Extreme Rainfall in Taiwan: Seasonal Statistics and Trends

LEXI HENNY,a CHRIS D. THORNCROFT,b HUANG-HSIUNG HSU,c AND LANCE F. BOSARTa

Abstract: Taiwan regularly experiences precipitation extremes of hundreds of millimeters per day, especially between May and September. In this study, Taiwan's extreme rainfall (ER) is analyzed over a 56-yr time period in different seasons and geographic regions, using a recently released, high-resolution gridded rainfall dataset. ER is defined using a seasonally and geographically varying 99th-percentile threshold to better resolve the characteristics of the most intense rainfall seen in different locations and times of year. The resulting monthly ER rates are largest in typhoon season and smallest in fall, winter, and spring. ER is spatially homogeneous in the mei-yu and typhoon seasons and concentrated in northern Taiwan during the rest of the year. A trend analysis revealed a positive trend in island-mean ER for the winter, spring, and typhoon seasons. In winter and spring, these trends are most pronounced in the north. In the mei-yu season, ER has increased most over the southwestern mountain slopes; in typhoon season, ER has increased consistently over much of Taiwan. These changes often exceed 1% yr⁻¹. In many areas, typhoon season accounts for the largest fraction of the observed annual ER trend. TCs produce most of the observed typhoon season ER and ER trend, with nearly half of the typhoon season ER trend being associated with increases in TC frequency and duration around central and northern Taiwan. Certain regional changes in ER characteristics, particularly in areas with low sample size or complex seasonal contributions, merit further investigation in future work.

Key words: Asia; Hurricanes; Orographic effects; Climate variability; Hurricanes/typhoons; Anomalies; Climate variability; Interdecadal variability; Seasonal cycle; Seasonal variability; Trends

1. Introduction

Located off the southeast coast of China between 21° and 26°N, Taiwan experiences a monsoon climate, cycling between warm, moist southwesterly flow in the summer and cool, dry northeasterly flow in the winter (Chen and Chen 2003; Chen et al. 2007). Abundant warm-season moisture, combined with terrain that extends to nearly 4000 m above sea level (see Fig. 1), creates an ideal environment for rainfall of hundreds of millimeters per day (e.g., Trier et al. 1990; Li et al. 1997; Chen et al. 2007; Xu et al. 2009, and others). Such heavy rainfall has the potential to cause massive economic damage, disrupt infrastructure, and threaten lives, so much so that the World Bank in 2005 listed Taiwan as the country with the most exposure to three or more natural hazards (Dilley et al. 2005). Papers often focus on extreme rainfall from specific weather types, especially tropical cyclones (TCs), or on island-averaged heavy rainfall. The aim of this study is to take a more general view of extreme rainfall (ER) in Taiwan, including consideration of the different seasons as well as geographic distribution on the island.

The rainy season in Taiwan begins with mei-yu season, typically defined as mid-May to mid-June, when the island experiences frequent incursions of the quasi-stationary mei-yu front (Chen and Chen 2003). During mei-yu season, low-level winds are typically from the west and southwest, with frequent embedded mesoscale convective system (MCS) activity bringing the most intense rains. By July, these rainbands have shifted north and TCs become the dominant source of extreme rainfall. Additionally, during this time, diurnal convection provides some of the highest hourly rainfall rates (Wang and Chen 2008; Wu et al. 2019).

Beginning in September, the circulation shifts so that winds are more from the northeast (Chen and Chen 2003). Due to the north–south-oriented mountain ranges that line the eastern half of the island, this shift in wind direction also means a shift in the location of the highest rainfall, from southern and western regions to northern coastal regions. Rainfall amounts are reduced due to lower moisture availability, but the northern part of Taiwan may still receive heavier rainfall in association with southward-moving cold fronts (Chen and Chen 2003; Chen et al. 2007; Hung and Kao 2010). Certain northern areas receive nearly 300 mm month⁻¹ of rain in these seasons, with some extreme events producing over 100 mm day⁻¹ (Henny 2019).

Taiwan’s extreme rainfall has increased rapidly during recent decades (Chen et al. 2007; Shiu et al. 2009; Tung et al. 2016, and others). This change is faster than would be expected from a simple Clausius–Clapeyron scaling of increased moisture with increased temperature (Shiu et al. 2009). Annually, the extreme rainfall increase comes mainly from increases in typhoon extreme rainfall, which mask weaker increasing trends in non-typhoon extreme rainfall (Chang et al. 2012). The very large increases in typhoon extreme rainfall (Su et al. 2012; Chu et al. 2014, 2018) have been associated with an increase in TC activity since the turn of the millennium (Tu et al. 2009; Chang et al. 2013; Wu et al. 2016). However, activity declined once again after 2012, calling into question whether this shift is part of a long-term trend.

DOI: 10.1175/JCLI-D-20-0999.1

© 2021 American Meteorological Society. For information regarding reuse of this content and general copyright information, consult the AMS Copyright Policy (www.ametsoc.org/PUBSReuseLicenses).
While TCs are responsible for the most extreme rainfall, non-TC rainfall has also experienced changes on multidecadal time scales. For example, Hung and Kao (2010) describe an abrupt increase after 1980 in frontal winter rainfall over the northern and western plains of Taiwan (as opposed to northern coastal orographic rainfall, which has not increased). Huang and Chen (2015) found that May and June frontal convective rainfall has decreased in Taiwan from 1982 to 2012 due to a northward shift of the region of maximum meridional temperature gradient, while diurnal convection has increased in association with a strengthening daytime land–sea thermal contrast.

Although there have been many studies describing Taiwan’s total and extreme rainfall, work has typically focused on island averages and/or a single weather type or season. The purpose of this study is to provide a comprehensive, high-resolution view of seasonal extreme rainfall averages and trends, adjusted for geographic location and time of year by using a seasonally and geographically varying 99th-percentile threshold. The dataset that we use, constructed by the Taiwan Climate Change Projection Information and Adaptation Knowledge Platform (TCCIP), has not yet been fully explored. This presents a unique opportunity to analyze the characteristics and trends of extreme rainfall at high spatial resolution.

The paper is structured as follows: section 2 will describe our data and methodology, section 3 will depict seasonal extreme rainfall statistics, and section 4 will include trends and changes in these statistics, as well as a more detailed analysis of these changes. Conclusions are given in section 5.

2. Data and methodology

a. Rainfall data and trends

TCCIP maintains a 1 km × 1 km daily gridded rainfall dataset derived from a combination of data from the Central Weather Bureau (CWB), the Water Resources Agency, the Taiwan Power Company, and the Irrigation Association (Weng and Yang 2018). The CWB stations that contribute to this dataset are shown as a function of altitude and year added in Fig. 1a. While this is an extremely dense dataset overall, there are very few stations at the highest altitudes, and most stations have been added since the completion of the Automatic Rainfall and Meteorological Telemetry System (ARMTS) in 1997 (Chen et al. 2007). Therefore, there are large uncertainties in remote mountainous regions, approaching 50 mm day$^{-1}$ in some areas during typhoon season (Weng and Yang 2018).

We consider measurable rainfall to be present when the recorded value in the TCCIP gridded dataset is at least 0.1 mm day$^{-1}$. Seasonal rainfall at a grid point is the sum of all measurable rainfall during that season at that grid point. To calculate the extreme rainfall threshold for a season at a grid point, we take the daily measurable rainfall for all years during the season and calculate the 99th percentile using linear interpolation. This is done according to season and grid point so that the analysis is not completely dominated by the effects of orography and the monsoon cycle. Statistical significance of trends is assessed using a Mann–Kendall test (Hirsch et al. 1982; Hirsch and Slack 1984; NCAR 2014). Since this test reports only the sign of the trend, we use either linear regression
or Theil–Sen slope estimators to compute the approximate trend magnitude (Theil 1950; NCAR 2014).

**b. Tropical cyclone best track data**

To separate TC from non-TC extreme rainfall, we use TC data from the International Best Track Archive for Climate Stewardship (IBTrACS; https://www.ncdc.noaa.gov/ibtracs/). TC position and intensity are catalogued at 6-h intervals. TC ER is defined as ER that occurs when a TC center resides within the box covering 18°–29.5°N, 116°–126°E (Fig. 2). If the TC center is within this box on a given day, then that day is registered as a TC rainfall day. Previous studies have used similar boxes, ranging in size from the smaller region of 19.5°–27.5°N, 117.5°–124.5°E (Chu et al. 2014) to the larger region of 12°–34°N, 110°–132°E (Wu et al. 2017). Our definition is taken from Tu and Chou (2013), who found that most ER takes place when a typhoon is within 500 km of a given station.

3. **Extreme rainfall statistics according to season**

a. **Background and seasonal extreme threshold definitions**

Figure 3 shows the mean daily total and extreme rainfall as a function of day of year, spatially averaged over Taiwan. Due to the nature of the East Asian summer monsoon, Taiwan experiences a surge in total and extreme rainfall from late May through mid-June. From July to September, TCs frequently make landfall or pass near the island, creating a second peak in rainfall. Therefore, we use the following season definitions in our work consistent with previous climatological studies for the region (e.g., Chen and Chen 2003):

- **Winter:** 1 December–28/29 February
- **Spring:** 1 March–14 May
- **Mei-yu season:** 15 May–30 June
- **Typhoon season:** 1 July–30 September
- **Fall:** 1 October–30 November

In winter, island-averaged rainfall is low, staying below 3 mm day$^{-1}$ for the most part (Fig. 3). Spring sees only a slight increase in rainfall, with values still consistently below 5 mm day$^{-1}$. However, by the time of the mei-yu season, mean rainfall rises rapidly to its highest values of the year. Extreme rainfall is also elevated at this time, after being extremely small during the cold season. This is the first active phase of the East Asian summer monsoon (Ding and Chan 2005; Chen 1992). After a brief lull near the transition from mei-yu season to typhoon season, total and extreme rainfall begin to increase again, attaining their second peak in early August before falling dramatically at the start of October. The drying trend continues throughout the fall, leading to the driest time of year in December and January.

Figure 4 shows the 99th-percentile threshold for each season and annually, plotted along with smoothed topography. During winter, the threshold is largest over northern areas. By spring, the maximum has shifted and broadened to include all of western Taiwan. Western and especially southwestern Taiwan experience intense rainfall in mei-yu season, since atmospheric moist static energy (MSE) and moisture content have increased with the warm, southwesterly monsoon flow (Chen and Chen 2003; Chen et al. 2007). The typhoon season has the largest 99th-percentile thresholds. Because typhoon tracks passing over the island, south of the island, and north of the island will produce different orographically forced patterns of rainfall, the extreme threshold is large in many mountainous regions, including east-facing, west-facing, and north-facing slopes. Finally, during fall, the 99th-percentile threshold is large in the east and small in the west, due to predominant northeasterly flow and late-season TCs (Chen 2007).
and Chen 2003). Note that during the transition seasons (spring and fall) the ER threshold patterns are precisely opposite. This highlights the interaction between seasonal wind reversal and local mesoscale terrain as an important factor for monsoon rainfall (see Chang et al. 2005)

b. Seasonal cycle of accumulated extreme rainfall

In Fig. 5, the shading corresponds to the actual amount of extreme rainfall (i.e., the monthly-mean accumulation of rainfall from days above the extreme threshold). Because ER days number only 1% of measurable rainfall days, the climatological-mean monthly accumulation will generally be smaller than the ER threshold shown in Fig. 4.

The large seasonal and geographic differences in Taiwan’s ER are highlighted below.

- **Winter** (Fig. 5b): ER is largest near the northeastern coastline. During this time, northerly winds bring showers and cold fronts into northeastern Taiwan, so that the heaviest rainfall occurs on the northern coast and the windward slopes of the northeastern mountains (Chen and Chen 2003; Chen et al. 2007). Southwestern parts of Taiwan, meanwhile, receive almost no ER, implying that rainfall frequency is low.

- **Spring** (Fig. 5c): ER is largest in northwestern Taiwan, with peak values that are similar to those in winter but more widespread. There is a smaller maximum in northern Taiwan, where orographic ascent occurs on the windward slopes of local hills. During spring, low-level southwesterly flow prevails by late March as the west Pacific subtropical high retreats eastward and cold fronts with embedded convection often move...
southeastward from the leeside of the Tibetan Plateau to southern China and Taiwan (Chen and Chen 2003).

- **Mei-yu season (Fig. 5d):** ER is much larger in general during mei-yu season (note the different color bar scales). The largest values are now located over west-southwestern facing mountain slopes. During mei-yu season, there are frequent incursions of the mei-yu front, in which elongated zonal rainbands are accompanied by strong southwesterly monsoon flow (Chen 1992; Chen and Chen 2003; Wang and Chen 2008). These events have been associated with rainfall amounts of over 600 mm (e.g., Chen and Yu 1988; Chen 1992; Chen et al. 2005), sometimes in as little as 12 h (Arakane et al. 2019).

- **Typhoon season (Fig. 5e):** ER is largest during this season, with TCs producing daily rainfall values in excess of 1000 mm day$^{-1}$ (e.g., Typhoon Morakot in 2009). Typhoon season is characterized by frequent typhoon incursions (e.g., Chang et al. 2013) and convection (Chen and Chen 2003). Because typhoon tracks passing over the island, south of the island, and north of the island will produce different orographically forced patterns of rainfall, ER is large in many mountainous regions, including east-facing, west-facing, and north-facing slopes.

- **Fall (Fig. 5f):** ER exhibits a strong east-to-west contrast in this season, as well as a large northeast peak along the Yilan Valley, an ocean-facing plain with steep terrain to the west. Western Taiwan receives essentially no ER during this season, indicating low rainfall frequency. The prevailing low-level flow turns northeast in late September, and most rainfall in this season is related to late-season typhoons or early-winter cold fronts (Chen and Wang 2000; Chen and Chen 2003).

![Figure 5](image-url)
In general, we would expect that a higher 99th-percentile threshold (Fig. 4) would correspond to larger amounts of ER (Fig. 5). However, there are some areas where it is not this simple. In winter, both the coastal northeastern and the mountainous northwestern regions have a high 99th-percentile threshold, but the northeastern locations receive much more total ER. In spring, there are two large peaks in the 99th-percentile threshold in the northwestern mountains and southwestern mountains, but the northwestern location receives noticeably more ER. And in fall, the entire eastern seaboard has large 99th-percentile thresholds, but a small region in Yilan County receives by far the largest ER totals.

These locations are depicted in Figs. 6a–c, and the corresponding rainfall histograms are shown in Figs. 6d–f. In winter and spring, the accumulated ER difference is because the drier regions have longer-tailed rainfall intensity distributions; they receive fewer rainfall events, but their extreme events are more likely to produce extremely high totals. In fall, on the other hand, the difference is simply one of frequency: the Yilan County location receives more rainfall at all intensities but has the same histogram shape. These results highlight a shortcoming of simply looking at the 99th-percentile threshold in order to judge how extreme the rainfall is in a given location. To get a more complete picture, it is necessary to also include...
analysis of the rainfall frequency as done here. Further ER frequency analysis is available in Henny (2019).

c. Tropical cyclone contributions to extreme rainfall

Because of its location in the nexus of diverging typhoon tracks in the tropical western Pacific, Taiwan is impacted by three to four typhoons every year, on average (Wu and Kuo 1999). Tropical cyclones are extremely important for ER in Taiwan, with previous research indicating that they are associated with the majority (over 70% in some regions) of all ER in Taiwan, by some definitions (e.g., Chang et al. 2012; Wu et al. 2017).

Figure 7 depicts the fraction of ER that comes from TCs, using our box of 18°–29.5°N, 116°–126°E (Fig. 2). Annually, a large fraction of Taiwan’s ER comes from TCs – from a low of 30% in the southwest to a high as 80% in the east (Fig. 7a). Only the southern and eastern regions of Taiwan experience TC-related ER in winter, with most of that associated with a single typhoon (Typhoon Nanmadol in early December 2004). Spring sees almost no TC-related ER, but in mei-yu season

---

**Figure 7.** The percentage of extreme rainfall in each season and annually that is associated with TCs. This includes any rainfall occurring when a TC center (of any strength) is within the box 18°–29.5°N, 116°–126°E. Constructed using IBTrACS best track data.
there is a resurgence in the east (Figs. 7c,d). TCs account for almost all of Taiwan’s typhoon season ER (Fig. 7e), due to higher TC frequency in this season. The TC-related ER fraction is also very high during fall (Fig. 7f), but with much of the island seeing virtually no ER (Fig. 5f) only the northeastern region will have large amounts of TC-related ER during this season. Note that these are not maps of total TC-related ER, but rather ones of TC-related ER as a fraction of total ER. Over the southwestern plain in typhoon season, the TC-related ER fraction is lower simply because of higher total ER values (Fig. 5e), not because there is any less TC-related ER. Similarly, there is actually a minimum in the fraction of fall ER coming from TCs in Yilan County, indicating that some of the large ER totals are due to moist flow unrelated to TCs (Fig. 7f).

Based on previous work, TCs are most commonly seen south of the island during mei-yu season and fall (Henny 2019). These southerly TCs are also associated with elevated ER east of the Central Mountain Range, because a TC located south of the island will have a circulation that impinges upon the eastern mountain slopes. In fall, the circulation of such a TC is more likely to interact with the emerging northeasterlies in northern Taiwan, producing the large observed northeastern ER maximum (Fig. 5f; Chen and Chen 2003; Henny 2019).

d. Summary

The location of Taiwan’s maximum extreme rainfall depends on the interaction of low-level flow with topography in each season. For example, in mei-yu season, strong southwesterly flow produces an ER maximum over the southwestern mountain slopes, whereas in winter northerly flow and frontal passages lead to enhanced ER over the northern part of the island. ER magnitude also undergoes a marked seasonal cycle, with mei-yu season, typhoon season, and fall having higher ER totals than winter or spring. The typhoon and mei-yu seasons stand out as having the largest and most uniformly distributed ER.

Within each season, there are large geographic differences in the amount of ER, which may depend on rainfall frequency and the shape of the ER distribution. The former, rainfall frequency, is a limiting factor in certain regions in winter, spring, and fall. During this “dry season,” large parts of the island receive little rainfall. But the intensity of extreme events can also be an important factor, and certain regions might experience less frequent, but more intense, ER events.

TCs are responsible for most of the extreme rainfall that occurs in typhoon season and fall. They are also an important factor in eastern Taiwan in mei-yu season, likely due to the passage of TCs to the south of the island. TC-related ER is much smaller in winter and spring, but can still occur, especially in southern Taiwan. In fall, there is a large maximum in Yilan County ER, which is mostly associated with TCs and may come about from the interaction of TC circulations with northeasterly monsoon flow. This topic merits further investigation in future work.

4. Trends in extreme rainfall

Taiwan’s annual island-average extreme rainfall has been increasing (Chen et al. 2007; Shiu et al. 2009; Tung et al. 2016; Wu et al. 2019), especially since the year 2000 (Chang et al. 2013; Tung et al. 2016; Liang et al. 2017). In this next section, we will follow two complementary approaches for defining and calculating ER trends. First, we will aggregate the annual TCCIP extreme rainfall into island-mean values, computing the trend in this island-mean ER from 1960 to 2015 for each season and for TC and non-TC contributions. Second, we will calculate trends in annual ER at each grid point, obtaining a high-resolution map of Taiwan’s spatially varying ER trends and changes in each season. In each case, trend values and significance are derived from a Mann–Kendall test and Theil–Sen slope estimators (Theil 1950; Hirsch et al. 1982; Hirsch and Slack 1984; NCAR 2014).

a. Island-average changes

1) Rainfall intensity distributions

Figure 8 shows histograms of daily gridded rainfall values during the first (1960–87) and second (1988–2015) halves of the analysis period. These intervals were chosen simply as the maximal equal-length intervals within the analysis period and are not meant to represent changepoints in the rainfall time series. The first half is plotted in solid blue, while the second half is empty bars. This helps to illustrate the very large differences in rainfall at high intensities, particularly beyond the island-mean extreme threshold (shown in red).

In winter, rainfall intensities above 200 mm day$^{-1}$ have become an order of magnitude more common (though still rare). In fact, there are even observations in the 800–920 mm day$^{-1}$ range, due to Typhoon Nanmadol in 2004. Spring shows a smaller but still quite large increase in >200 mm day$^{-1}$ rainfall during the second half of the analysis period, while mei-yu season has especially large increases above 400 mm day$^{-1}$. The season that stands out the most, however, is the typhoon season, which has an entire range of rainfall observations in the 1000–1600 mm day$^{-1}$ range that were not present in the first half of the period. This is a very significant change in the character of extreme rainfall. Fall has less consistent changes, with decreases at the highest intensities. Annually, the seasonal contributions sum to produce a 1988–2015 rainfall distribution that is much changed from its 1960–87 counterpart, with large increases at high intensities.

Included in the rainfall histograms is the number of dry (<0.1 mm) days, shown in text in the upper left of each panel in Fig. 8. In winter, there has been only a slight decrease in the number of dry days, but in spring there has been a large decrease, likely reflecting the fact that the winter increases in rainfall are more heavily weighted toward very high intensities where frequency is low. Interestingly, typhoon season and especially mei-yu season have seen increases in the number of dry days, even as their extreme rainfall grows—a phenomenon also observed in Chu et al. (2014). This means that precipitation has become less frequent, but more intense, on average, in these seasons.

Figure 9 visualizes this another way by putting all of these intensity distributions on the same axis and comparing them to the mean monthly rainfall rate at each intensity. Typhoon season has the highest rainfall frequency, above 120 mm day$^{-1}$, but mei-yu season actually has the most rainfall in the 10–120 mm day$^{-1}$ range (Fig. 9a). Interestingly, fall actually has more rainfall
above 320 mm day$^{-1}$ than the mei-yu season. This would make sense given that most fall ER is due to late-season TCs, which tend to be more heavily weighted toward the highest precipitation intensities.

Changes between the first and second half of the analysis period are shown in Fig. 9b. Typhoon season shows increased rainfall at all intensities except $\sim$0–20 mm day$^{-1}$, with a larger effect at larger intensities. The mei-yu season has shifted to
higher intensities, with decreases in light-to-moderate rainfall. Winter and spring have consistent increases, but their absolute magnitude is very small compared to the changes in typhoon and mei-yu seasons. Fall is an outlier, with small changes of both signs and no clear overall trend. Ultimately, none of the other seasonal changes come close to the magnitude of the typhoon season rainfall increase at intensities above 300 mm day\(^{-1}\).

Averages and trends for seasonal ER totals, seasonal ER frequency, and seasonal ER intensity (intensity being averaged over the ER region only) are shown in Table 1. There is a clear seasonal cycle in the amount of ER, with total and intensity both peaking in typhoon season. In contrast, ER frequency actually peaks in mei-yu season, reflecting the higher frequency of measurable rainfall in that season. Winter, spring, and typhoon season all have statistically significant increasing trends in ER. In winter and spring, the frequency trends are statistically significant, while the intensity trends are not. In typhoon season, however, both meet the significance criteria for at least the \(p \leq 0.10\) level.

Together, mei-yu season and typhoon season make up Taiwan’s warm season, during which the island is under the influence of moist, warm southwesterly flow and sees large total and extreme rainfall totals. However, typhoon season exhibits large, statistically significant increasing trends in ER, whereas mei-yu season does not. This agrees with the results of Chang et al. (2012), who found that JJA TC-related rainfall has increased while non-TC rainfall has not. Furthermore, it suggests the presence of mechanisms other than increased water vapor capacity due to global warming. Either 1) the typhoon season trends are due to changes in typhoon properties (frequency, tracks, translation speed) unrelated to moisture availability or 2) the lack of mei-yu season trends is due to factors that counteract the effects of moisture availability changes (or some combination of these possibilities). Based on previous studies confirming increases in TC frequency and decreases in translation speed near Taiwan, the first theory is very likely to be true.

### TABLE 1. Characteristics of extreme (top 1%) rainfall in Taiwan

<table>
<thead>
<tr>
<th>Season</th>
<th>Total (mm month(^{-1}))</th>
<th>Total trend (%)</th>
<th>Frequency (days month(^{-1}))</th>
<th>Frequency trend (%)</th>
<th>Intensity (mm day(^{-1}))</th>
<th>Intensity trend (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>4.85</td>
<td>0.57*</td>
<td>0.061</td>
<td>0.6</td>
<td>68.93</td>
<td>0.22</td>
</tr>
<tr>
<td>Spring</td>
<td>7.48</td>
<td>0.98</td>
<td>0.078</td>
<td>1.19</td>
<td>87.76</td>
<td>0.092</td>
</tr>
<tr>
<td>Mei-yu season</td>
<td>27.14</td>
<td>1.18</td>
<td>0.13</td>
<td>0.42</td>
<td>181.01</td>
<td>0.16</td>
</tr>
<tr>
<td>Typhoon season</td>
<td>37.12</td>
<td>0.07</td>
<td>0.11</td>
<td>1.04</td>
<td>318.83</td>
<td>0.19*</td>
</tr>
<tr>
<td>Fall</td>
<td>15.35</td>
<td></td>
<td></td>
<td></td>
<td>234.5</td>
<td></td>
</tr>
</tbody>
</table>

### 2) INTERDECADAL VARIABILITY

As seen in previous figures, extreme rainfall in Taiwan has undergone significant changes—typically increases—over the course of the 56-yr analysis period. These increases may be due to a consistent increase in annual ER in a particular season, or to a few years with very large ER. This latter case raises the possibility that a trend or change in ER may be due entirely to several very large events.
Figure 10 illustrates how outliers can significantly change trends within the ER time series. In this figure, “Event ER” denotes the total ER occurring on consecutive ER-producing days. This is depicted by colored dots in the figure. Annual total ER is depicted by the colored line, and the trends in annual ER with and without the top five ER events are shown by the thick and thin black lines, respectively. For winter (Fig. 10a), the top five events have all occurred since 1980, and the ER trend is much smaller—but more significant—without those events. All of the top five events in spring occur between 1990 and 1997, evidently a very active period for spring rainfall that also enhances the ER trend (Fig. 10b). Mei-yu season is more interesting, in that the top five ER events—three of which occurred in 2005, 2006, and
2012—actually account for the whole ER trend (Fig. 10c). Without these events, there is actually a weak decreasing trend (not statistically significant). A similar signal is seen in the typhoon season, where the top five events (all since the year 2000) are solely responsible for the statistical significance of the season’s increasing ER trend (Fig. 10d). As in previous figures, fall has no consistent trends (Fig. 10e). Annually, all of the top five ER events have occurred since the late 1990s (Fig. 10f), which is to be expected with an increasing trend. What is more interesting is the fact that mei-yu season and typhoon season trends are due almost entirely to a few very extreme events.

Given their importance for seasonal ER trends, these top events might inform us of the true causes of the observed ER shifts. While detailed weather-tying is beyond the scope of this study, the top events in each season have been examined for any association with TCs in the western North Pacific (not shown). In some seasons, the attribution is straightforward. The top five typhoon season ER events are all associated with landfalling TCs, and it is likely that most of the extreme events are as well, since 60% to 90% or more of typhoon season ER is TC-related (Fig. 7e). On the other hand, none of the top five spring ER events is associated with TCs. In winter, four of the five events are not TC-related, with the outlier being Typhoon Nanmadol in early December 2004, which made landfall in southwestern Taiwan and produced copious rainfall totals of >500 mm over eastern Taiwan. In fall, the events are again associated with TCs, although two of them pass just south of the island instead of making direct landfall.

Mei-yu season is more ambiguous. One of the events, in June 1990, was the result of a landfalling TC. Despite the other four not being classified as TC rainfall, three of those events occurred about 5–7 days after a TC moved northeastward away from Taiwan. In the 1966 case, a weak TC crossed over Taiwan from west to east; in the 2005 and 2012 cases, a stronger TC recurved well east of Taiwan. Because there is no proven link between these TCs and the subsequent ER events, the rainfall is assumed not to be TC-related. Whether such TCs modify the southwesterly monsoon flow and monsoon trough to facilitate extreme events is a topic for future work.

b. Geographically varying changes

1) Trend analysis

Figure 11 shows geographic plots of the percent-wise ER trends in each season, as well as annually, with stippling to indicate statistical significance at the 5% level. Due to low sample size in many areas, we restricted the analysis to grid points that have at least 10 years with nonzero ER in the given season (although there may have been multiple ER events within each season). Based on these figures, seasonal ER trends in Taiwan have the following properties:

- **Annual** (Fig. 11a): Summing the seasonal contributions yields large, increasing, statistically significant ER trends over most of Taiwan. These trends are pronounced over the western mountain slopes, and over the far northern region of the island. Trends exceed 5% yr\(^{-1}\) over the mountain slopes of southwestern Taiwan.

- **Winter** (Fig. 11b): Only the northeast coastal regions have at least 10 years with nonzero ER. Within this area, ER is mostly increasing, sometimes by as much as 3%–5% yr\(^{-1}\). Most of the statistically significant ER trends are positive and located in the northeastern part of Taiwan. There is large spatial variability; in some cases, the trend flips from positive to negative over just a few kilometers.

- **Spring** (Fig. 11c): Trends are more mixed, but most of the statistically significant trends are once again positive, and of roughly the same magnitude as the winter trends. Most of the increasing trends are in northeastern Taiwan. The northwest coast and central mountains have some statistically significant positive trends, but they are less widespread. At higher elevations, there is no conclusive, large-scale increase in the areas with sufficient sample size.

- **Mei-yu season** (Fig. 11d): There are generally positive ER trends over western mountain slopes, with some negative trends on the eastern side. Low-elevation areas are mostly excluded due to low sample size. Increasing trends in the north are as high as 5% yr\(^{-1}\) locally. Since the southwesterly monsoon flow is important during mei-yu season, these trends raise the question of whether there have been changes in the regularity, magnitude, or moisture content of this flow, all of which should be explored in future work.

- **Typhoon season** (Fig. 11e): This season has the most consistent and extensive trends, with much of the southern part of Taiwan experiencing statistically significant increasing trends of 2%–3% yr\(^{-1}\). Northeastern Taiwan is another hotspot for statistically significant, increasing ER trends—including the Yilan Valley region, which experiences elevated ER in typhoon season and fall (Figs. 4f and 5f). In contrast, the southeastern coastal region has mixed-to-negative trends that are mostly not statistically significant. Previous work by Chang et al. (2013) and Henny (2019), has shown that the ER increases are associated mostly with westward-moving TCs impacting the eastern coast of the island, especially those making landfall along the central and northern parts of the eastern coastline.

- **Fall** (Fig. 11f): Little information is conveyed for fall, since most of the island has low rainfall frequency, meaning that only the northeast tip of Taiwan has enough ER years to perform trend analysis. Trends in this region are highly variable.

These figures highlight several important points. The first is that, while the typhoon season does have more statistically significant trends, these trends are not much larger, percentage-wise, than those of winter or spring. The typhoon season trends are much larger in an absolute sense, and more spatially consistent. The typhoon season therefore contributes the most to Taiwan’s increasing annual ER trends, but it is not the only season with changes in the tail of its rainfall distribution.

For completeness, Fig. 12 shows the difference in monthly mean ER between the 1960–87 and 1988–2015 time periods, extending the results of Fig. 11 in a nonrigorous way that allows us to see ER differences in regions with fewer ER events. This reveals changes that were absent in the trend analysis. First, there has been a large increase in fall ER in western Taiwan, with decreases over eastern Taiwan. Since most fall ER is TC-related, these changes are likely the result of changes in fall TC activity near...
Taiwan. Additionally, in mei-yu season, there are very large increases in ER in the southwest, likely corresponding to the large ER events after 2000 (Fig. 10). In winter, ER increases extend to southern Taiwan, but in spring southern Taiwan has seen ER decreases. These changes merit investigation in future work.

2) SEASONAL CONTRIBUTIONS BY REGION

To evaluate the large trends seen in extreme rainfall in Taiwan in more detail, we selected several regions that have experienced statistically significant increasing annual ER trends and plot time series of annual ER by season. Figure 13 shows the points plotted against annual ER trends in the left column, and the corresponding ER time series with seasonal contributions plotted in the right column. The three regions chosen—one over the southwestern mountains and coastal plain, another in the central mountains, and a third near the northeast coast and Taipei Basin—have very different ER evolutions, stemming from different seasonal contributions:

- **Southern region** (Fig. 13a): This region has experienced a large, sudden increase in ER primarily during the 2004–11
period, due mainly to changes in the typhoon season rainfall (Fig. 13b). Although there have been anomalously active mei-yu seasons in 2005, 2006, and 2012, their contribution to the increase is much smaller than the typhoon season contribution. The typhoon season ER increase is likely associated with the noted increase in TC activity during this period (e.g., Chang et al. 2013; Wu et al. 2016). It is as a result of this increase that the region has experienced “trends” of up to 5% yr$^{-1}$ in annual ER.

- **Central region** (Fig. 13c): Again, there is a pronounced increase in ER later in the analysis period, roughly from 2004 to 2012 (Fig. 13d). The change is smaller than that in the southern region, with a smaller typhoon season contribution. This region also has larger interannual variability than the southern region. Taken as a whole, these changes contribute to trends of 2%–4% yr$^{-1}$ over the analysis period.

- **Northeastern region** (Fig. 13e): This region experienced higher activity starting in the late 1990s and has complex seasonal contributions to ER (Fig. 13f). There is no clearly dominant season; rainfall in northern Taiwan is not as season-dependent as rainfall in southern Taiwan. During the 1998–2015 active period, there are large contributions from fall, mei-yu season, and typhoon season, with winter and spring only slightly less important. 1998 and 2000 are notable for their very large fall ER totals, likely from late-season TCs. These various seasonal contributions result in increasing ER trends of up to 2% yr$^{-1}$.

These results imply that ER totals and trends in southern Taiwan depend on one or two weather types, whereas those in northern Taiwan come from a variety of weather patterns. In the “dry season” of winter and spring, northern Taiwan still
Fig. 13. Area analyses of extreme rainfall changes. (a),(c),(e) Annual ER trends, as in Fig. 11, but for a region of statistically significant increasing annual ER trends. (b),(d),(f) The annual-mean ER for these regions from 1961 to 2015, with stacked bars color-coded according to seasonal contribution.
experiences moist northeasterly monsoon flow as well as frontal passages, while southern Taiwan is mostly dry. But in mei-yu season, typhoon season, and fall, northern Taiwan still receives extreme rainfall from mei-yu frontal systems, TCs, and diurnal convection, like the rest of the island.

c. Tropical cyclone contribution to extreme rainfall changes

Although most seasons exhibit large increases in extreme rainfall, typhoon season has the most spatially consistent and largest trends. Within typhoon season, TCs account for the majority of Taiwan’s extreme rainfall (Fig. 7). Therefore, the importance of TC-related ER for Taiwan’s overall ER trends—as well as some broad causes of these trends—is now investigated.

Tables 2 and 3 show the same calculations as in Table 1, but for TC-related and non-TC-related ER, respectively. During winter and spring, TC contributions to ER are negligible, and there are statistically significant positive trends in non-TC ER. In mei-yu season, approximately 30% of ER comes from TCs, but neither category of ER has statistically significant trends. Most typhoon season ER (91.3%) comes from TCs, as does most of the positive ER trend. Finally, during fall, TC-related ER again accounts for the vast majority (85.7%) of total ER, but the increases that have been observed are not statistically significant.

Given that typhoon season TCs are responsible for much of the typhoon season ER increase, the broad causes of this increase in TC-related ER are now considered. In Fig. 14, mean typhoon season TC characteristics within the near-Taiwan box are plotted by year. Total TC track density (i.e., the number of TC points within the box each season) varies widely between about 25 and 100, with no clear trend despite slightly higher averages after 1988 (Fig. 14a). TC frequency and intensity have large interdecadal variability, but also no compelling trend. TC duration within the box, however, comes closer to having a statistically significant increasing trend ($p = 0.13$). This fits with previous work that has shown that increased TC ER is the result of increased TC duration, especially for TCs making landfall in central and northern Taiwan (Chang et al. 2013). The recent increase in central and northern landfalling TC frequency shown in previous analysis (Henny 2019) and literature (Chang et al. 2013; Wu et al. 2016) is a smaller-scale feature that would not be resolved by a sum over the entire 18°–29.5°N, 116°–126°E box.

For a higher-resolution perspective, Fig. 15 depicts monthly mean TC track density plotted in $1° \times 1°$ boxes near Taiwan for the 1960–87 and 1988–2015 time periods. In mei-yu season, changes are mixed in the vicinity of Taiwan, with increases farther south (Fig. 15c). In fall, there are again increases in TC activity to the south of Taiwan, as well as a notable jump in activity just off the northeastern coast of Taiwan (Fig. 15i). However, in typhoon season, there are large increases in TC track density across central and northern Taiwan (Fig. 15f), supporting previous results. These increases also appear to the southeast, suggestive of a recurving storm track.

Based on the five near-Taiwan squares with the largest track density increase outlined in Fig. 15, extreme rainfall rates are shown in Fig. 16. From 1960 to 1987, typhoon season extreme rainfall occurring when a TC center resides in these five squares was on the order of 10–20 mm month$^{-1}$ in many locations. However, in the 1988–2015 period, much higher values of up to 60+ mm month$^{-1}$ were observed. This represented an increase of over 40 mm month$^{-1}$ in some regions, and an island-mean increase of 11.46 mm month$^{-1}$. Since the typhoon season ER increase shown in Fig. 12 averages to 24.76 mm month$^{-1}$, this means that this one zone of increased TC activity accounted for 46.3% of the total typhoon season change.

These results are broadly consistent with previous literature that identifies increased TC frequency near central and northern Taiwan, as well as an increase in the duration of these TCs, as the

| TABLE 2. As in Table 1, but for TC-related ER only. In winter and spring, $N < 5$ signifies that there are fewer than 5 years with TCER. For added context in mei-yu season, typhoon season, and fall, the linear regression slope and significance values are shown in parentheses. |
|---------------------------------|-------|--------|--------|------|
|                                | Winter | Spring | Mei-yu season | Typhoon season | Fall |
| Total (mm month$^{-1}$)        | 0.74   | 0.24   | 8.08     | 33.89 | 13.16 |
| Total trend (%)                | $N < 5$ | $N < 5$ | 0 ($-1.04$) | 1.02 ($2.27^*$) | 0 ($1.23$) |
| Frequency (days month$^{-1}$)  | 0.004  | 0.002  | 0.04     | 0.098  | 0.046 |
| Frequency trend (%)            | $N < 5$ | $N < 5$ | 0 ($-1.07$) | 0.92 ($1.93^*$) | 0 ($1.58$) |
| Intensity (mm day$^{-1}$)      | 103.92 | 77.34  | 173.83   | 319.93 | 248.75 |
| Intensity trend (%)            | $N < 5$ | $N < 5$ | $-0.18$ ($-0.02$) | 0.2 ($0.03$) | $-0.27$ ($-0.01$) |

| TABLE 3. As in Table 1, but for non-TC-related ER only. |
|---------------------------------|-------|--------|--------|------|
|                                | Winter | Spring | Mei-yu season | Typhoon season | Fall |
| Total (mm month$^{-1}$)        | 4.11   | 7.24   | 19.07   | 3.23  | 2.19 |
| Total trend (%)                | 0.63   | 1.16   | 0.64    | 0.054 | 0   |
| Frequency (days month$^{-1}$)  | 0.057  | 0.076  | 0.091   | 0.01  | 0.009 |
| Frequency trend (%)            | 0.59   | 1.34*  | 0.9     | 0.055 | 0   |
| Intensity (mm day$^{-1}$)      | 68.06  | 86.81  | 177.59  | 271.12 | 218.72 |
| Intensity trend (%)            | 0.21   | 0.15*  | 0.25    | 0.11  | $-0.51$ |
primary cause of increased TC-related ER in Taiwan (Tu et al. 2009; Chang et al. 2013; Wu et al. 2016). This duration change has been attributed to a long-term slowing of steering flows in the WNP and northward shift of the WNP TC track in response to a strengthening subtropical high over the WNP (Wu et al. 2005; Chu et al. 2012; Liang et al. 2017). Previous work (Henny 2019) has also identified an increase in the frequency of tracks that are highly curved or irregular in the vicinity of Taiwan, changing direction sharply or repeatedly—a behavior that may be related to the influence of the prominent Central Mountain Range topography (e.g., Hsu et al. 2018).

d. Summary and discussion

Extreme rainfall in Taiwan has increased rapidly from 1960 to 2015 in all seasons except fall, with winter and typhoon season having particularly pronounced increases in rainfall at high daily intensities, despite warm season increases in dry days. Spatially, there is large variability in ER trends, likely associated with the complex topography of the island. However, because ER totals are largest over windward mountain slopes, these regions will tend to have the largest increasing trends as well. In areas where ER is infrequent enough to make trend analysis difficult, there may still be large increases in the average rate of ER: for example, increases in western Taiwan fall ER, southern Taiwan winter ER, and mei-yu season southern mountain ER.

Despite large percentage trends in winter and spring, the majority of extreme rainfall, even using a seasonal 99th-per-centile threshold, occurs in the warm season, which spans the mei-yu season and typhoon season. Mei-yu season exhibits large interannual variability in ER, with three of its five most extreme events having occurred in the 8-yr span from 2005 to 2012. Still, these few extreme events are not enough to create a statistically significant increasing trend in mei-yu season ER.

Typhoon season contributes most to the annual increasing ER trend and has the most spatially consistent ER increases. Within typhoon season, TC ER is responsible for most of the increasing trend. In particular, an increase in TC activity near

Fig. 14. Changes in (a) total track density, (b) mean TC duration, (c) mean TC frequency (number of storms), and (d) mean TC intensity within the 18°–29.5°N, 116°–126°E box around Taiwan. Annual values are plotted with a dashed line, while 5-yr running means are shown in bold.
central and northern regions of Taiwan accounts for nearly half of the typhoon season ER increase from 1960–87 to 1988–2015. There is some evidence of an increase in near-Taiwan TC duration (possibly implying a slowing of translation speed), in agreement with previous studies (Chu et al. 2012; Chang et al. 2013).

5. Conclusions

In this study, seasonal extreme rainfall (ER) in Taiwan was examined using a high-resolution daily rainfall dataset released by the Taiwan Climate Change Projection Information and Adaptation Knowledge Platform (TCCIP). Means and trends were calculated, and IBTrACS best track data were used to separate seasonal ER into TC and non-TC components. Extreme events and TC activity near Taiwan were briefly explored.

Seasonally, the location of extreme rainfall is highly dependent upon Taiwan’s orography and the prevailing wind direction. In winter and spring, the most extreme rainfall, as well as the largest trends, occurs in northern Taiwan. In mei-yu and typhoon seasons, ER totals and trends are larger over the

FIG. 15. TC track density for (a),(b) mei-yu season, (d),(e) typhoon season, and (g),(h) fall season, during the (a),(d),(g) first (1960–87) and (b),(e),(h) second (1988–2015) halves of the analysis period. (c),(f),(i) The difference between the two periods, Track density is defined on a $1^\circ \times 1^\circ$ grid within the TC-rainfall box shown in Fig. 2. All TCs identified in the IBTrACS dataset are present, including subtyphoon strength systems. Track density values are normalized to be in units of points per month. In (f), a region of large near-Taiwan TC activity increase has been outlined.
entire island, but especially pronounced over the southwestern mountain slopes. These warm-season ER values are much higher than their cold-season counterparts, and although there are statistically significant increases in winter and spring ER, mei-yu season and especially typhoon season make up the bulk of the total ER increase—even using our seasonally varying 99th-percentile threshold.

This study adds to a body of work that distinguishes between TC and non-TC extreme rainfall changes (Chang et al. 2012) and emphasizes magnitude of recent increases in TC-related ER (Su et al. 2012; Chang et al. 2013; Chu et al. 2014; Wu et al. 2016). By our measure, close to 90% of typhoon season ER over central and northern Taiwan comes from TCs; a large majority of all typhoon season and fall ER falls into this category. But even in mei-yu season, when most ER does not meet our definition of TC-related ER, TCs do play a role. TCs account for over half of mei-yu season ER over much of eastern Taiwan, and one of the top five extreme events in this season is a landfalling TC. Two of the three most recent of these extreme events followed recurving TCs, but are not themselves classed as TC-related ER.

Typhoon season TC-related ER increases are associated with increased TC track density near central and northern Taiwan; previous work (Henny 2019; Chu et al. 2012; Chang et al. 2013) has indicated a slowing of TC translation speed and increased numbers of TCs making landfall in central and northern Taiwan. The results of this study conform to this narrative—namely, that increases in TC-related ER are due to changes in local TC activity patterns, not the global warming-driven increase in moisture capacity. It is, of course, possible that these TC activity patterns are adjusting in response to larger-scale responses to a changing climate. Chu et al. (2012), for example, linked weakened west Pacific steering flows to slower TC translational speeds and increased likelihood of recurving TCs.

The analysis revealed a collection of smaller but still statistically significant ER increases, such as the large percentage increases in winter and spring ER and the increase in western Taiwan fall ER. These changes are often the result of sudden, pronounced shifts in ER activity. Whether these changes are part of a longer trend, or a result of interdecadal variability, poses an interesting question for further analysis. Mei-yu season ER, and particularly the large-scale meteorological patterns and TC–monsoon interactions responsible for extreme events, presents another avenue for inquiry. This statistical study of a high-resolution rainfall dataset is intended to serve as a reference for such studies in the future.

Acknowledgments. This research was supported by the National Science Foundation Partnership for International Research and Education Program between the United States and Taiwan, OISE-1545917, awarded to the University at Albany, SUNY. The authors thank the anonymous reviewers, as well as reviewer C. P. Chang, for their helpful feedback.

Data availability statement. TCCIP rainfall data access is through https://tccip.ncdr.nat.gov.tw/ds_03_eng.aspx. TC track data used in this study are freely available at https://www.ncdc.noaa.gov/ibtracs/.

REFERENCES


Y.-T. Yang, and H.-C. Kuo, 2016: Statistical characteristic of heavy rainfall associated with
typhoons near Taiwan based on high-density automatic rain
doi.org/10.1175/BAMS-D-15-00076.1.

Wu, L., B. Wang, and S. Geng, 2005: Growing typhoon influences

of extreme hourly precipitation in Taiwan during 2003–12.
MWR-D-17-0230.1.

Wu, Y., S.-Y. S. Wang, Y.-C. Yu, C.-Y. Kung, A.-H. Wang, S. A.
Los, and W.-R. Huang, 2019: Climatology and change of
extreme precipitation events in Taiwan based on weather
10.1002/joc.6159.

Xu, W., E. J. Zipser, and C. Liu, 2009: Rainfall characteristics and
convective properties of mei-yu precipitation systems over
South China, Taiwan, and the South China Sea. Part I: TRMM
10.1175/2009MWR2982.1.