ERM values using the 5-yr 2-day rainfall data from Fig. 1 in the regions impacted by Hurricane Harvey's rainfall. These two different metrics are used as previous studies have shown that results for tropical cyclone (TC) precipitation changes may change depending on the metric used (Stansfield and Reed 2023; Mazza and Chen 2023).

In this study, tropical cyclones are classified by their maximum intensity, while the storm was producing rainfall over

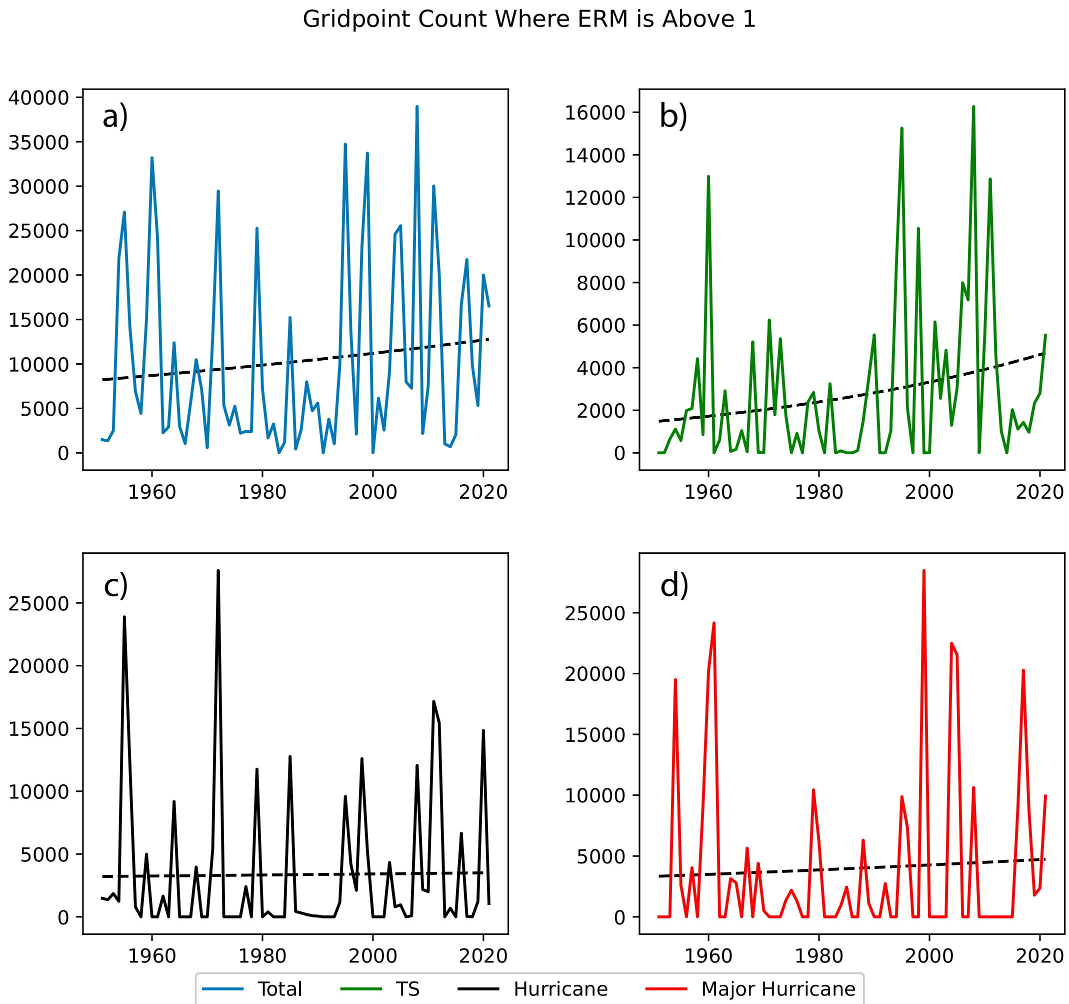

FIG. 4. As in Fig. 3, but for the annual counts of the number of grid points where ERM associated with a tropical cyclone occurred over the CONUS is greater than 1.

the CONUS within the 500-km radius. This intensity may be greater than the landfall intensity, but it allows for a consistent approach with storms that did not make landfall but produced rain over the CONUS. The intensities are binned as either tropical storms (35–63 kt; 1 kt ≈ 0.51 m s^{-1}), hurricanes (64–95 kt), or major hurricanes (≥96 kt).

4. Results

a. Trends of tropical cyclone rainfall events

Figure 3 shows the annual counts of the number of grid points with tropical-cyclone-related rainfall. Using a Poisson regression curve, the number of points for all storms has increased by about 50% over the 71-yr period (Fig. 3a). When broken down by intensity, tropical storm strength systems (Fig. 3b) are primarily responsible for this upward trend. The trends for total storms and tropical storm strength systems are significant at 90% and 95%, respectively. The trends are smaller and not statistically significant for category 1–2 hurricanes and major hurricanes. Years with no storms affecting land also become more common at these higher intensity thresholds—most notably the so-called major hurricane drought when no major hurricanes made landfall in CONUS during 2006–15 (Hart et al. 2016). This increasing trend is not being caused by an increase in the number of landfalls, as there is no evidence for an increase in the number of tropical cyclone landfalls (Klotzbach et al. 2018). There are a few studies that suggest that inland tropical cyclone tracks are lengthening, but these studies are controversial (Li and Chakraborty 2020; Chan et al. 2022).

Figure 4 shows the annual counts of the number of grid points over the CONUS associated with a tropical cyclone rainfall event where ERM > 1. In other words, this is the number of 5-yr 2-day events associated with tropical cyclones by year. The Poisson regression curve was significantly increasing for tropical storms, but not for the other categories. The trends for these extreme events are smaller than those for all grid points with TC-related rainfall (Fig. 3). This pattern

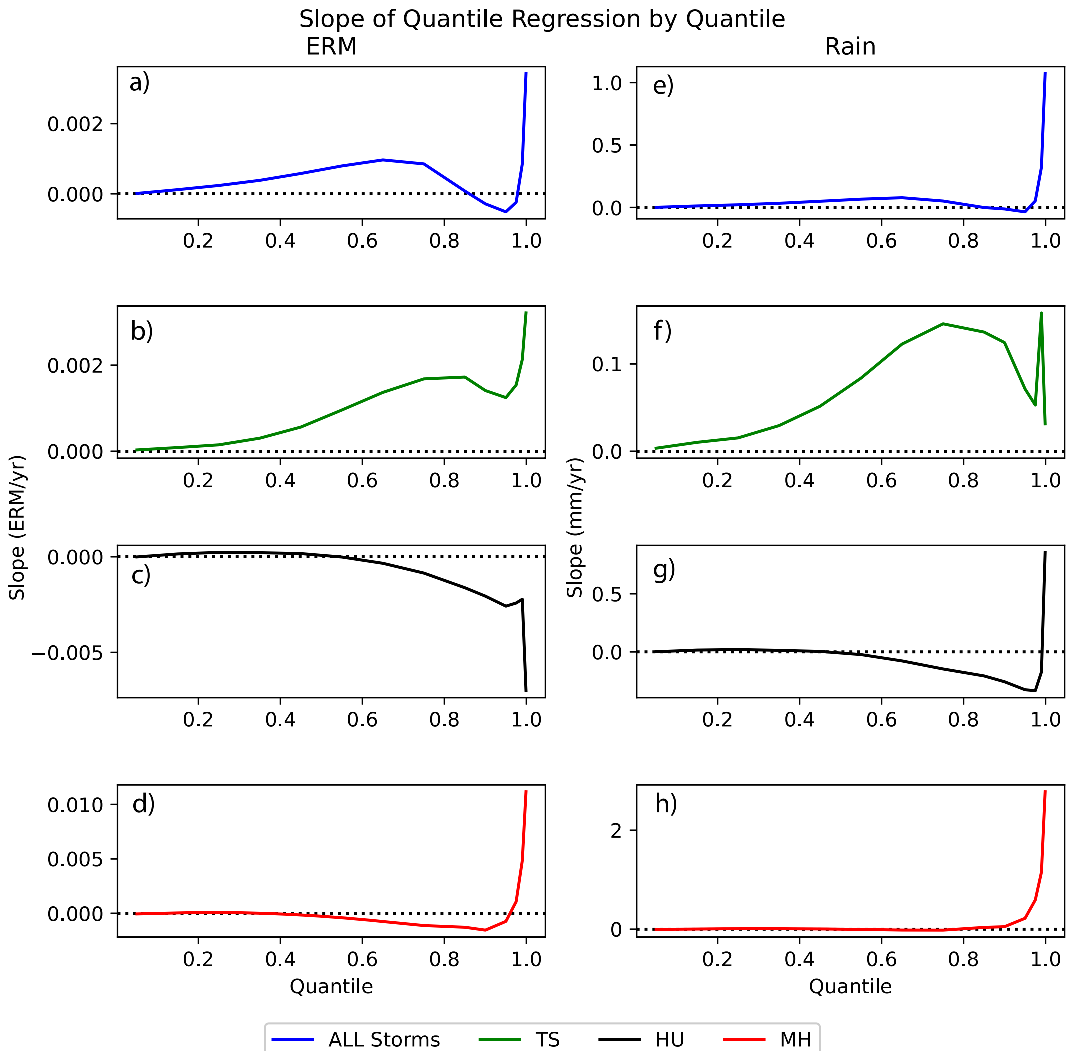

FIG. 5. The slope of quantile regression by quantile (slope values given in change per year) of annual tropical-cyclone-associated (left) ERM and (right) rainfall (mm) for (a),(e) all storms, (b),(f) tropical storms, (c),(g) hurricanes, and (d),(h) major hurricanes. The zero slope line is shown dotted.

suggests that the fraction of TC-related points that exceed a 5-yr 2-day event is increasing at a smaller rate over time.

b. *Quantile regression of extreme tropical cyclone rainfall*

The rainfall totals and ERM values at every grid point were computed for every CONUS-impacting tropical cyclone between 1951 and 2021 using the nClimGrid-Daily gridded rainfall dataset. This resulted in 71 years of tropical cyclone rainfall records. A quantile regression was computed for all of the tropical-cyclone-affected grid points for the entire historical record (18 373 201 total points) (Mann 1945). Figure 5 shows the results of the quantile regression by showing the slope by percentile for the 10th, 20th, … , 80th, 90th, 95th, 97.5th, 99th, and 99.9th percentiles. Figures 5a–d depict the ERM results, and Figs. 5e–h show the rainfall results.

The slopes for all storms (Figs. 5a,e) show increasing values for all quantiles below around the 85th percentile. These increases in moderate rainfall are driven primarily by similar trends in tropical storms (Figs. 5b,f). The slope becomes negative around the 95th percentile for all storms (Figs. 5a,e). This decrease appears to be driven by hurricanes (Figs. 5c,g) and major hurricanes (Figs. 5d,h). However, the increasing trend in tropical storm rainfall has a local minimum in this range as well.

The tropical storm rainfall (Fig. 5f) and the hurricane ERM (Fig. 5c) have slopes at some of the higher percentiles that do not align with the neighboring quantiles. These could be artifacts of numerical instability in the tails even though the samples are still very large (on the order of 10^5–10^6 data points). Nonetheless, in all the other panels, increasing trends are found for the highest quantiles that are in line with their neighboring quantiles. These increasing trends for the upper tail are larger for higher-intensity storms. Recall that no major hurricane rainfall occurred during 2006–15 (Fig. 3d). However, removing the

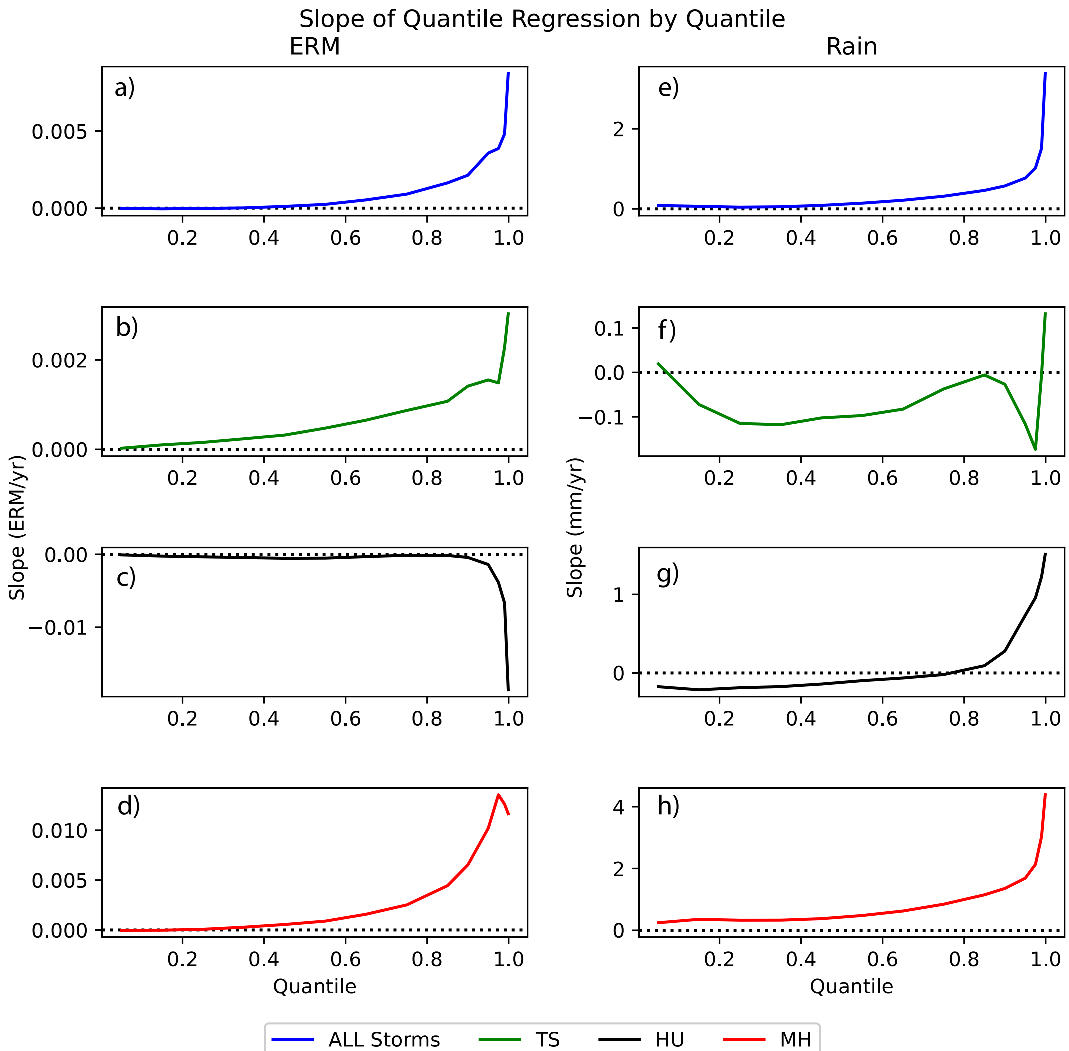

FIG. 6. As in Fig. 5, but only for points where the ERM > 1.

recent period (2017–21) does not significantly change the trend (not shown).

To further focus on the most extreme rainfall events, Fig. 6 repeats the quantile regression for only those points where the ERM > 1. In general, the increasing trends at higher quantiles are even more apparent within this subset of extreme events. The rainfall for tropical storms (Fig. 7f) is one exception where the quantile slopes are small and inconsistent. The hurricane ERM also has a strong decreasing trend at the upper quantiles, and the hurricane rainfall has a decreasing trend at the lower quantiles. However, even with these exceptions, Fig. 6 indicates increasing magnitudes of tropical-cyclone-related extreme rainfall.

c. *Spatial changes in extreme tropical cyclone rainfall*

Figure 7 shows the spatial distribution of the count of tropical cyclone rainfall events by location and intensity in the CONUS. As expected, tropical cyclone rainfall event count decreases farther inland from the Atlantic/Gulf of Mexico coastlines. When determining changes in the magnitude of extreme rainfall events between climatic periods, only regions with greater than 50 tropical cyclone rainfall events for tropical cyclones of all intensities in the historical record between 1951 and 2021 were considered to ensure a sufficient sample size. These regions are shown by the white contour in Fig. 7a.

For the spatial maps, we will compare 1951–70 with 2001–20 as a supplement to the quantile regression shown earlier. In addition to being the earliest and latest 20-yr periods in the data, they are both active tropical cyclone eras for the Atlantic (Goldenberg et al. 2001; Schreck et al. 2021). The intervening period 1971–2000 is dominated by an inactive period (1971–94).

Figure 8 shows a map of the maximum ERM and rainfall from tropical cyclones from 1951 to 1970 compared with 2001 to 2020. As would be expected, the highest tropical cyclone rainfall magnitudes can be found in Florida and the coastal regions of the Gulf of Mexico. The ERM values also tend to

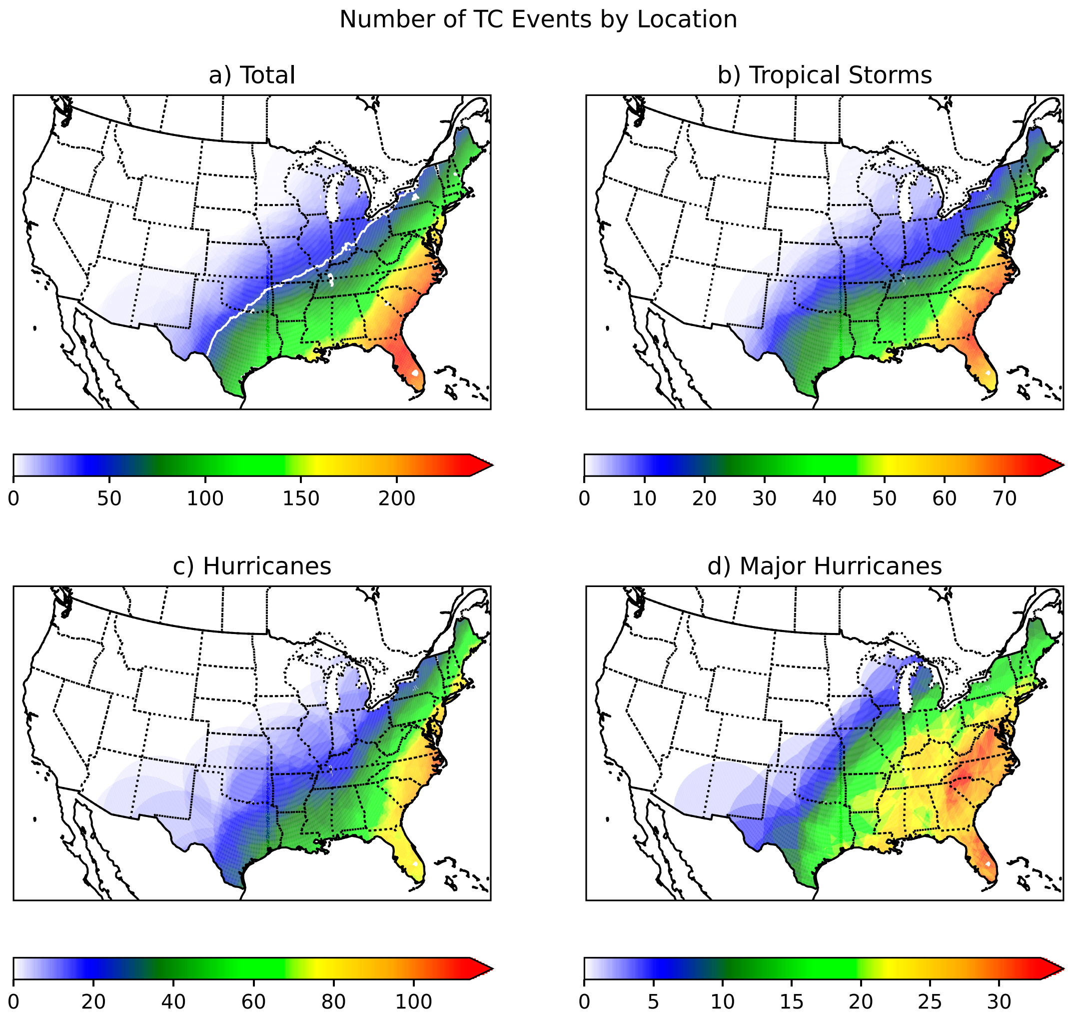

FIG. 7. Map of the count of tropical cyclone rainfall events by location and maximum storm intensity while affecting land in the CONUS. The count is shown for (a) all tropical cyclones (white contour shows 50 event lines), (b) tropical storms, (c) hurricanes, and (d) major hurricanes.

be highest in these regions as well, though there are exceptions such as in New England. Both ERM and rainfall show large increases between the two epochs.

Figure 9a shows the magnitude of the difference in maximum observed ERM between the two periods, while Fig. 9b shows the magnitude of the difference in maximum rainfall. The hatched regions show where the resulting differences are significant at 95% according to a bootstrap test. For the bootstrap resampling test, each grid point was resampled separately and each point was resampled 1000 times. From Fig. 9, it is apparent that most of the tropical-cyclone-impacted regions in the eastern CONUS have had a higher-magnitude ERM event in the most recent 2 decades compared with 1951–70, but that this increase is not at the level of being significant at most points individually.

To understand the significance of the overall percentage of the area showing an increase, a field significance test was also needed. The likelihood of such a large percentage (70.1%) of the area showing an increase in magnitude with time for both the ERM and maximum rainfall was infinitesimally small (significant at a greater than 99.9% probability). The largest positive differences are seen in southern Appalachia, Tennessee, Alabama, Mississippi, and the coastal regions of the Carolinas. Only a few locations had higher maximum observed ERM and rainfall events in the early period (1951–70), which included Virginia and parts of New England. These regions tend to be impacted by weaker storms and less frequent storms (see Fig. 5) than the coastal regions further south along the Atlantic coast and Gulf of Mexico. This could potentially partly explain why those regions have not seen the same increases in maximum tropical cyclone ERM and rainfall as locations further south that experience stronger and more frequent tropical cyclones.

Figure 10 is the map of the mean ERM from tropical cyclones from 1951 to 1970 (Fig. 10a) compared with 2001 to 2020 (Fig. 10b). Additionally, Fig. 10 shows the map of the mean

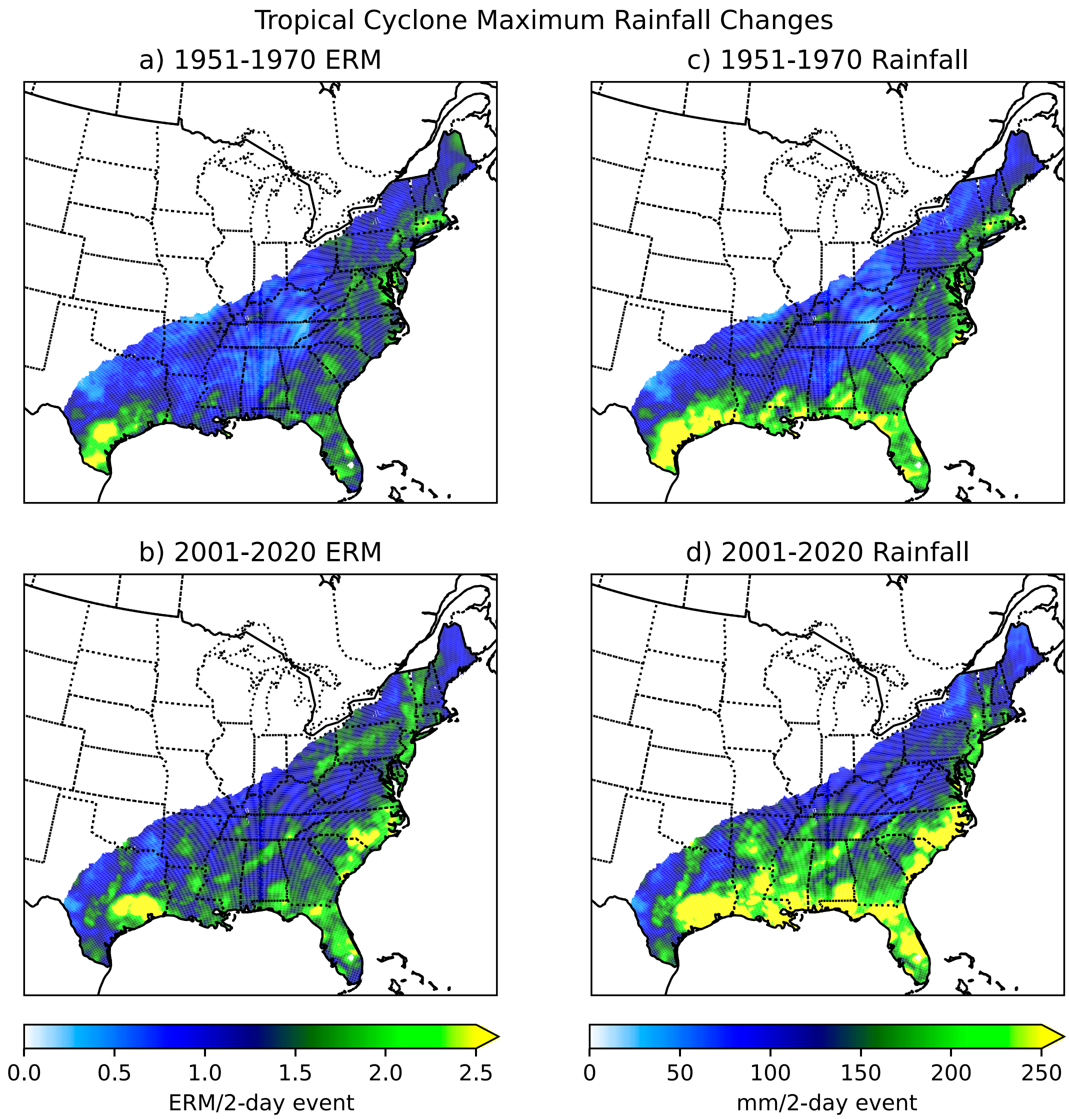

FIG. 8. Map of the maximum ERM from tropical cyclones from (a) 1951 to 1970 compared with (b) 2001 to 2020. Similarly, the map of the maximum rainfall associated with tropical cyclones from (c) 1951 to 1970 compared with (d) 2001 to 2020. Only the points where more than 50 tropical cyclone rainfall events occurred are shown.

rainfall associated with tropical cyclones from 1951 to 1970 (Fig. 10c) compared with 2001 to 2020 (Fig. 10d). Computing the mean of tropical cyclone ERM and rainfall for all grid points for the two time periods reduces the potential impact of individual tropical cyclones relative to the maximum values. Figures 10a and 10c clearly show that the values of average tropical cyclone ERM and rainfall are lower during 1951–70 when compared to 2001–20 (Figs. 10b,d) across most of the coastal regions of the southeastern CONUS. Along the coastlines where ERM and tropical cyclone rainfall tend to be the highest, typical ERM values show an increase from about 0.3 to 0.5 or higher in many locations, with rainfall increases from 60 to 80 mm in the early period to 80+ mm in many locations from 2001 to 2020. Similar increases in ERM and tropical cyclone precipitation can be seen further inland as well; in fact, some of the largest magnitude increases are near central Mississippi and northern Alabama.

Figure 11a shows the magnitude of the difference in the mean observed tropical cyclone ERM between the two periods, while Fig. 11b shows the magnitude of the difference in mean tropical cyclone rainfall. As illustrated in Fig. 9, the hatched regions show where the resulting differences are significant at 95% according to a bootstrap test. The bootstrapping was performed as shown in Fig. 9. Figure 11 shows that almost all of the regions frequently impacted by tropical cyclones in the CONUS have had an increase in the mean ERM and the mean rainfall produced by tropical cyclones between 1951–70 and 2001–20. Particularly, large increases occurred

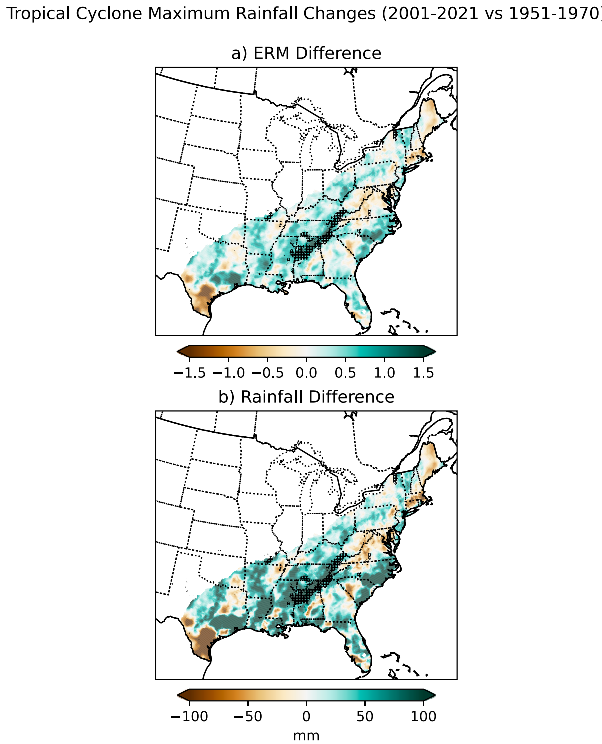

FIG. 9. Map of the difference in maximum (a) ERM per 2-day event and (b) rainfall per 2-day event associated with tropical cyclones between 2001–20 and 1951–70. Only the points where more than 50 tropical cyclone rainfall events occurred are shown. Hatched areas are significant at 95% according to a bootstrap resampling test.

in the mean ERM and rainfall values around Louisiana, Mississippi, and Alabama. These regions experienced mean ERM increases between 0.2 and 0.4 per event. The average rainfall associated with tropical cyclones in these regions also increased between 20 and 40 mm or more per event from 1951–70 to 2001–20. The increases in the mean tropical cyclone ERM and rainfall are indicative of the typical tropical cyclone producing more rainfall in recent years. Only a few regions with frequent tropical cyclone impacts did not show increases in mean ERM and rainfall from tropical cyclones, and these regions tend to have a lower frequency of tropical cyclone events. Once again, a field significance test was performed and it was determined that the likelihood of such a large percentage of the area (73.6%) showing an increase in magnitude with time for both the ERM and maximum rainfall was also infinitesimally small. Two regions with exceptions to the increases seen in most regions are in south Florida and most of eastern Texas, where the mean ERM and rainfall values have decreased, despite the high number of tropical cyclone rainfall events.

5. Conclusions

Extreme rainfall associated with tropical cyclones poses a significant threat to life and property. Modeling studies suggest that the threat from extreme rainfall will be exacerbated by anthropogenic climate change (Knutson et al. 2010; Gori et al. 2022). Observed tropical cyclone precipitation over the United States has been increasing (Kunkel et al. 2010; Shearer et al. 2022). Recent destructive tropical cyclones such as Hurricane Harvey (2017) and Hurricane Florence (2018) have shown the destructive potential and threats to life and property posed by extreme rainfall from tropical cyclones. This study showed that the threats posed by these storms have been observed to be increasing in recent decades. We examined both the actual rainfall values and the extreme rainfall metric (ERM), which compares the rainfall to its local 5-yr 2-day event threshold. The number of grid points impacted by tropical cyclone rainfall has shown a significant increase during the 1951–2021 time period, which was largely driven by tropical storms. This trend could be related to changes in storm frequency and/or inland penetration. However, no significant trends have been found for landfall over the CONUS (Klotzbach et al. 2018), and inland penetration could be sensitive to changes in observational networks and operational procedures.

The number of points experiencing 5-yr events (ERM > 1) also increased during the period, but at a slower rate. The heaviest rain is likely to occur near the coast, so any trends in inland penetration (physical or observational artifacts) would have less impact on this metric. These results suggest that the threat of extreme rainfall from tropical cyclones has become more widespread in recent decades.

Changes in the intensity of the tropical-cyclone-related rainfall were examined using quantile regression of both rainfall and the ERM. For tropical storms, rainfall rates and ERM have increased for all quantiles. Hurricanes and major hurricanes have seen decreases in moderately strong rainfall (roughly 50th–90th percentiles) but large increases in extreme rainfall ($\geq$95th percentile). The increases in extreme precipitation become more clear when only considering points where the ERM > 1. These results align with several previous studies that also showed increases in precipitation from tropical cyclones, particularly from the strongest storms (Kunkel et al. 2010; Stansfield et al. 2020; Shearer et al. 2022). These trends in the rainfall distribution should not be sensitive to changes in storm frequency or duration. Instead, this pattern suggests that stronger storms may be more efficient at tapping the increased water vapor associated with a warmer climate.

Most tropical-cyclone-prone regions of the CONUS (i.e., those experiencing at least 50 events from 1951 to 2021) observed higher maximum and mean tropical-cyclone-related rainfall and ERM in 2001–20 compared with 1951–70. The most statistically significant increases occurred from northern Alabama to the southern Appalachians.

The increasing destructiveness of tropical cyclones is among the most tangible effects of climate change. Our physical understanding of how climate change is affecting rainfall is arguably stronger than for any other tropical-cyclone-related threat. Tropical-cyclone-related rainfall can also extend farther inland and be more life-threatening than other hazards (Rappaport 2014). For these reasons, we believe tropical-cyclone-related rainfall is an ideal candidate to be monitored

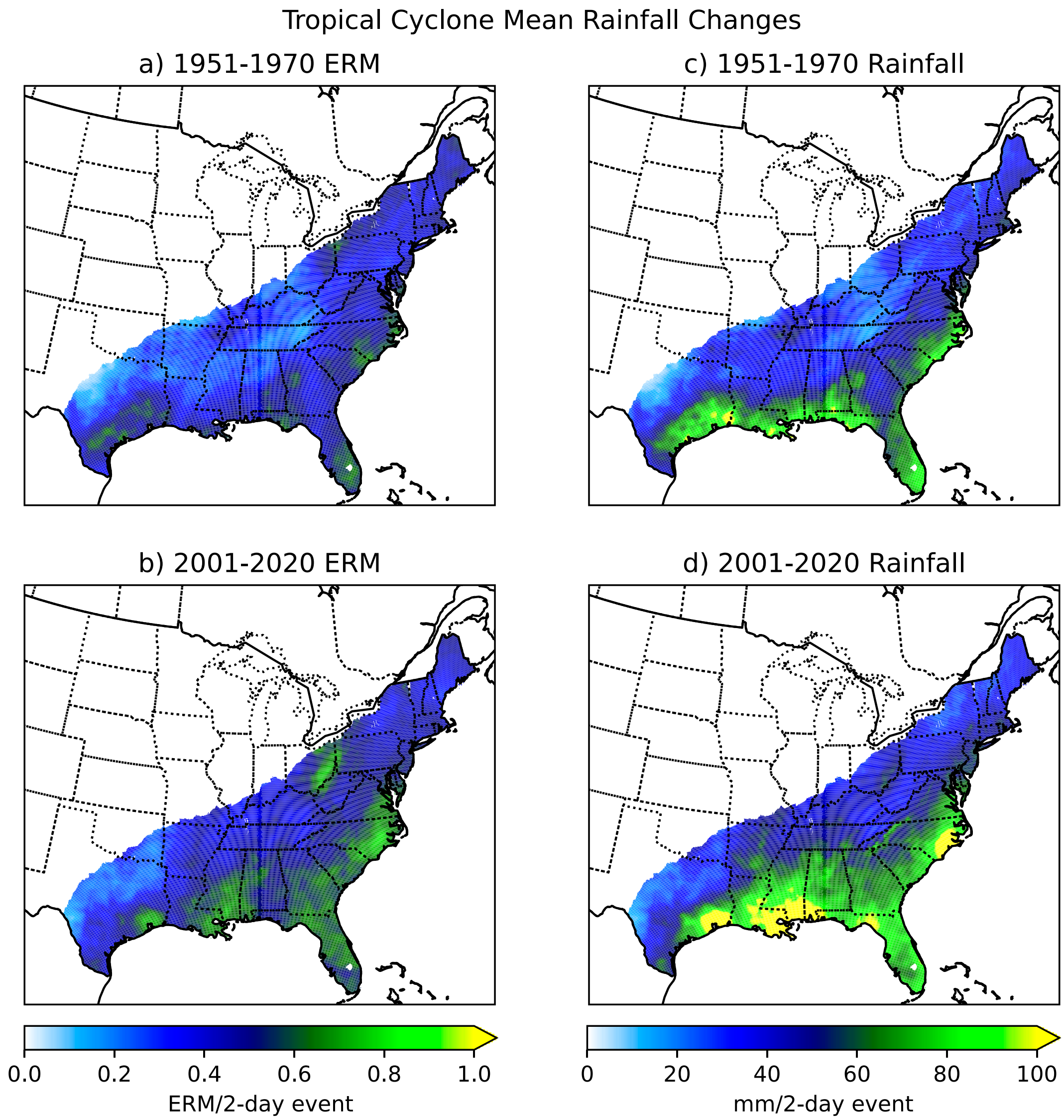

FIG. 10. Map of the mean ERM per 2-day event from tropical cyclones from (a) 1951 to 1970 compared with (b) 2001 to 2020. Similarly, the map of the mean rainfall per 2-day event associated with tropical cyclones from (c) 1951 to 1970 compared with (d) 2001 to 2020. Only the points where more than 50 tropical cyclone rainfall events occurred are shown.

with a climate change indicator. In this study, we propose the annual area impacted by tropical-cyclone-related 5-yr 2-day rainfall (ERM > 1, Fig. 6) for such an indicator. This indicator illustrates the growing area affected by extreme rainfall from tropical cyclones. These time series can be supplemented with maps (Figs. 8–11) that show how the mean tropical-cyclone-related rainfall and maximum tropical-cyclone-related rainfall have changed from the previous active era to the current one.

Future studies should examine the causes and pathways for the trends observed here. We do not attempt to make any detection claims (vs natural variability) or attribution of the observed trends to anthropogenic forcing. However, our comparison of two active periods (1951–70 vs 2001–20) should constrain the effects of hurricane variability from the Atlantic meridional overturning circulation (Goldenberg et al. 2001; Klotzbach and Gray 2008; Zhang et al. 2019) and from anthropogenic aerosols before the enforcement of the Clean Air Acts (Booth et al. 2012; Villarini and Vecchi 2012, 2013). The comparison of active eras and the focus on rainfall rates (as opposed to total rainfall) should reduce the sensitivity of the results to changes in tropical cyclone frequency. Also, the focus on the maximum 2-day rainfall rate will reduce (but not eliminate) the effects from the slowing trends in tropical cyclone translation speed (Kossin 2018; Hall and Kossin 2019; Kossin 2019). However, the increasing trend in tropical-cyclone-related points with ERM > 1 could be related to changes in storm frequency, inland penetration, and/or translation speed.

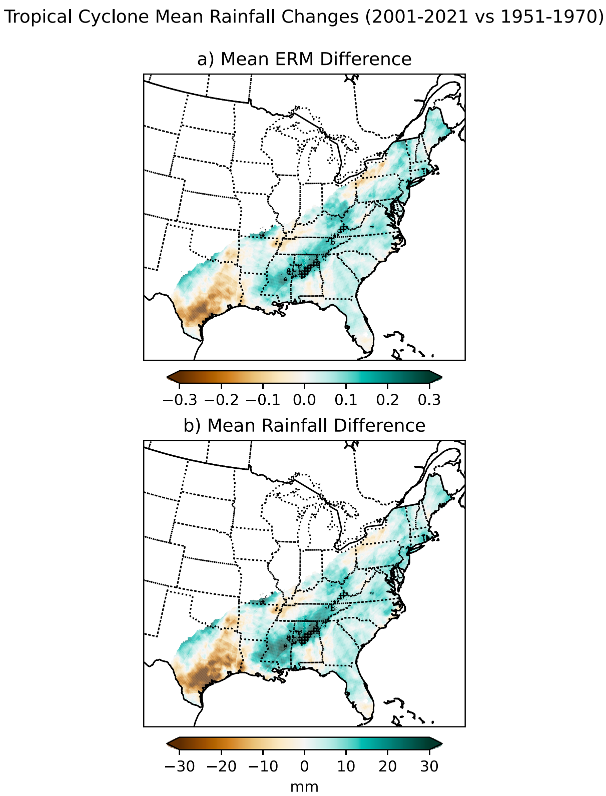

FIG. 11. Map of the difference in (a) mean ERM per 2-day event and (b) mean rainfall per 2-day event associated with tropical cyclones between 2001–20 and 1951–70, only the points where more than 50 tropical cyclone rainfall events occurred are shown. Hatched areas are significant at 95% according to a bootstrap resampling test.

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Data availability statement. All nClimGrid-Daily rainfall data that were used in this study are freely available through the NOAA NCEI at https://doi.org/10.25921/c4gt-r169. All HURDAT tropical cyclone data are available through the NOAA NHC at https://www.aoml.noaa.gov/hrd/hurdat/Data_Storm.html.

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