Extreme typhoon rainfall of Taiwan

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Extreme Typhoon Rainfall of Taiwan

by

Alexa Henny

A Thesis
Submitted to the University at Albany, State University of New York
In Partial Fulfillment of
the Requirements for the Degree of
Master of Science

College of Arts and Sciences
Department of Atmospheric and Environmental Sciences
Spring 2019
ABSTRACT

Taiwan has experienced large increases in extreme rainfall (ER, defined as top 1% by daily total) over the past 60 years. Using 1 km gridded daily rainfall data provided by the Taiwan Climate Change Projection and Adaptation Information Platform (TCCIP), we analyze Taiwan's rainfall means and trends seasonally and as a function of intensity. ER accounts for about 17% of rainfall in Taiwan, but across much of the island, the 1960-2015 ER trend exceeds the non-extreme rainfall (NR) trend. Most ER occurs during the months of May – October, when warm, southwesterly monsoon flow and frequent typhoons lead to high rainfall totals in southern and eastern regions. In each season, with the possible exception of Mei-Yu Season, ER has increased over most of the island.

Comparing TCCIP rainfall data to typhoon track data taken from the International Best Track Archive for Climate Stewardship (IBTrACS) allows us to separate ER into TC-related and non-TC-related components. 50-90+% of ER is associated with TCs. While non-TC-related ER has increased dramatically, the TC-related ER increase is substantially larger, due to its larger starting value. We then define nine TC track types: N, C, S, North, South, Reverse South, Rain, Curved, and Yilan types. Out of the first six – the location-based track types – N and C types produce the largest share of the ER per storm, and South-type TCs are by far the most frequent. N-type TCs have become slower-moving, while C-type TCs have become more frequent. Together, these two categories – comprising TCs making landfall on the central and northern east coast – are responsible for the majority of the increasing TC-associated ER trend. However, Curved-type TCs have become more
frequent, indicating an increase in storms with erratic motion near the island. This trend may be linked to changes in the steering flow, and accounts for a large percentage of the TC-associated ER trend in its own right.

ACKNOWLEDGEMENTS

I would like to thank my co-advisors Chris Thornicroft and Lance Bosart for their guidance throughout this project. This research was supported by the National Science Foundation Partnership for International Research and Education (PIRE) Program between the United States and Taiwan, OISE 1545917, awarded to the University at Albany, SUNY.
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1. Introduction

Taiwan resides off the southeast coast of China between 21 and 26 degrees north, along the boundary between the tropics and the extratropics (Fig. 1). It has a monsoon climate, characterized by warm, moist southwesterly flow from May to September, and cooler, drier northeasterly flow from November to April (Chen and Chen 2003; Chen et al 2007). Convection is common during the warm season, peaking in August (Chen et al 2007). Tropical cyclones (TCs) may occur at any point in the warm season, but overwhelmingly fall between July and September. From November to February, the flow becomes northeasterly, pulling down cold fronts that generate frequent showers and stratiform rainfall in the north (Chen and Chen 2003). By May and June, the flow rotates around to the southwest once more, with incursions from Mei-Yu fronts: quasi-stationary, east-west oriented baroclinic regions typically extending from eastern China over Taiwan (Yeh and Chen 1998).

Thus, Taiwan receives rainfall from multiple common weather types. Moreover, due to its southern latitude, storm systems can draw on the tropical moisture reservoir. Combined with orographic enhancement from high terrain (Fig. 2) - including the island’s prominent Central Mountain Range (CMR) - this produces high rainfall rates. Heavy Mei-Yu frontal rainfall has been reported in excess of 100 mm/day, (e.g. Li et al 1997; Trier et al 1990; Chen et al 2007; Tu et al 2014), with Mei-Yu season rainfall exceeding 500 mm in places (Yeh and Chen 1998, Chen and Chen 2003; Xu et al 2009). TC rainfall can be even more extreme, as illustrated by the infamous Typhoon Morakot, which produced over 1000 mm/day and 3000 mm total (Chien and Kuo 2011; Wu et al 2011). Mid-July to late-August rainfall approaches 1000 mm in some regions (Chen and Chen 2003). Winter rainfall is not
quite as heavy, but it comes close in the north, where it is very frequent if not intense (Chen and Chen 2003; Chen et al 2007; Hung and Kao 2010). Annually, rainfall exceeds 2,000 mm throughout the northern part of the island (TCCIP).

Such heavy rainfall has the potential to cause massive economic damage, disrupt infrastructure, and threaten lives. Typhoon Morakot led to the worst flooding in 50 years in southern Taiwan (Liang and Wu 2011), as well as catastrophic landslides (Tsou et al 2011), 618 deaths, and over US$600 million in agriculture and fishery losses (Hong et al 2011). From 1961 to 1982, heavy rainfall events caused more than 100 casualties and US$86 million in economic losses every year (Shieh 1986). Localized rainfall in excess of 130 mm/day is frequently responsible for flooding and landslides (Lin et al 2002). Risks are especially high because of Taiwan’s large population of 23.58 million. Since the mountains are sparsely populated, this means that Taiwan houses the population of Florida in one-tenth the area.

Heavy rainfall in Taiwan has been extensively studied (Chen et al 2007, Shiu et al 2009, Tu et al 2013, Tung et al 2016, Wu et al 2017, etc). Heavy rainfall tends to occur most frequently over the windward mountain slopes: southern and western slopes in the warm season, and northern and eastern slopes in the cold season (Chen et al 2007). Typhoon rainfall distributions depend largely on the typhoon location relative to the island (Wu et al 2016). However, the most extreme events, such as Morakot, come about through a combination of factors: typhoon position relative to the mountains (Chang et al 1993; Wu et al 2002; Tsai and Lee 2009; Wu et al 2013), translation speed, and interaction with the Asian monsoon system (Wu et al 2009).
Previous studies agree that Taiwan has seen large increases in extreme rainfall during recent decades (Chen et al 2007, Shiu et al 2009, Tung et al 2016, and others). However, these reports employ a variety of extreme rainfall definitions, and focus on different weather types and seasons. Some studies examine changes in year-round heavy rainfall (Chen et al 2007; Shiu et al 2009; Tung et al 2016). Some classify events according to weather type, often focusing on typhoon rainfall (Chang et al 2012; Wu et al 2017), while others categorize typhoons according to position of other characteristics (Wu et al 2016; Wu et al 2017). For example, the CWB classifies typhoons by track, the three most common categories being North (N), Central (C), and South (S) –type typhoons. These are east-to-west-moving, landfalling typhoons that approach the northern, central, and southern regions of the island, respectively.

Chen et al (2007) report that heavy (>15 mm/hr) rainfall increases were observed during the 1990s and early 2000s in northern and eastern Taiwan, but not in western Taiwan. Shiu et al (2009) find that heavy (>10 mm/hr) rainfall increased between 1961 and 2005, while light (<4 mm/hr) rainfall decreased. Following the theme of a sudden shift around the turn of the century, Tung et al (2016) found no clear trend in the annual daily maximum rainfall before 2002, when there is a regime change to higher values. In general, decreasing light rainfall is a common result in climate change scenarios due to increasing static stability (e.g. Hartmann et al 2000). However, in Taiwan, heavy rainfall has scaled faster with temperature than would be expected from the Clausius-Clapeyron equation (Shiu et al 2009).

Sorting rainfall contributions by weather type, Chang et al (2012) calculate that typhoon rainfall accounts for 20-50% of all rainfall in Taiwan, and typhoon extreme rain
(95% threshold) accounts for 50-70+% of all extreme rain. Wu et al (2017) show that annually, typhoons account for the majority of very heavy rainfall, using 5, 10, and 20-year return values of a generalized extreme value (GEV) distribution. Typhoon rainfall has increased over Taiwan over recent decades (Su et al 2012; Chu et al 2013). Within typhoon rainfall, different tracks have different characteristics: N-type typhoons are most common and also the wettest in the pre-landfall and overland phases, while C-type typhoons are wettest in the exit phase (Chang et al 2013). This is because C-type typhoons maintain the most interaction with the SW monsoon flow during the exit phase, while N-type typhoons have the most terrain interaction. S-type typhoons produce the least island-mean rainfall in all three phases, and are faster moving than N-type typhoons.

Among recent studies, there is consensus that 2000-2004 marks a turning point in typhoon activity. Of the nine typhoons with the heaviest rainfall, eight occurred in 2004 or later (Chang et al 2013; Wu et al 2016). Most of these storms were N-track typhoons. Tung et al (2016) identified a climate regime change in Taiwan in 2002-2003, and Tu et al (2009) found that typhoon frequency jumped dramatically around 2000. Typhoon numbers per year increased for N-, C-, and S-type typhoons, but especially for C-type typhoons. Meanwhile, N-type typhoons became longer-lived (Chang et al 2013). The longer duration, together with an increase in southwest monsoon water vapor flux (SWF), caused an increase in exit phase rainfall for all three categories. Chang et al (2013) found this regime change to be due to a combination of changing track distribution and longer duration. The northward shift of typhoon tracks into the region results from a weaker West North Pacific Subtropical High (WNPSH), a stronger Asian summer monsoon trough, and enhanced lower-level positive vorticity anomalies (Wu et al 2005; Liang et al 2017). The
increase in duration comes from the weakening of steering flows over the subtropical western portion of the WNP in the previous 50 years, which is also related to the weaker WNPSH (Chu et al 2012; Liang et al 2017).

Previous studies use station data to investigate specific subsets of typhoons – typically landfalling typhoons – or else typhoon rainfall as a whole. However, these studies do not look at the spatial distribution of rainfall, at less-common typhoon track types, or at changing typhoon characteristics. In this study, we will (1) assess changes in Taiwan’s rainfall distribution throughout the seasons, (2) investigate changes in the distribution of near-island typhoons, and (3) link changing typhoon characteristics to changing rainfall characteristics. This will provide a more comprehensive overview of the changing nature of Taiwan’s typhoons and their rainfall.

Section 2 contains data and methodology information. Section 3 presents annual and seasonal rainfall means and trends for Taiwan. Section 4 looks at TC influences on ER, leading into Section 5, which gives a brief overview of WNP TC variability and describes our TC track categories. Conclusions are given in section 6.
Figure 1: Taiwan Counties (http://ontheworldmap.com/taiwan/taiwan-county-map.html) with inlaid map of the Lanyang River Basin (Wikipedia)
Figure 2: CWB conventional weather stations and rain gauges plotted by (top) altitude in meters and (bottom) year added.
2. Data and Methodology

We use high-resolution rainfall data to examine the rainfall characteristics of Taiwan during different seasons and in different locations. We also compare this to TC track and intensity data in order to sort notable rainfall events by TC location. We use TC rather than typhoon as our tropical system, because our analysis includes events that do not attain typhoon strength.

2.1 Rainfall data and methodology

Rainfall data comes from the Taiwan Climate Change Projection and Adaptation Information Platform (TCCIP, https://tccip.ncdr.nat.gov.tw/v2/index.aspx), and is daily with 1 km resolution from 1960-2015. Given that we are looking at rainfall patterns across the whole island, this is actually higher resolution than we need, and so we degrade it to 10 km in order to lessen the computational load. This dataset is derived from a combination of data from rain gauges and traditional weather stations belonging to the CWB (https://www.cwb.gov.tw/eng/), from the Water Resources Agency (https://eng.wra.gov.tw), from Taiwan Power Company (http://www.taipower.com.tw/en/), and from the Irrigation Association. The CWB stations and gauges are displayed by altitude and year added in Fig. 3. While this is an extremely dense dataset, there are very few stations at high elevation, and most stations have been added since the completion of Automatic Rainfall and Meteorological Telemetry System (ARMTS) in 1997 (Chen et al 2007). Because so few of the 21 long-term stations are in the
mountains, the long-term stations underestimate heavy rainfall by 23-44% (Wu et al 2016). Using these stations, there is an additional bias towards larger rainfall in central Taiwan due to all three high-altitude long-term stations being located there.

Due to the scarcity of observations in the mountains, there are large uncertainties in these regions, approaching 50 mm/day in certain remote areas in the typhoon season (Weng and Yang 2018). Therefore, we compute an alternate version of the 10-km grid, composed of those grid points located within 5 km of a rain gauge (Fig. 3). Trends at these data-rich points are used to check the results obtained from initial analysis using the whole dataset.

For the purpose of this study, we consider measurable rainfall to be at least 0.1 mm of rain in a day. Annual rainfall at a grid point is defined as the sum of all measurable rainfall during that year at that grid point. Frequency is the number of days per year with measurable rainfall, and intensity is the mean rainfall on those days. Rather than looking at total rainfall, the figures presented here depict two categories of rainfall. These are

- Non-extreme rainfall (NR): bottom 99% of measurable daily rainfall
- Extreme rainfall (ER): top 1% of measurable daily rainfall

This definition is similar to those used by Su et al (2012) and Tu and Chou (2013), who use, among other thresholds, the top 1% of hourly precipitation.

The threshold used to differentiate between NR and ER is determined individually for each grid point, to account for regional or orographic variation in mean rainfall intensity. All measurable daily rainfall totals at the grid point are ordered from least to greatest, from which the 99th percentile value is interpolated. This is an annual threshold, in that it takes into account data from all seasons. During the analysis, we found that, predictably, this is
not useful for analyzing ER in the cold season, which is much drier than the warm season. Therefore, we have adapted the definition by using seasonal thresholds, in addition to the annual threshold. All plots of seasonal ER use seasonal extreme thresholds, and plots of annual ER use an annual extreme threshold. This way, we take into account the large seasonal cycle in rainfall.

Seasonal ER and NR means have units of mm/month, while seasonal ER and NR trends have units mm/yr, indicating the change in season-total rainfall per year. Statistical significance of rainfall trends is assessed using a Monte-Carlo test (n=10,000). This involves generating 10,000 random resamplings and calculating the probability that the new trend sign matches the original trend sign. In some cases, a trend would have attained statistical significance by linear regression, but would fail the Monte Carlo test, indicating that the trend is dominated by a small number of outliers, the removal of which would yield a dataset showing little change.

Rainfall trend significance is plotted only at the data-rich grid points shown in Fig. 3, because the large uncertainties in the mountainous region preclude confidence in any trends found there.

2.2 TC Data and Methodology

TC location, dates, and intensity come from the International Best Track Archive for Climate Stewardship (IBTrACS, Knapp et al 2010; data access: https://www.ncdc.noaa.gov/ibtracs/index.php?name=ibtracs-data-access), and specifically the Joint Typhoon Warning Center (JTwC) WNP best track dataset. Using these data, we can
separate TC rainfall from non-TC rainfall. We can also classify TC rainfall according to TC location relative to the island, as well as TC track and rainfall characteristics. TC rainfall is defined as any rainfall occurring on any day during which a TC center is within the box bounded by 18 N, 29.5 N, 116 E, and 126 E (the domain of Fig. 29). Previous studies also employ a rectangular box around Taiwan to define typhoon rainfall, but the size of the box varies. Wu et al (2017) used a very large box spanning 12-34 N and 110-132 E, while Chu et al (2013) and Chen and Chen (2011) used a smaller box spanning 19.5-27.5 N and 117.5-124.5 E. Yeh (2002) used bounds 18-28 N, 116-126 E, the same method as Tu and Chou (2013), who computed that most ER takes place when a typhoon is within 500 km of the island, and later demonstrated that their results remained the same for smaller domains.

TC duration is defined as the number of track segments (between 6-hourly time steps) within the whole domain, multiplied by 6 hours per segment. In order to test for sensitivity to domain size, we tested a smaller box spanning 20 N – 27.25 N, 118 E – 123.75 E. This box sits approximately halfway between the domain boundary and the Taiwan coastline, i.e., about 250 km from Taiwan. The results did not differ significantly from those using the larger domain (not shown). TC track length is the sum of the length of these segments. Average intensity is the mean of the TC’s maximum wind speed at each track vertex lying within either the whole domain or the box, and TC speed is track length divided by duration. The final measure of TC track properties, angle of rotation, is the sum of the angles between adjacent segments within the smaller box 20 N - 27.25 N, 118 E – 123.75 E, meant to approximate a distance of 250 km from the island.

We define 9 track categories: 6 based on track location, and 3 based on other track or rainfall characteristics. These are:
• **N-type:** TC center between 24 N and 25 N at 122 E; moving westward at this longitude, and ultimately landfalling.

• **C-type:** TC center between 23 N and 24 N at 122 E; moving westward at this longitude, and ultimately landfalling.

• **S-type:** TC center between 22 N and 23 N at 122 E; moving westward at this longitude, and ultimately landfalling.

• **North-type:** TC center crosses 121.5 E moving westward north of the island, not making landfall.

• **South-type:** TC center crosses 120.75 E moving westward south of the island, not making landfall.

• **Reverse South-type:** TC center crosses 120.75 E moving eastward south of the island, not making landfall.

• **Rain-type:** top 27 (top 3%) TCs by island-mean storm total rainfall.

• **Curved-type:** top 32 (top 12%) TCs by total angle of rotation within the box 118 E - 124 E, 20 N - 27 N

• **Yilan-type:** Storm total rainfall maximum occurs in Yilan County, within the box 121.37-121.62 E, 24.34-24.59 N. These are the coordinates of the degraded 10 km resolution TCCIP rainfall data that bound the typical inland Yilan County rainfall maximum.

See Figs. 29 and 54 for illustrations of these definitions.
These definitions and the methods used are not the same as those in some other papers, which report slightly different results. For example, Chang et al (2013) divide 84 landfalling typhoons from 1960 – 2011 into categories similar to our N-, C-, and S-type tracks. We have 99 of these tracks, despite only analyzing four more years of data. However, 4 of the tracks we included were tropical depressions, and several more were of tropical storm strength; these may not have been included in other studies.

Finally, ERA-Interim wind data (Dee et al 2011; data access: http://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/) are used to calculate the mean 850-hPa wind vector in the box 119.53129 E – 123.04692 E, 21.403465 N – 26.315735 N while the TC center is within the larger domain 18 N – 29.5 N, 116 E – 126 E. This small box is used to approximate the mean wind over the island during the TC rainfall period. The coordinates are simply those of the ERA-Interim wind data.
Figure 3: (Right) CWB conventional weather stations and rain gauges plotted by (top) altitude in meters and (bottom) year added. (Left) The 10-km grid points that fall within 5 km of one of these stations.
3. Rainfall variability

3.1 Annual means and trends

Non-extreme rainfall (NR) has two attributes that stand out. First, it generally increases with elevation, most of the 1200 mm+ totals occurring over high terrain (Fig. 4a). Second, there is an absolute maximum in NR in the far northeast, extending from the mountains of Yilan County to the northern coast. Southwestern Taiwan has larger NR intensity, while northeastern Taiwan has higher NR frequency. Together, these patterns nearly cancel each other out, leaving elevation as the dominant correlation with the exception of the far northern maximum (Figs. 4ace).

Extreme rainfall (ER) is also very elevation-dependent – more so even than NR (Fig. 4b). ER has a very large maximum in inland Yilan County, just south of the valley formed by the Lanyang River (Fig. 1). Meanwhile, the northern coastal plain falls well outside of the ER maximum. ER frequency is greater in the northeast, while intensity is greater in the southwest (Fig. 4df). However, in the case of ER, there is also a maximum in central-northern regions, including inland Yilan County. The ER peak occurs where the broad frequency peak coincides with high average intensity.

In these respects, the ER and NR patterns are very similar, with variation primarily in the location of the northeastern maximum. However, the annual amounts of ER and NR differ considerably (Fig. 4). NR totals fall between 1000 and 2900 mm, compared to a range of 70 to 650 mm for ER. Averaging the annual ER and NR over the island, we obtain the annual-mean, island-mean values of 269.5 mm and 1593.2 mm, respectively (not shown).
That is, the wettest 1% of days with measurable rainfall account for approximately 17% of all rainfall.

The similarity between NR and ER totals does not carry over to their trends (Fig. 5). Both ER and NR exhibit statistically significant increasing trends over most of the island (Fig. 5ab). While the ER trends are clearly elevation-dependent, the NR trends are more consistent over the island. Moreover, the largest ER trends occur in the south, while the largest NR trends occurring in the north. When these trends are split into frequency and intensity components, it turns out that for ER, frequency is increasing more rapidly than intensity (not shown). Annually and seasonally, percentage increases in NR frequency and intensity are similar, while percentage increases in ER frequency far exceed those in ER intensity (not shown).

In order to get a more intuitive sense for these changes, we examine the rainfall intensity distribution in the first (1960-1987) and second (1988-2015) halves of the analysis period (Fig. 6). At very low intensities, there is no change between the two periods. At intensities that are heavier but not extreme, the second period has slightly more rainfall. But as rainfall intensity increases past the extreme threshold, post-1988 rainfall exceeds pre-1988 rainfall by increasingly large amounts. In the 400 mm/day to 600 mm/day range, for example, the second period has roughly five times as many instances as the first. At even higher intensities, there have been a number of events that exceed anything seen in the first period. Because there are no decreases at any intensity, there are more total rainfall reports in the second period.
3.2 Seasonal means and trends

In order to break the year up into realistic weather regimes, we use the following five seasons:

1. **Winter**: 1 December – 28 / 29 February
2. **Spring**: 1 March – 14 May
3. **Mei-Yu season**: 15 May – 14 June
4. **Typhoon season**: 1 July – 30 September
5. **Fall**: 1 October – 30 November

Winter, fall, and Mei-Yu seasons are as in Wang et al (1984) and Chen and Chen (2003). In order to fill the gap between spring and Mei-Yu season, spring has been extended by 15 days (1 - 14 May). Wang et al (1984) and Chen and Chen (2003) define typhoon season as mid-July to late August. This definition is meant to match up with the second rainfall maximum of the year, rather than the entire high TC-activity period of July to September. We use this latter definition, also used in Chu et al (2013a), in order to separate the TC influence out from other weather types. Finally, late June lacks both the Mei-Yu frontal influence of Mei-Yu season and the frequent TCs of typhoon season, and so is omitted.
3.2.a. Winter

Winter in Taiwan is characterized by cold surges accompanied by strong northeasterly winds (Chen and Chen 2003). During winter, spring, and late fall, temperatures are lower, the atmosphere is more stable, and rainfall is lighter than in the warm season (Chen et al. 2007). There is less moisture availability and lower moist static energy (MSE) (Chen et al. 2007; Chen and Chen 2003), leading to less total rainfall. What rain does occur is mostly large-scale, as convection is not generally significant until March and reaches its peak frequency in the summer (Chen and Chen 2003). Hung and Kao (2010) document two distinct mechanisms for winter rainfall in northern Taiwan. For the plains, frontal systems are most important, while for the windward slopes, orographic lift is most important. Hung et al. (2014) link subseasonal variations in winter rainfall to the MJO.

Due to a combination of northeasterly flow and northern frontal systems, rainfall is largest in the hills that cover much of the far northeastern region of Taiwan (Fig. 7; Chen and Huang 1999; Chen and Chen 2003). A very large maximum occurs immediately adjacent to the coastline, but a broader region of high rainfall spans most of Northeastern Taiwan. Areas within the coastal maximum experience frequent ER events, whereas the broader maximum sees frequent ER and NR, but the low average NR intensity indicates that there is less moderate to heavy rainfall than in the coastal maximum. Compared to the annual rainfall, these rainfall amounts are actually quite low, with the exception of the northeast coastal maximum, which accounts for over 800 mm over the three months of winter (Fig. 7).
In winter, NR and ER distributions have pronounced peaks over the northeast (Fig. 6). The same holds true for NR and ER trends (Fig. 8). Both NR and ER are increasing over nearly the entire island, especially in the north and east. Many of these trends are statistically significant. Comparing the first and second half of the period, extreme intensities have increased drastically in frequency (Fig. 9). Dry days and light intensities are equally common in both periods, but intensities above roughly 10 mm/day have seen substantial increases. Moreover, there was only one grid point of over 200 mm/day before 1988, whereas there were over 100 such grid points after 1988. While total rainfall frequency has increased for winter, much of that frequency increase is associated with ER. In fact, the extreme tail of the rainfall intensity distribution increases more during winter than it does annually.

Hung and Kao (2010) conclude that winter rainfall on northern windward slopes has not changed, while that in the northern plains increased abruptly since 1980. They argue that this increase is associated with increased SSTs in the SCS, along with a decrease of the East Asian Winter Monsoon (EAWM) over recent decades. Together, these changes allow more moisture transport into southern China, which then makes any frontal systems – associated with northern plains rainfall – more likely to produce high-intensity rainfall. We have not looked this closely at northern Taiwan, though there does appear to be a spot of negative or neutral trends over the terrain of Yangmingshan National Park, in the far north (Fig. 11). This is one of the locations where winter rainfall is more highly correlated with northeasterly flow, along with coastal Yilan County (Hung and Kao 2010).
3.2.b. Spring

During spring, increasing 850-hPa westerly flow begins bringing warmer and moister air to Taiwan (Chen and Chen 2003). Cold fronts move in from the west, bringing increased convection. The WNPSH is retreating to the east throughout the spring, and by early May, southwesterly flow begins to reach the island and bring with it higher moisture and MSE levels at low levels. Chen and Chen (2003) find a much more even rainfall distribution during spring than during winter, with an emphasis on the western mountain slopes due to eastward-bound cold fronts.

Our results are similar. The northeast coastal maximum has become less pronounced compared to winter, giving way to a maximum over the western mountain slopes around 24-24.5 N (Fig. 10). This applies both to ER and to NR. Meanwhile, southern regions receive much more rainfall than in winter, though still very little compared to the warm season. Rainfall is generally light in the east and heavy in the west, while is it common in the north and infrequent in the south. Combined, these patterns result in the greatest rainfall occurring in the northwest. This represents a shift from winter, when the northeastern coastal region experienced the most frequent and heaviest rainfall.

Spring ER and NR have statistically significant increasing trends over much of the island (Fig. 11). NR has increased over the eastern half of Taiwan, from the southern mountains all the way to the Taipei area. The largest increases coincide with the NR maximum (Figs. 10, 11). There are large increases over the central eastern coastline, where NR is comparatively low at this time of the year.
Dry days and very light rainfall have not changed in frequency from the first to the second half of the study period (Fig. 12). Heavier, non-extreme rainfall is larger in the second half. As with the annual rainfall distribution, higher intensities have larger percent increases, and the highest intensities are largely unique to the second half of the period. This indicates both an overall increase in rainfall frequency, and an increase in the fraction of extreme rainfall. NR frequency and intensity are increasing, but ER frequency and intensity are increasing more rapidly.

3.2.c. Mei-Yu Season

The first distinguishing factor of the Mei-Yu season is the magnitude of the rainfall, close to three times the monthly rainfall of winter or spring (Figs. 7,10,13). Some areas in the southern and central mountains receive over 500 mm of NR in just one month – almost 25% of their annual total (Figs. 4, 13). During this time, Mei-Yu frontal systems move into the region from southern China, as well as convective systems embedded in the southwest monsoon flow, which has become well-established by Mei-Yu season (e.g. Chen and Chen 2003, Chen 2007). The cold season has ended; southwest flow brings in high moisture- and high MSE-content air at low levels, and the atmosphere becomes conditionally unstable (Chen and Chen 2003). These frontal and convective systems approaching from the west and southwest make the western and southwestern mountain slopes the heavy rain hotspots (Fig. 13ab).

The other exceptional aspect of the Mei-Yu season is the high rainfall frequency. NR occurs on 10-20 days of the month, with much of the island being in the upper half of that
range (Fig. 13). Only the western and southern coastal plains have less than 11 NR days during the month. ER is most common in the south and west, in the central mountains near 24 degrees N, and to a lesser extent along the northwest coast. The Mei-Yu season does share one thing with spring; the intensity is largest over the west and south, while frequency is more evenly distributed, though skewed slightly to the east. The NR intensity range is larger than the NR frequency range, so that intensity dominates the NR rainfall totals. For ER, there is a large frequency maximum in the central mountains, where the mountains jut out to the west. Flow from the west and southwest likely causes pronounced orographic ascent in this region.

Rainfall trends for the Mei-Yu season are highly variable in space (Fig. 14). NR trends resemble a patchwork of positive and negative, with more negative trends inland and more positive trends near the coasts. ER trends are positive in the far northwest, as well as the western and southern mountain slopes; the southern mountain slopes have the largest and most statistically significant trends. The lack of significance might be a result of the short length of Mei-Yu season – 1 month, versus 2 to 3 for the other seasons.

Dry days are more frequent post-1988 than pre-1988, and light to moderate rainfall is less frequent (Fig. 15). Heavy but non-extreme rainfall is equally common in both periods, and extreme rain is more frequent in the second period, especially at higher intensities. Observations above 500 mm/day have occurred only since 1988. Unlike winter and spring, Mei-Yu season does not display a consistent increase in rainfall frequency between the two periods. Rather, there are decreases at light to moderate intensities, balanced by increases at extreme intensities.
Huang and Chen (2015) found that May and June frontal convection has decreased in Taiwan, while diurnal convection has increased. This is likely because the region of favorable temperature gradient for frontal convection has shifted northward, from 20-30 N to north of 30 N. While we have not analyzed the causes of Mei-Yu rainfall changes, the idea of opposing influences fits well with our image of mixed trends.

3.2.d. Typhoon season

According to Chen and Chen (2003), the late summer monsoon trough reaches its northernmost position in August, affecting Taiwan and inducing the second rainy season. Because the island is under the influence of southwesterly flow, abundant heat and moisture is being funneled into southwestern regions in particular; and because the atmosphere is unstable, this moisture can easily be translated into convection. Most of the rainfall during this time is convective in nature (Chen and Chen 2003). Afternoon rainshowers are common over the western windward slopes of the mountains. Rainfall in the southeast is maximized in late July, a difference that has to do with more frequent passage of TCs south of the island during that time (Chen and Chen 2003). Meanwhile, rainfall in the north and east is relatively low, as those areas are in the lee of the southwesterly flow.

Typhoon season has a lower monthly NR than Mei-Yu season, but higher ER (Fig. 16). NR has shifted to the far southwest, with a strong maximum on the southwest mountain slopes and adjacent coastal regions, where Chen and Chen (2003) describe convection associated with the monsoon flow. ER has a southern maximum, but is largest in the northeast, in and around Yilan County (Fig. 1, Fig. 16b). The NR maximum comes from a
combination of high frequency in the southwest and high intensity in the far south, while the ER maximum comes largely from frequent ER in the northeast. These significant differences between NR and ER distributions likely mean that ER has a different cause to NR. In later subsections, we will examine the characteristics of TC versus non-TC rainfall in order to confirm or deny the hypothesis that ER is disproportionately associated with TC rainfall, which is more frequent in the northeast than in the southwest.

ER is increasing everywhere except eastern coastal regions between 23 and 24 N, as well as some of the northwestern coastal plain (Fig. 17). The largest increases occur over the southern and western mountain slopes, as well as over inland Yilan County, though the southern increases are slightly larger. Interestingly, the southern mountains receive less ER than inland Yilan County, despite the larger increasing ER trend. These two ER maxima may be associated with different weather types (more in section 6). NR, on the other hand, has mixed trends: positive in the west and north, and mostly negative in the mountains (Fig. 17).

The mean frequency of dry days has not changed from the first to the second half of the study period (Fig. 18). Light rainfall has also remained the same, aside from a very small decrease at the lightest intensities. Like in other seasons, heavy NR has become slightly more frequent, whereas ER has become drastically more frequent, especially at very high intensities. Rainfall in excess of 700 mm/day is mostly confined to the post-1988 period. In effect, the rainfall distribution has broadened, with a more gradual tail extending to higher frequencies than in earlier years. There has also been a general increase in rainfall frequency, possibly partially offset by decreases in very light rainfall.
3.2.e. Fall

Chen and Chen (2003) document a fall rainfall maximum at most stations in the north and northeast. During this time, the summer monsoon trough moves southward, while the WNPSH ridge axis retreats eastward, leaving Taiwan in increasing easterly flow. By late September, northeasterly monsoon flow has set in at 850-hPa; as low-level northeasterly flow strengthens, upper-level westerlies bring in disturbances that can produce heavy rainfall in the north and northeast (Chen and Chen 2003).

The rainfall distribution reflects this shift in the monsoon flow: both NR and ER have a strong east-west gradient, with high rainfall in the east and very low rainfall in the west (Fig. 19). Some of the patterns of winter have begun returning: NR and ER both peak in Yilan County, with NR having a secondary maximum in the northern coastal region. There is also a weaker maximum in the east around 23.5 N. ER is most frequent in Yilan County, while NR is both frequent and intense in this area. Northern coastal NR is frequent, but not as intense as that in Yilan County. Unlike winter, when the wind has turned fully north and northeast, fall has more easterly flow, resulting in lower totals in the northern coastal region and higher totals in Yilan County. The large ER intensity peak in the southwest occurs in a region of very low frequency, and is therefore likely due to small sample size.

Most of the statistically significant rainfall trends occur in the west, especially with respect to NR (Fig. 20). Smaller increases extend throughout the southwest as well. There is a negative NR trend in one spot in the central eastern region of Taiwan; but this is a location with low station density and so does not represent a statistically significant trend. ER trends exhibit the same pattern, although they are larger much larger over the
mountains than along the western coastline. There has been some increase in the northwest, and some decrease in the southeast.

Dry days and very light rainfall are no more common post-1988 than pre-1988 (Fig. 21). Heavy, non-extreme rainfall has become more frequent, but changes in ER are small and mixed. Unlike in other seasons, the rainfall distribution has changed little during fall. In fact, it was the first half of the period that had the most extreme events above 700 mm/day.

3.2.f. Confirmation

In order to confirm that the ER trends with greater certainty, we omit the high-uncertainty mountainous region (Fig. 3). Even though these remote regions tend to have larger trends, omitting them still leaves mostly positive ER trends (Fig. 22). More than 80% of ER trends are positive in every season except fall, which still has a majority of positive trends. Additionally, many of these trends are statistically significant. Typhoon season has by far the largest ER trends, with the peak of the distribution extending nearly to 5 mm/year, as opposed to less than 1 mm/year for the other seasons.

3.2.g. Overview

Taiwan’s rainfall is dominated by a large seasonal cycle, with less rainfall in the cold season (winter, spring, and late fall) and more rainfall in the warm season (Mei-Yu season, typhoon season, and early fall). This is particularly true for ER, which varies from ~10-20 mm in rainy areas during the cold season, to ~50-100 mm in those same areas in the warm
season, even using seasonal extreme thresholds. With an annual extreme threshold, there is virtually no ER during the cold season (not shown).

ER is increasing drastically for every season except fall. During the warm season, light rainfall is decreasing in frequency while heavy rainfall and ER increase in frequency. During the cold season, light rainfall remains unchanged while heavy rainfall and ER increase in frequency. These changes are generally largest where there is already copious rainfall. For example, the largest ER totals and trends are in the north during the cold season, due to the northeasterly monsoon flow interacting with Taiwan’s mountain ranges. But during the warm season, the largest ER totals and trends are in the south and west, under the influence of the moist southwesterly flow seen during these months.

The largest and most impactful changes, though, are in the most extreme rainfall intensities, well above the 99th percentile. Every season except fall has seen a marked increase in the most intense rainfall. The rainfall distribution has expanded to include previously unheard-of intensities. Rainfall above 200 mm/day in winter, 250 mm/day in spring, 500 mm/day in Mei-Yu season, and 700 mm/day in typhoon season occurs almost exclusively in the second half of the study period 1960-2015.
Figure 4: Annual non-extreme rain (NR) (a) total, (c) frequency, (e) and intensity; annual extreme rain (ER) (b) total, (d) frequency, and (f) intensity. Rainfall data are from TCCIP. Rainfall data degraded from 1 km to 10 km spatial resolution. ER is defined as the top 1% of wet days at a grid point; NR is defined as the bottom 99% of wet days at a grid point.
Figure 5: Trends in annual (a) NR total and (b) ER total. Blue circles indicate statistical significance at the 5% level using a Monte Carlo test.

Figure 6: Histogram of annual daily rainfall. 1960-1987 is plotted in blue, while 1988-2015 is outlined in black. The dashed vertical red line indicates the spatially-averaged top 1% daily rainfall threshold. Intensity is plotted on the x-axis, and number of grid points is plotted on the y-axis. The first bin holds non-measurable rain (<0.1 mm) and dry days.
Figure 7: Winter NR (a) total, (c) frequency, (e) and intensity; winter ER (b) total, (d) frequency, and (f) intensity.
Figure 8: Trends in winter (a) NR total and (b) ER total. Blue circles indicate statistical significance at the 5% level using a Monte Carlo test.

Figure 9: Histogram of winter daily rainfall. 1960-1987 is plotted in blue, while 1988-2015 is outlined in black. The dashed vertical red line indicates the spatially-averaged top 1% daily rainfall threshold. Intensity is plotted on the x-axis, and number of grid points is plotted on the y-axis. The first bin holds non-measurable rain (<0.1 mm) and dry days.
Figure 10: Spring NR (a) total, (c) frequency, (e) and intensity; spring ER (b) total, (d) frequency, and (f) intensity.
Spring

Figure 11: Trends in spring (a) NR total and (b) ER total. Blue circles indicate statistical significance at the 5% level using a Monte Carlo test.

Daily rainfall intensity

Figure 12: Histogram of spring daily rainfall. 1960-1987 is plotted in blue, while 1988-2015 is outlined in black. The dashed vertical red line indicates the spatially-averaged top 1% daily rainfall threshold. Intensity is plotted on the x-axis, and number of grid points is plotted on the y-axis. The first bin holds non-measurable rain (<0.1 mm) and dry days.
Figure 13: Mei-Yu season NR (a) total, (c) frequency, (e) and intensity; Mei-Yu season ER (b) total, (d) frequency, and (f) intensity.
Mei-Yu Season

Figure 14: Trends in Mei-Yu season (a) NR total and (b) ER total. Blue circles indicate statistical significance at the 5% level using a Monte Carlo test.

Figure 15: Histogram of Mei-Yu season daily rainfall. 1960-1987 is plotted in blue, while 1988-2015 is outlined in black. The dashed vertical red line indicates the spatially-averaged top 1% daily rainfall threshold. Intensity is plotted on the x-axis, and number of grid points is plotted on the y-axis. The first bin holds non-measurable rain (<0.1 mm) and dry days.
Figure 16: Typhoon season NR (a) total, (c) frequency, (e) and intensity; typhoon season ER (b) total, (d) frequency, and (f) intensity.
**Typhoon Season**

Figure 17: Trends in typhoon season (a) NR total and (b) ER total. Blue circles indicate statistical significance at the 5% level using a Monte Carlo test.

Figure 18: Histogram of typhoon season daily rainfall. 1960-1987 is plotted in blue, while 1988-2015 is outlined in black. The dashed vertical red line indicates the spatially-averaged top 1% daily rainfall threshold. Intensity is plotted on the x-axis, and number of grid points is plotted on the y-axis. The first bin holds non-measurable rain (<0.1 mm) and dry days.
Figure 19: Fall NR (a) total, (c) frequency, (e) and intensity; fall ER (b) total, (d) frequency, and (f) intensity.
Figure 20: Trends in fall (a) NR total and (b) ER total. Blue circles indicate statistical significance at the 5% level using a Monte Carlo test.

Figure 21: Histogram of fall daily rainfall. 1960-1987 is plotted in blue, while 1988-2015 is outlined in black. The dashed vertical red line indicates the spatially-averaged top 1% daily rainfall threshold. Intensity is plotted on the x-axis, and number of grid points is plotted on the y-axis. The first bin holds non-measurable rain (<0.1 mm) and dry days.
Figure 22: Histograms of ER trends in high-station-density regions. Hatching signifies that the trend is statistically-significant at the 5% level, using a Monte Carlo test. This figure shows that typhoon season ER trends are much larger than ER trends in other seasons.
4. TC vs non-TC rainfall

The remainder of the study will focus on TC rainfall. Since typhoon season has the most extreme rainfall, we will begin by looking more closely at typhoon season ER. Following that, we will separate annual rainfall into TC and non-TC categories, looking at averages and trends in the two. Section 5 will then break the TC rainfall down according to track type.

4.1. EOF modes of typhoon season rainfall

In order to objectively diagnose the spatial variability of typhoon season rainfall, we use empirical orthogonal function (EOF) analysis, a statistical technique in which a field is partitioned into orthogonal modes, which might be associated with independent weather patterns. These modes might be associated with separate atmospheric processes, or they might be mathematically independent but not represent different processes (NCAR 2013, https://climatedataguide.ucar.edu/climate-data-tools-and-analysis/empirical-orthogonal-function-eof-analysis-and-rotated-eof-analysis). Most of the variance of atmospheric processes is usually contained within the first few modes.

Kuo et al (2015) analyzed annual precipitation in Taiwan, obtaining a similar result of three important modes: a mode due to southwest monsoon and typhoon rainfall, explaining 65% of the variance in the rainfall data; a mode related to the monsoon interaction with the CMR, explaining 16% of the variance; and a north-south mode coming from the Pacific Decadal Oscillation (PDO), explaining 7% of the variance. Yeh (2002)
carried out EOF analysis on typhoon rainfall, describing the resulting three modes in terms of near-island typhoons (Fig. 23). Mode 1 is an in-phase mode showing rainfall increasing over the whole island as a typhoon approaches. Mode 2 shows an out-of-phase rainfall distribution, with northern typhoons leading to more rainfall in the north and southern typhoons leading to more rainfall in the south. Mode 3 is similar to mode 2, except with an east-west gradient instead of a north-south gradient. Typhoons that move to the west of the island tend to produce more rain in the west, while those to the east of the island produce more rain in the east.

Typhoon season ER shows the same three modes described by Yeh (2002). Mode 1 shows an in-phase distribution, with ER increasing or decreasing over the whole island. The amplitude of this mode increases in the center of the island, and is lowest in the southeast. Mode 1 explains approximately 32% of the variance in the ER data. From 1960 to 2015, the principal component time series of mode 1 has an increasing trend in its variance. This trend is statistically significant at the 5% level using linear regression. Mode 2 is an out-of-phase mode, with the south having low rainfall when the north has high rainfall, and vice versa. As with mode 1, the principal component time series of mode 2 has increasing variance. Mode 3 is another out-of-phase mode, with an east-west gradient. High rainfall in the west is correlated with low rainfall in the east, and high rainfall in the east is correlated with low rainfall in the west. Mode 3 has also seen an increase in time series variance.
4.2. Annual TC vs non-TC rainfall and trends

Using the 21 long-term conventional CWB stations from 1960 to 2014, Su et al (2015) found that extreme rainfall – defined there as the top 5% of rainfall – accounts for 40% of the total rainfall, and that ~68% of extreme rainfall is typhoon-related. Typhoon rainfall accounts for 20-50% of all rainfall, and typhoon extreme rainfall accounts for 50-70%+ of all extreme rainfall (Chang et al 2012). Non-typhoon heavy rainfall days – defined as days with at least 1 gauge exceeding 15 mm/hr and daily total exceeding 50 mm) – account for 60-90% of heavy rainfall days. This comes as no surprise, as typhoons are some of the most extreme rainmakers worldwide: recently, U.S. hurricanes Harvey (maximum rainfall of 1539 mm) and Florence (maximum rainfall of 913 mm) have demonstrated just how devastating the rain bands of a slow-moving TC can be. Multiple papers (Tu and Chou 2013, Chu et al 2014) have detailed the increase in typhoon rainfall in Taiwan. They have also found that monsoon (i.e. non-typhoon) rainfall is actually neutral or decreasing.

In this study, TC rainfall is defined as any rainfall occurring when a TC center resides within a box containing Taiwan and bounded by 116 E, 126 E, 18 N, and 29.5 N (as in Fig. 32). All other rainfall is considered non-TC rainfall. Tu and Chu (2013) used this definition for typhoon rainfall on the basis that typhoon rainfall becomes significant when the typhoon is within ~500 km of the island. Note that this is an annual total, not a seasonal one. Since TCs can occur outside of typhoon season, restricting to the typhoon season would not capture the true total TC rainfall contribution.

We have found that TC ER accounts for ~40-90+ % of ER (Fig. 24). TC ER is larger in the east, and smaller (though still a majority of ER) in the west (Fig. 24). Since most TCs
near Taiwan move westward (see section 5), it makes sense that the western coastal plain sees less TC rainfall; the eastern slopes spend longer in the path of the TC winds, and catch the flow while the TC is stronger. Note also that the inland Yilan county rainfall peak is present in TC ER, but does not show up non-TC ER. Non-TC ER occurs in the southwest, where there is abundant warm-season rainfall due to the moist southwesterly flow (see Figs. 13, 16).

TC ER trends are much larger than non-TC ER trends (Fig. 25). TC ER trends appear to be at least twice the magnitude of non-TC ER trends. TC ER is increasing in the southwest and near Yilan County, regions with already-large TC ER (Fig. 24). These increases come from both frequency and intensity. Non-TC ER is increasing broadly over the western half of the island, especially western mountain slopes. Like the seasonal ER trends, TC and non-TC ER trends are associated more with an increase in ER frequency than with an increase in mean ER intensity, although both do contribute (not shown).

Because we have used an annual extreme threshold for these calculations, the results do not match up precisely with the ER results for the various seasons. If we had used seasonal ER thresholds, there would be significantly more non-TC ER, since almost none of the cold season ER is associated with TCs. However, with the annual threshold, cold season rainfall almost never exceeds the annual threshold, so that there is very little non-TC ER.
Figure 23: (Row 1) EOF modes of ER during typhoon season. The three highest-variance modes are displayed. Percent variance is shown in the lower left of each panel. (Row 2) Squared principle component time series of ER EOF modes during typhoon season. The three highest-variance modes are displayed. Trend lines are displayed in blue. A yellow dot signifies statistical significance at the 5% level using linear regression. A green dot signifies statistical significance at the 5% level using a Monte Carlo test.
Figure 24: Annual-mean typhoon and non-typhoon ER. The bottom row depicts the fraction of total rainfall associated with TCs.
Figure 25: Trends in annual-mean non-typhoon and typhoon ER. White circles indicate statistical significance at the 5% level based on a Monte Carlo test, excluding regions with low station density.
5. TC characteristics

Now that we have seen that TC ER accounts for most of the annual ER increase, we will determine the specific source of the TC ER increase. TC ER can be classified according to the track or rainfall properties of the TC. In section 2, we defined nine track categories, six based on track location and three based on other TC characteristics such as rainfall pattern or track length. The primary goal of this section is to compute and discuss the rainfall characteristics of each of these track types.

5.1. Large-scale TC activity

Figure 30 shows the TC track density and mean intensity in the western North Pacific from 1960 to 2015. Taiwan lies just north of an active track extending into the South China Sea. However, regions east of the island still experience high TC activity. Relatively high TC activity extends north and east of Taiwan, with lower track densities further to the north and east.

Though Taiwan lies on the edge of the most active storm track, it is at the ideal latitude to receive intense TCs (Fig. 26). East of the island from approximately 16 N to 30 N, mean TC intensity is in the 60-80 kt range. There is a sharp drop off to the west in the South China Sea, as well as to the south. Though TCs may be common further to the south, strong TCs require time to ramp up, at which point they have typically traveled further north.

typhoons and increases in re-curling typhoons in future-climate projections, due to slower easterlies allowing for beta drift to deflect the storms further poleward. This shift has already begun, and is associated with the weakening of the WNPSH and the strengthening of the Asian summer monsoon trough (Chu et al 2013, Tu et al 2009, Gong et al 2018). On a large scale, this has resulted in an abrupt increase in typhoon activity north of 20 N since 2000 (Tu et al 2009).

Based on the identification of 2000 as a regime change, we have plotted in Fig. 26 the 2-degree resolution track density maps for 1960-1999 and 2000-2015. Fig. 27 (top) shows the difference of these two fields. The picture is generally what is described in the literature: more decreases in western regions south of 20 N, and more increases over Taiwan and further north: regions that would be affected by a more recurving storm track. However, 2000-2015 being a rather short period to draw conclusions from, we have also calculated the 2-degree resolution track density trend, and tested for trends at the 5% significance level using a Monte Carlo test. The result is similar to the difference plot, with positive trends over and near Taiwan, some of which are statistically significant (Fig. 27, bottom). In this case, the map is quite noisy, with large shifts in trends from one region to the next and seemingly little pattern to the changes. Whereas the pre- and post-2000 density change is more positive to the north and more negative to the south, the 56-year trends are mixed throughout the region.
5.2. Location-based track types

Because of the high topography, TC position is a key factor in determining the rainfall distribution – in fact, Chang et al (2013) describe typhoon position and size as the only two factors used in CWB forecasters’ empirical rainfall forecast model. Different TC locations will result in different wind directions over the topography of the island, which in turn will lead to a different distribution of orographically-enhanced precipitation. Therefore, we define common TC track categories that have important differences in TC properties, following the concept used by the Central Weather Bureau. There are three landfalling TC categories meant to capture different rainfall distributions of east coast-landfalling systems, as well as three non-landfalling TC categories meant to represent the common tracks passing north and south of the island. These categories are defined in section 2, and illustrated in Fig. 28.

i.) N-type

N-type TCs are fairly common, with 34 cases between 1960 and 2015 (Fig. 29). Most N-type TCs approach from the east-southeast, with a secondary cluster approaching from the south-southeast. These storms’ mean latitude falls mostly between 23 N and 26 N, with the majority of those between 24 N and 26 N – around the northern part of the island. This results in mean northwesterly 850-hPa winds over the island (Fig. 32), leading to large orographically-enhanced storm total rainfall and annual ER over northwestern-facing
mountain slopes (Fig. 29). There is an especially broad maximum in the north, closer to the center of the typical N-type TC.

In terms of their seasonal distribution, N-type TCs occur almost exclusively during the typhoon season (Fig. 30). They are spread fairly evenly throughout the months of July, August, and September, with the latest occurrence being near the beginning of October. Their average latitude most often falls between 24 N and 26 N, with a few cases that approach more from the south and therefore have a more southerly mean latitude.

These TCs exhibit no statistically significant changes in frequency, despite large inter-decadal variability emphasized by the particularly active period of 2005-2015 (Fig. 29). Most years there is either one N-type TC, or zero N-type TCs. Though N-type TC frequency has not increased, N-type ER has increased over most of northern and western Taiwan, especially in the southern central mountains. These ER trends come from increasing ER frequency and intensity (not shown). ER increases are statistically significant over the southwest and the far north.

N-type TC speed has decreased, and conversely, duration has increased (Fig. 31). These changes are statistically significant. Speed and duration are highly correlated with rainfall indices for this track type (Table 2). Therefore, the decrease in N-type TC speed is a probable cause of the increase in annual ER. Decreased speed fits with the notion of a slower steering flow (e.g. Chu et al 2012). The cause of this change, as well as similar changes in other track types, will be the subject of future work.
ii.) C-type

C-type tracks are less common, with 22 TCs compared to N-type’s 34 (Fig. 33). Geographically, this is a much narrower category, since N-type (S-type) tracks can be arbitrarily far north (south) at 122 E, as long as they make landfall. Since these storms pass over the center of the island, the wind over northern regions cancels out the wind over southern regions, leading to a smaller mean (Fig. 36). The weak mean easterly flow that does occur may simply be the steering flow of the TC. Consequently, these storms produce very large storm total rainfall and annual ER (Fig. 33) in orographically-favorable locations, and smaller values elsewhere. The center of the island may not be as favorable in this case, since it lies right in the path of the TC. Areas to the north (south) will receive strong mean easterly (westerly) winds during the passage of the TC. The center of the island, however, will receive strong but inconsistent winds as the eye passes overhead.

These TCs have a similar seasonal distribution to the N-type TCs. They occur almost entirely within typhoon season, and are evenly spread throughout July, August, and September (Fig. 34). There is only one case falling outside typhoon season, around day 320 (mid November).

C-type TCs have increased in frequency somewhat, although that trend can be attributed to inter-annual or inter-decadal variability (Fig. 33). There was a roughly decade-long drought of these systems around 1980. Still, without the extremely active 2005-2009 period, there would be no apparent trend in C-type TC frequency. C-type ER has increased over most of the island, particularly in the south and the northeast where C-type ER is already large. The C-type ER increase is slightly larger than the N-type ER increase.
Again, the ER increase is due to both frequency and intensity increases (not shown). As with the seasonal ER, frequency has the larger percent increase than intensity.

C-type TCs exhibit a statistically significant increase in speed and corresponding decrease in duration (Fig. 35). Since speed and duration are statistically significantly correlated with rainfall indices for this track type (Table 3), the speed increase would typically be associated with a decrease in storm total rainfall and annual-mean ER. Some other factor must offset this change. One candidate is storm frequency. Even though there is no statistically significant trend, there has still been an increase in mean C-type TC frequency over the second half of the period as compared to the first half of the period (Fig. 33). Moreover, there may be relevant changes in storm characteristics that have not been investigated here or that are not statistically significant.

iii.) S-type

S-type TCs are slightly more common than N-type TCs, with 39 cases from 1960 to 2015 (Fig. 37). These storms’ angle of approach varies widely. Some tracks approach from the east-southeast, while others move almost due north, meeting the latitude criterion at 122 E but impacting the central and northern parts of the island. Consequently, there is especially large spread in these tracks after landfall, with some moving north or recurving to the east while others continue west and north into mainland China. Despite the recurving cases, the mean latitude of these systems within the domain is lower than for the N- or C-type TCs (Fig. 38). Most fall between 21 N and 24 N. Because of their more southerly
location, S-type TCs produce mean easterlies over the island (Fig. 40). These easterlies intersect with the eastern mountain slopes, leading to enhanced orographic ER over eastern locations (Fig. 37). Meanwhile, western and northern Taiwan receive almost no ER from this track category.

With S-type TCs, we begin seeing a larger spread in seasonal timing (Fig. 38). Like the N- and C-type TCs, these span the duration of typhoon season. However, there have been several cases of S-type TCs occurring before typhoon season, or even in Mei-Yu season. This storm track may be more favorable in the early-summer flow pattern. Alternatively, more southern ocean regions may develop favorable conditions for TC development earlier in the year.

These storms have not become any more or less frequent (Fig. 37). Most years see anywhere from zero to two S-type TCs, but the 5-year running mean is fairly steady with only slight inter-annual fluctuations relative to other track types. S-type ER is increasing over the southern central mountains, though not to the extent that N- or C-type ER is increasing. This S-type ER increase is not occurring over the region of high S-type ER, meaning that the S-type ER distribution has shifted to the south and west. The distinctive southern ER increase comes mostly from an increase in ER intensity (not shown). S-type ER frequency increases are more uniform across the island.

S-type TC speed has decreased statistically significantly, while duration has increased (Fig. 39). Duration and speed are statistically significantly correlated with rainfall indices for these tracks, meaning that we should expect lower speed to be associated with higher storm total rainfall and annual ER. This does fit with the observed increase in annual ER (Fig. 37). Intensity is also highly correlated with rainfall, likely because S-type TCs
produce most of their rainfall in the pre-landfall phase (Chang et al 2013), as well as being faster-moving and having less terrain interaction than N- and C-type TCs. Therefore, changes in intensity might play into the rainfall trends, even though intensity changes were not found to be statistically significant.

**iv.) Summary of landfalling track types**

Previous studies (e.g. Chang et al 2013) have found that all three east-landfalling track categories have increased in frequency since 2000. Others have referenced a regime change in 2000, with an abrupt increase in typhoon activity near Taiwan since then (Tu et al 2009). Our results are more mixed: while east coast landfalling TC frequency has been higher since 2000 (Fig. 41), it is not sufficient to constitute a statistically significant increasing trend. Moreover, TC frequency as a whole within the domain has not increased at all since 1990 – at least, not without taking into account factors like duration or track length, or TC severity (Fig. 41). Perhaps this has to do with the different definitions we have used, or the fact that we have included TCs of tropical storm and tropical depression intensity. Lee and Chia (2008) documented a century trend of decreasing landfalling typhoons in Taiwan. Our results apply only to east-coast landfalling TCs, and only to the period 1960-2015; broadening those categories may change the nature of the observed trends.

In their analysis, Chang et al calculated large differences approaching 60% in the landfalling track types by comparing 2004-2011 to 1960 – 2003. While this holds true in
our analysis for N- and C-type TCs, none of these decadal increases are sufficient to imply a statistically significant trend at the 5% level.

\[ v.\) North-type \]

North-type TCs are about as common as S- or N-type TCs, with 36 cases from 1960 to 2015 (Fig. 42). These storms pass north of the island from east to west. Some pass very near the northern part of the island, while others remain hundreds of kilometers away. There are more tropical depression-strength systems in this category than in the three landfalling categories. While there is large variation in the mean latitude of these tracks (Fig. 43), their angle of approach is fairly consistent. Most of these systems come from the southeast and subsequently make landfall in China. Because of their northerly latitude, winds over the island are predominantly from the northwest (Fig. 45), resulting in orographically-enhanced ER over northwest-facing mountain slopes (Fig. 42). Nevertheless, these systems produce less ER than any of the landfalling types, since the TC center remains well offshore.

Whereas the other track types occur throughout the typhoon season and possibly beyond, North-type TCs are confined to a narrow time window in the middle of summer (Fig. 43). Most of these systems occur between days 200 and 260, or mid July – mid September. Around mid-July, the strong 850-hPa southwesterly flow begins weakening, becoming weak and erratic by late August (Chen and Chen 2003). North of the island, the flow is from the southeast by late August, turning east and then northeast in late September. This transitional period may allow more TCs to move north of the island without being
deflected by strong southwesterlies. Additionally, the water may be slower to warm at these latitudes, making sustained TC activity less favorable early in the season.

These storms have no statistically significant trends in frequency, though there may be large interannual variability (Fig. 42). 1989 was a particularly active year, with five North-type TCs. Likewise, trends in North-type ER are weak and mixed, though they tend to be more negative than positive. Few of these trends attain statistical significance.

North-type TC rainfall is correlated much more with duration than with speed or intensity (Table 5), simply because many of these systems track near the edge of the domain and thus spend much less time within it. There are no statistically significant trends in N-type TC duration, speed, or intensity. Around 1990, these storms began occurring later in the season (Fig. 44). However, the cause of this change or its effects on rainfall remain unclear.

\textit{vi.) South-type}

South-type TCs are by far the most frequent of any track category in this study (Fig. 46). These storms belong to the active storm track that passes south of Taiwan and into the South China Sea (Fig. 26). Most of these tracks are relatively straight and zonal, with a small northerly component. Because of the definition of this category, mean TC latitude ranges from approximately 18 N to 22 N, the only exceptions being the few cases that track north into the Taiwan Strait (Fig. 47). These southerly TCs induce strong easterly winds over the island (Fig. 49), leading to large orographic ER over the eastern mountain slopes and a large
east-west rainfall gradient (Fig. 46). This is a very similar ER distribution to that of the S-type TCs, except with even less rainfall in the west. Though this type produces statistically significant annual ER, their storm-wise rainfall is the lowest of any type so far (Fig. 46). It is only because of their high frequency that the annual total is so high.

These systems continue the trend of more southerly storms having a larger seasonal spread. South-type TCs may occur at any point from late Mei-Yu season to late fall, although the highest concentration still lies in typhoon season (Fig. 47). Conditions at these latitudes may remain favorable for sustained TC activity for a longer period than regions further north. Moreover, the 850-hPa flow here is often weaker than that to the north (Chen and Chen 2003), making this storm track more probably early and late in the season.

South-type TCs have not increased or decreased in frequency over the 1960 – 2015 period (Fig. 46). These systems exhibit some interdecadal variability, with a rise in activity between roughly 1985 and 1995. However, the ER produced by South-type TCs has decreased sharply over most of the eastern coastal region, and some of these trends are statistically significant (Fig. 46). This ER decrease is nearly equal in magnitude to the ER increases associated with any of the three landfalling track types (Figs. 29, 33, 37).

TC speed, duration, and intensity are all important factors for South-type TC rainfall (Table 6). The correlations are smaller than for the landfalling track types. However, there has been a statistically significant decrease in the intensity of South-type TCs from 1960 to 2015 (Fig. 48). The data are quite noisy, but the trend still passed the Monte-Carlo test. Lower intensity would be associated with less rainfall, especially for these non-landfalling systems where the primary rainfall mechanism is orographic ascent of the broad TC
circulation. This trend likely explains at least part of the decrease in annual ER from South-type TCs.

**vii.) Reverse South-type**

Between 1960 and 2015, there were 35 TCs moving eastward to the south of Taiwan (Fig. 50). In most cases, these systems are actually moving to the northeast, rather than due to the east. They tend to be quite weak—mostly tropical depression and tropical storm strength, with no systems of major hurricane strength. Some of these systems come directly from the South China Sea, while others appear to be recurring TCs that made landfall in the Philippines before turning northeastward. Though they are east-bound, these storms’ mean southerly latitude (Fig. 51) means that they, like the South- and S-type TCs, produce mean easterly winds (Fig. 52). This results in orographically-enhanced ER over eastern mountain slopes (Fig. 50). Over the west, by contrast, these systems produce no ER. Reverse South-type TCs produce less total rainfall and annual ER (Fig. 50) than any previous track type, likely because they are non-landfalling and weak.

These storms have a very interesting seasonal distribution, occurring mostly very early or very late in the season (Fig. 51). There is a flare-up of Reverse South-type TC activity during Mei-Yu season, and another in mid to late fall. Few of these systems actually occur during typhoon season. The early peak makes sense because this is when the 850-hPa flow recurrences over the Philippines and turns southwesterly, like many of these systems (Chen and Chen 2003). During late fall, though, the flow has turned northeasterly, which would seem to be unfavorable for a system moving to the northeast.
Like the other non-landfalling track types, Reverse South-type TCs have no frequency trend, but significant interdecadal variability, with peaks in activity around 1980 and 2000 (Fig. 50). Interestingly, these systems experience a sudden absence of activity starting in 2009. Still, they have increasing annual ER, at least prior to the 2009 drop-off. Annual ER is trending upward throughout the entire eastern and northern part of the island, coinciding with the region where these systems are capable of producing ER. While these increases are statistically significant, they are much smaller than those associated with other track categories, since the amount of ER produced by these storms is so much smaller.

Reverse South-type TCs have no statistically significant trends in duration, speed, or intensity (not shown). Intensity is highly correlated with rainfall indices for these systems (Table 7). This is likely because Reverse South-type TCs have low average intensity. Like the other non-landfalling types, these systems create ER primarily through their circulation interacting with the mountains, so that changes in the strength of that circulation have a large impact on ER. Changes in intensity could still play a role in ER trends, even if they are not statistically significant.

viii.) Summary: location-based track types

TC track density has increased in the immediate vicinity of Taiwan, but this does not imply statistically significant increases over the entire domain 18 – 29.5 N, 116 – 126 E. In fact, none of the six location-based track types have statistically significant increasing trends in frequency, although C-type comes closest to statistical significance at the 5% level. What has changed is the contribution of each type to Taiwan’s extreme rain (ER). N- and C-type
TCs have the largest statistically significant trends in annual ER, due to N-type TCs becoming slower and C-type TCs becoming more frequent. However, there are also statistically significant contributions by S-type TCs, which have seen increased annual ER, and South-type TCs, which have seen decreased annual ER.

Each track type has a characteristic ER distribution based largely on the storms’ location relative to the island. The latitude and longitude of the TC determine the mean wind over the island, while determines the locations of optimal orographic enhancement. As a result, storms located further south produce large ER in the east, while those located further north produce large ER in the north and west. C-type TCs, passing through the center of the island, have a more balanced ER distribution.

According to model projections, westward-moving typhoons should become less frequent in the future, while recurving typhoons should increase in frequency due to reduced easterlies allowing more time for beta drift to advect storms poleward (Colbert et al 2015). This trend of slower steering flow resulting in lower SCS typhoon activity has already been observed (Chu et al 2013, Wu et al 2005, Tu et al 2009). Changes in recurving TCs near Taiwan may be investigated in future work.

c. Extreme track types

Previous studies have observed a tendency for typhoon tracks to make a loop before landfall in Taiwan, especially recently (Jian et al 2008, Huang et al 2011). As a TC approaches the island from the east, the channeling effect induces a mean northerly wind anomaly over the inner core of the TC, pushing it southward (Huang et al 2011).
Subsequently, terrain-induced weakening on the western side creates a southerly anomaly, pushing the storm back north. These highly irregular tracks can be devastating for the island, keeping the typhoon nearly stationary over warm waters just off the coast, extending the heavy rains and strong winds by 6 hours or more.

In order to learn more about irregular and otherwise exceptional TCs, we will look at three extreme TC categories. The first, Rain-type, will be composed of those storms that produce the most rainfall across the island. The second, Curved-type, will be those TCs with the greatest near-island direction change. The third, Yilan-type, will be those storms with an absolute rainfall maximum over interior Yilan County, in the northeastern part of the island. The Curved- and Yilan-type definitions are illustrated in Fig. 53.

\textit{i.) Rain-type}

Rain-type TCs have tracks spread all over the map, with a slight preference for N- and C-type landfalling systems (Fig. 54). Because mean TC latitude varies so widely over the vicinity of Taiwan (Fig. 55), there is no dominant wind direction over the island during the near-island TC lifetime (Fig. 57). However, there is still a slight preference for easterlies over westerlies, resulting in slightly lower storm total rainfall and annual ER in the west than in the east (Figs. 54, 57). This may be due to a preference for westbound systems with easterly steering flow, or it might be due to the fact that no North-type tracks are included in this category, whereas multiple South-type tracks are included.
These systems occur mostly during typhoon season, with a few cases extending beyond on either side (Fig. 55). Given that this category is combination of landfalling track types and South-type tracks, it makes sense that there would be some spread, if not as much as evinced by the South-type tracks.

Rain-type TCs have large variations in frequency, but no consistent trend (Fig. 54). There was a peak in activity around 1990, and another between 2000 and 2010. Since these are only the top 27 rain-makers, frequency is not often larger than one storm per year. Despite the lack of a frequency trend, Rain-type ER is increasing rapidly everywhere except the southeastern coastal plain (Fig. 54), confirming that the most extreme TCs rain-wise are becoming even more extreme. Many of these trends are statistically significant. The largest of these trends occur where Rain-type ER is already large, namely over the southwestern mountain slopes and in the Yilan County area.

Rain-type TC speed decreased statistically significantly over the 1960 to 2015 period, although much of that trend seems to be due to several very slow-moving systems in the second half of the period (Fig. 56). Because speed is statistically significantly correlated with rainfall indices for these TCs (Table 9), we would expect an increase in storm total rainfall and annual ER as a result of the speed decrease. Given that there are no statistically significant trends in duration, intensity, or storm frequency, the speed decrease is likely responsible for the observed Rain-type annual ER increase. The most extreme rain-makers have become slower and wetter over the past several decades.
ii.) Curved-type

Curved-type TCs occur mostly around and to the south of Taiwan, some exiting to the north and some making landfall in China (Fig. 58). By definition, these tracks change direction often and rapidly, indicating weak steering flow. Combining weak steering flow with a wide range of storm mean latitudes (Fig. 59) results in weak and variable mean winds over the island during the storm lifetime (Fig. 60). As a result, storm total rainfall and annual ER are more evenly distributed over the island, with higher amounts over steeper mountain slopes (Fig. 58). In the central and southern regions, ER is largest on the western mountain slopes, since this is where the circulation of a storm off the east coast would wrap around to impinge on the topography. In the northeast, there is another large ER maximum associated with easterly or northeasterly flow.

Curved-type TCs have a slightly narrower seasonal distribution than Rain-type TCs, falling mostly within typhoon season (Fig. 59). The only track category with large spread beyond typhoon season – South-type – is unlikely to intersect with Curved-type TCs, since most of the South-type tracks are relatively straight. Therefore, this category is populated by landfalling track types and non-landfalling tracks that move irregularly off the coast without making landfall. From another perspective, prevailing 850-hPa winds are weakest during typhoon season (Chen and Chen 2003), making this the time of year with weakest steering flow. Therefore, erratic TC motion is more likely during typhoon season than during other seasons, when there are enhanced southwesterly or northeasterly winds.

This is the only track category that has a statistically significant increase in frequency, as shown by the red trend line (Fig. 58). This increase comes from a large jump
in activity since 2000. In order to try other definitions, we created a track category (not shown) composed of the storms with the longest track length within the domain. For the large domain, the frequency increase was not statistically significant. However, for a smaller domain around the island, similar to the domain used in the definition of curved-type TCs, there was a statistically significant increase. This reinforces the finding of an increase in near-island track deviations. There is also the mitigating factor of data collection to consider: older observations may have lower effective spatial resolution, creating an artificial trend in the small-scale fluctuations measured here.

Annual ER is increasing over essentially the entire island (Fig. 58). These increases are similar in magnitude to those seen from Rain-type TCs. However, this category is slightly smaller – n=32 vs n=35 for Rain-type TCs. This means that Curved-type TCs are the type responsible for the largest annual ER increase, relative to the number of storms. Again, the southeast coastal plain stands out as the sole area with negligible trends.

Out of intensity, speed, and duration, only intensity is statistically significantly correlated with rainfall indices for Curved-type TCs (Table 12). Moreover, there are no statistically significant trends in intensity, speed, or duration. However, the large increase in Curved-type ER can be explained by the increasing frequency of this track type (Fig. 58). There are no trends in storm-wise rainfall (not shown), meaning that the change is attributable to the number of storms.
iii.) Yilan-type

Yilan-type TCs are quite numerous, with 54 cases between 1960 and 2015 (Fig. 61). Many of them are recurving and make landfall in the north of the island or stay just off the coast, although there are some cases that remain south of the island. These include a number of weak systems – tropical depression and tropical storm strength – but also more category 4 and 5 TCs than other categories. This type has the largest spread in mean latitude of all the types that we have analyzed (Fig. 62), with values ranging from 18 N to 26 N. The common factor of these systems is the easterly to northeasterly winds that they almost invariably induce over the island (Fig. 66). This wind funnels into the Yilan Plain, a low-lying region cutting into the northeastern CMR (Fig. 67), creating a zone of enhanced convergence and orographic ascent. As a result, these storms produce very large storm total rainfall and annual ER over inland Yilan County, near and just south of the end of the valley (Fig. 65).

Yilan-type TCs have a large seasonal spread, but tend to occur later in the season than the other track types (Fig. 62). Activity peaks in September, tapering off gradually during the fall. The South-type tracks within this category may account for some of the fall occurrences. However, another factor during this time of year is the shift of the 1000-hPa and 850-hPa flow to the northeast (Chen and Chen 2003). Given that this shift occurs during September, it would make sense that the re-curving TCs represented in this category would disproportionately occur during this time.

This track category also has statistically significantly increasing annual ER (Fig. 61). However, the increases are not as large as for the other two extreme track categories,
especially given that these storms are more numerous. Most of the increases occur in the southwest and over inland Yilan County. The southwestern increase is unexpectedly large, nearly matching the magnitude of the Yilan increase. This suggests that, while these storms tend to produce a large ER maximum in Yilan County, more recent ones have been associated with more ER in the southwest as well. Plotting storm mean latitude against storm year shows that there was a shift to higher mean latitudes around 2000 (Fig. 63). In the first half of the period, there were more Yilan-type tracks to the south of the island (Fig. 64). In the second half, more of these tracks were C-type or N-type, and fewer stayed south of the island. Some of these landfalling tracks were also kinked before landfall, which would typically be associated with greater rainfall.

Duration is statistically significantly correlated with rainfall indices for Yilan-type TCs, with correlation coefficients in excess of 0.5 (Table 13). Like with the non-landfalling track types, this may be because of large variations in storm duration based on the geometry of the rectangular domain. Certain storms only pass through a short distance within the domain, while others travel the length of the domain (Fig. 61). However, there are no statistically significant trends in duration or speed for these systems. Instead, Yilan-type TC intensity increased statistically significantly over the 1960 – 2015 period (Fig. 65). Intensity does have a non-statistically significant but positive correlation with rainfall for Yilan-type TCs (not shown), meaning that increased intensity would correspond to increased rainfall. This increase, combined with the shift toward more landfalling systems, is likely responsible for some of the increase in Yilan-type annual ER.
Figure 26: TC (top) track density and (bottom) mean intensity from 1960 to 2015. Track density is defined as the number of TC center occurrences in each 1 x 1 degree grid box, and mean intensity is defined as the average maximum TC wind speed associated with these track points.
Figure 27: (Top) Track density change from 1960-1999 to 2000-2015. Track density is computed as in Fig. 29, except with 2 x 2 degree bins. (Bottom) Trends in annual 2 x 2 degree track density. Black circles indicate statistical significance at the 5% level using a Monte Carlo test.
Figure 28: The six location-based track types. N-, C-, and S-types must make landfall after passing north of 24 N, between 23 and 24 N, and south of 23 N at 122 E, respectively. North- (South-) type tracks pass north (south) of the island at 121.5 E (120.75 E), moving from east to west. Reverse South-type tracks pass south of the island at 120.75 E, moving from west to east.
Figure 29: (Upper left) N-type TC tracks, 1960-2015. Track lines are colored according to TC intensity. Filled contours are storm total rainfall, in mm. The number of TCs is indicated in the upper right. (Lower left) N-type TC frequency, with 5-year running mean. In the case of a statistically-significant frequency trend, the trend line is plotted in red. (Upper right) Annual mean N-type ER, that is, ER occurring when the center of a N-type TC resides within the domain 116-126 E, 18-29.5 N. (Lower right) Annual mean N-type ER trends. White circles indicate statistical significance at the 5% level, as determined by a Monte Carlo test.
Figure 30: TC latitude vs day of year. The vertical lines indicate, in order: the start of Mei-Yu season (May 15), the start of typhoon season (July 1), the start of fall (October 1), and the start of winter (December 1). All TCs that pass through the domain are shown in gray. N-type TCs are highlighted in blue. Average storm latitude is given in degrees.
Table 1: Rainfall, speed, and intensity parameters of TC track types. The current track type is highlighted. “Mean rain” is the island-mean, storm-total rainfall. “Max rain” is the maximum storm-total rainfall. “Speed”, “Intensity”, and “Duration” refer to the average speed and intensity of the TC while in the domain, and the time spent in that domain, respectively. Rainfall data are kept at 1 km resolution for these calculations.

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<th>Duration (hrs)</th>
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### N-type

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*Table 2: Statistically-significant correlations. Each row orders speed, duration, and intensity by correlation with each of the three TC rainfall parameters.*

![Figure 32: Mean 850 hPa wind speed and direction for TCs in each storm type. Mean wind is calculated over the domain 21-26 N, 119-123 E, and over the duration of the TC, i.e., the time that the TC center is within 18-29.5 N, 116-126 E. Marker size scales with wind magnitude, and color changes with angle. Note that the markers indicate the direction of the wind vector, so that 90 degrees is a southerly wind.](image)
Figure 33: (Upper left) C-type TC tracks, 1960-2015. Track lines are colored according to TC intensity. Filled contours are storm total rainfall, in mm. The number of TCs is indicated in the upper right. (Lower left) C-type TC frequency, with 5-year running mean. In the case of a statistically-significant frequency trend, the trend line is plotted in red. (Upper right) Annual mean C-type ER, that is, ER occurring when the center of a C-type TC resides within the domain 116-126 E, 18-29.5 N. (Lower right) Annual mean C-type ER trends. White circles indicate statistical significance at the 5% level, as determined by a Monte Carlo test.
Figure 34: TC latitude vs day of year. The vertical lines indicate, in order: the start of Mei-Yu season (May 15), the start of typhoon season (July 1), the start of fall (October 1), and the start of winter (December 1). All typhoons that pass through the domain are shown in gray. C-type typhoons are highlighted in green. Average storm latitude is given in degrees.
Table 3: Statistically-significant correlations. Each row orders speed, duration, and intensity by correlation with each of the three TC rainfall parameters.

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Figure 35: Trends in TC characteristics. Mean rain, max rain, 95% rain, duration, intensity, and speed are assessed for statistically-significant trends. Those that are significant at the 5% level, as determined by a Monte Carlo test, are displayed with trend line.

1979-2015 mean 850 hPa wind

Figure 36: Mean 850 hPa wind speed and direction for TCs in each storm type. Mean wind is calculated over the domain 21-26 N, 119-123 E, and over the duration of the TC, i.e., the time that the TC center is within 18-29.5 N, 116-126 E. Marker size scales with wind magnitude, and color changes with angle. Note that the markers indicate the direction of the wind vector, so that 90 degrees is a southerly wind.
Figure 37: (Upper left) S-type TC tracks, 1960-2015. Track lines are colored according to TC intensity. Filled contours are storm total rainfall, in mm. The number of TCs is indicated in the upper right. (Lower left) S-type TC frequency, with 5-year running mean. In the case of a statistically-significant frequency trend, the trend line is plotted in red. (Upper right) Annual mean S-type ER, that is, ER occurring when the center of an S-type TC resides within the domain 116-126 E, 18-29.5 N. (Lower right) Annual mean S-type ER trends. White circles indicate statistical significance at the 5% level, as determined by a Monte Carlo test.
Figure 38: TC latitude vs day of year. The vertical lines indicate, in order: the start of Mei-Yu season (May 15), the start of typhoon season (July 1), the start of fall (October 1), and the start of winter (December 1). All typhoons that pass through the domain are shown in gray. S-type typhoons are highlighted in orange. Average storm latitude is given in degrees.
Table 4: Statistically-significant correlations. Each row orders speed, duration, and intensity by correlation with each of the three TC rainfall parameters.

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Figure 39: Trends in TC characteristics. Mean rain, max rain, 95% rain, duration, intensity, and speed are assessed for statistically-significant trends. Those that are significant at the 5% level, as determined by a Monte Carlo test, are displayed with trend line.

Figure 40: Mean 850 hPa wind speed and direction for TCs in each storm type. Mean wind is calculated over the domain 21-26 N, 119-123 E, and over the duration of the TC, i.e., the time that the TC center is within 18-29.5 N, 116-126 E. Marker size scales with wind magnitude, and color changes with angle. Note that the markers indicate the direction of the wind vector, so that 90 degrees is a southerly wind.
Figure 41: 5-year histogram of (top) East-coast landfalling TCs and (bottom) all near-Taiwan TCs. East-coast landfalling TCs are defined as all N-, C-, and S-type TCs. Near-Taiwan TCs are those tracking within the domain 18-29.5 N, 116-126 E.
Figure 42: (Upper left) North-type TC tracks, 1960-2015. Track lines are colored according to TC intensity. Filled contours are storm total rainfall, in mm. The number of TCs is indicated in the upper right. (Lower left) North-type TC frequency, with 5-year running mean. In the case of a statistically-significant frequency trend, the trend line is plotted in red. (Upper right) Annual mean North-type ER, that is, ER occurring when the center of a North-type TC resides within the domain 116°-126° E, 18°-29.5° N. (Lower right) Annual mean North-type ER trends. White circles indicate statistical significance at the 5% level, as determined by a Monte Carlo test.
North-type

Latitude vs day of year

Figure 43: TC latitude vs day of year. The vertical lines indicate, in order: the start of Mei-Yu season (May 15), the start of typhoon season (July 1), the start of fall (October 1), and the start of winter (December 1). All typhoons that pass through the domain are shown in gray. North-type typhoons are highlighted in cyan. Average storm latitude is given in degrees.

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Table 5: Statistically-significant correlations. Each row orders speed, duration, and intensity by correlation with each of the three TC rainfall parameters.
**North-type**

**Storm dates**

_**Figure 45:** Mean 850 hPa wind speed and direction for TCs in each storm type. Mean wind is calculated over the domain 21-26 N, 119-123 E, and over the duration of the TC, i.e., the time that the TC center is within 18-29.5 N, 116-126 E. Marker size scales with wind magnitude, and color changes with angle. Note that the markers indicate the direction of the wind vector, so that 90 degrees is a southerly wind._

*Figure 44: TC day of year throughout the 1960 – 2015 period.*
Figure 46: (Upper left) South-type TC tracks, 1960-2015. Track lines are colored according to TC intensity. Filled contours are storm total rainfall, in mm. The number of TCs is indicated in the upper right. (Lower left) South-type TC frequency, with 5-year running mean. In the case of a statistically-significant frequency trend, the trend line is plotted in red. (Upper right) Annual mean South-type ER, that is, ER occurring when the center of a South-type TC resides within the domain 116-126 E, 18-29.5 N. (Lower right) Annual mean South-type ER trends. White circles indicate statistical significance at the 5% level, as determined by a Monte Carlo test.
Figure 47: TC latitude vs day of year. The vertical lines indicate, in order: the start of Mei-Yu season (May 15), the start of typhoon season (July 1), the start of fall (October 1), and the start of winter (December 1). All typhoons that pass through the domain are shown in gray. South-type typhoons are highlighted in red. Average storm latitude is given in degrees.
South-type

<table>
<thead>
<tr>
<th></th>
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<th>Second</th>
<th>Third</th>
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</thead>
<tbody>
<tr>
<td><strong>Mean rain</strong></td>
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<td>Intensity (0.27)</td>
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<tr>
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<td>Speed (-0.22)</td>
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<td><strong>Max rain</strong></td>
<td>Speed (-0.29)</td>
<td>Intensity (0.28)</td>
<td>Duration (0.27)</td>
</tr>
</tbody>
</table>

*Table 6: Statistically-significant correlations. Each row orders speed, duration, and intensity by correlation with each of the three TC rainfall parameters.*

![Typhoon mean intensity](image)

**Figure 48:** Trends in TC characteristics. Mean rain, max rain, 95% rain, duration, intensity, and speed are assessed for statistically-significant trends. Those that are significant at the 5% level, as determined by a Monte Carlo test, are displayed with trend line.

![1979-2015 mean 850 hPa wind](image)

**Figure 49:** Mean 850 hPa wind speed and direction for TCs in each storm type. Mean wind is calculated over the domain 21-26 N, 119-123 E, and over the duration of the TC, i.e., the time that the TC center is within 18-29.5 N, 116-126 E. Marker size scales with wind magnitude, and color changes with angle. Note that the markers indicate the direction of the wind vector, so that 90 degrees is a southerly wind.
Figure 50: (Upper left) Reverse South-type TC tracks, 1960-2015. Track lines are colored according to TC intensity. Filled contours are storm total rainfall, in mm. The number of TCs is indicated in the upper right. (Lower left) Reverse South-type TC frequency, with 5-year running mean. In the case of a statistically-significant frequency trend, the trend line is plotted in red. (Upper right) Annual mean Reverse South-type ER, that is, ER occurring when the center of a Reverse South-type TC resides within the domain 116-126 E, 18-29.5 N. (Lower right) Annual mean Reverse South-type ER trends. White circles indicate statistical significance at the 5% level, as determined by a Monte Carlo test.
Figure 51: TC latitude vs day of year. The vertical lines indicate, in order: the start of Mei-Yu season (May 15), the start of typhoon season (July 1), the start of fall (October 1), and the start of winter (December 1). All typhoons that pass through the domain are shown in gray. Reverse South-type typhoons are highlighted in dark red. Average storm latitude is given in degrees.
Reverse South-type

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</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean rain</strong></td>
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<td>Duration (0.21)</td>
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</tr>
<tr>
<td><strong>95% rain</strong></td>
<td>Intensity (0.47)</td>
<td>Duration (0.22)</td>
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<tr>
<td><strong>Max rain</strong></td>
<td>Duration (0.50)</td>
<td>Duration (0.37)</td>
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*Table 7: Statistically-significant correlations. Each row orders speed, duration, and intensity by correlation with each of the three TC rainfall parameters.*

*Figure 52: Mean 850 hPa wind speed and direction for TCs in each storm type. Mean wind is calculated over the domain 21-26 N, 119-123 E, and over the duration of the TC, i.e., the time that the TC center is within 18-29.5 N, 116-126 E. Marker size scales with wind magnitude, and color changes with angle. Note that the markers indicate the direction of the wind vector, so that 90 degrees is a southerly wind.*
Figure 5.3: Definitions of Curved and Yilan track types. The angles of track direction change within the box (118 E – 124 E, 20 N – 27 N) are summed, and the tracks with the largest values are the Curved-type tracks. TCs that have an absolute rainfall maximum over inland Yilan County, approximated by the small box in northeastern Taiwan, populate the Yilan track type.
Rain-type

Figure 54: (Upper left) Rain-type TC tracks, 1960-2015. Track lines are colored according to TC intensity. Filled contours are storm total rainfall, in mm. The number of TCs is indicated in the upper right. (Lower left) Rain-type TC frequency, with 5-year running mean. In the case of a statistically-significant frequency trend, the trend line is plotted in red. (Upper right) Annual mean Rain-type ER, that is, ER occurring when the center of a Rain-type TC resides within the domain 116-126 E, 18-29.5 N. (Lower right) Annual mean Rain-type ER trends. White circles indicate statistical significance at the 5% level, as determined by a Monte Carlo test.
Rain-type

Figure 55: TC latitude vs day of year. The vertical lines indicate, in order: the start of Mei-Yu season (May 15), the start of typhoon season (July 1), the start of fall (October 1), and the start of winter (December 1). All typhoons that pass through the domain are shown in gray. Rain-type typhoons are highlighted in black. Average storm latitude is given in degrees.
Rain-type

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<th>Speed (kts)</th>
<th>Duration (hrs)</th>
<th>Intensity (kts)</th>
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<td>Yilan-type</td>
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<td>977.89</td>
<td>7.35</td>
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<td>59.64</td>
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Table 8: Rainfall, speed, and intensity parameters of TC track types. The current track type is highlighted. “Mean rain” is the island-mean, storm-total rainfall. “Max rain” is the maximum storm-total rainfall. “Speed”, “Intensity”, and “Duration” refer to the average speed and intensity of the TC while in the domain, and the time spent in that domain, respectively. Rainfall data are kept at 1 km resolution for these calculations.

<table>
<thead>
<tr>
<th>Mean rain</th>
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<th>Third</th>
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</thead>
<tbody>
<tr>
<td>95% rain</td>
<td>Speed (-0.37)</td>
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<tr>
<td>Max rain</td>
<td>Speed (-0.31)</td>
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Table 9: Statistically-significant correlations. Each row orders speed, duration, and intensity by correlation with each of the three TC rainfall parameters.

Figure 56: Trends in TC characteristics. Mean rain, max rain, 95% rain, duration, intensity, and speed are assessed for statistically-significant trends. Those that are significant at the 5% level, as determined by a Monte Carlo test, are displayed with trend line.

Figure 57: Mean 850 hPa wind speed and direction for TCs in each storm type. Mean wind is calculated over the domain 21-26 N, 119-123 E, and over the duration of the TC, i.e., the time that the TC center is within 18-29.5 N, 116-126 E. Marker size scales with wind magnitude, and color changes with angle. Note that the markers indicate the direction of the wind vector, so that 90 degrees is a southerly wind.
Figure 58: (Upper left) Curved-type TC tracks, 1960-2015. Track lines are colored according to TC intensity. Filled contours are storm total rainfall, in mm. The number of TCs is indicated in the upper right. (Lower left) Curved-type TC frequency, with 5-year running mean. In the case of a statistically-significant frequency trend, the trend line is plotted in red. (Upper right) Annual mean Curved-type ER, that is, ER occurring when the center of a Curved-type TC resides within the domain 116-126 E, 18-29.5 N. (Lower right) Annual mean Curved-type ER trends. White circles indicate statistical significance at the 5% level, as determined by a Monte Carlo test.
Figure 59: TC latitude vs day of year. The vertical lines indicate, in order: the start of Mei-Yu season (May 15), the start of typhoon season (July 1), the start of fall (October 1), and the start of winter (December 1). All typhoons that pass through the domain are shown in gray. Curved-type typhoons are highlighted in black. Average storm latitude is given in degrees.
Curved-type

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Table 12: Statistically-significant correlations. Each row orders speed, duration, and intensity by correlation with each of the three TC rainfall parameters.

Figure 60: Mean 850 hPa wind speed and direction for TCs in each storm type. Mean wind is calculated over the domain 21-26 N, 119-123 E, and over the duration of the TC, i.e., the time that the TC center is within 18-29.5 N, 116-126 E. Marker size scales with wind magnitude, and color changes with angle. Note that the markers indicate the direction of the wind vector, so that 90 degrees is a southerly wind.
Yilan-type

Figure 61: (Upper left) Yilan-type TC tracks, 1960-2015. Track lines are colored according to TC intensity. Filled contours are storm total rainfall, in mm. The number of TCs is indicated in the upper right. (Lower left) Yilan-type TC frequency, with 5-year running mean. In the case of a statistically-significant frequency trend, the trend line is plotted in red. (Upper right) Annual mean Yilan-type ER, that is, ER occurring when the center of a Yilan-type TC resides within the domain 116-126 E, 18-29.5 N. (Lower right) Annual mean Yilan-type ER trends. White circles indicate statistical significance at the 5% level, as determined by a Monte Carlo test.
Figure 62: TC latitude vs day of year. The vertical lines indicate, in order: the start of Mei-Yu season (May 15), the start of typhoon season (July 1), the start of fall (October 1), and the start of winter (December 1). All typhoons that pass through the domain are shown in gray. Yilan-type typhoons are highlighted in black. Average storm latitude is given in degrees.
Yilan-type

Mean latitude by year

Figure 63: TC latitude by year. Individual TCs are plotted by their year and mean latitude within the domain 18 N – 29.5 N, 116 E – 126 E.
**Yilan-type**

**Figure 64:** Yilan-type TC tracks during the first and second half of the period. Colors indicate intensity, while storm-total rainfall is contoured on the island.

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*Table 13: Statistically-significant correlations. Each row orders speed, duration, and intensity by correlation with each of the three TC rainfall parameters.*
Yilan-type

**Figure 65**: Trends in TC characteristics. Mean rain, max rain, 95% rain, duration, intensity, and speed are assessed for statistically-significant trends. Those that are significant at the 5% level, as determined by a Monte Carlo test, are displayed with trend line.

**Figure 66**: Mean 850 hPa wind speed and direction for TCs in each storm type. Mean wind is calculated over the domain 21-26 N, 119-123 E, and over the duration of the TC, i.e., the time that the TC center is within 18-29.5 N, 116-126 E. Marker size scales with wind magnitude, and color changes with angle. Note that the markers indicate the direction of the wind vector, so that 90 degrees is a southerly wind.

**Figure 67** (left): The topography of Taiwan, overlaid with lines that parallel the sides of the Yilan Plain (or Lanyang Plain).
6. Conclusions

The purpose of this study is to assess the changes in extreme rainfall (ER) in Taiwan, with a focus on TC influences. We began with an overview of ER totals and trends in different seasons, before comparing TC-associated ER with non-TC ER. Based on the results, we partitioned TC-associated ER into contributions from various track types, some based on location relative to the island and others based on notable TC properties.

Taiwan's ER distribution is determined largely by the direction of the prevailing wind. During the cold season, northeasterly flow brings larger ER in northern regions of the island, while the warm season sees large ER in southern and western regions of the island. The second factor controlling ER is moisture and MSE availability. During the warm season, moist, unstable, high-MSE air leads to copious rainfall, making warm-season ER many times greater than cold-season ER. The difference is so large that seasonal ER thresholds were required for there to be any cold-season ER at all.

Through all the different seasonal ER distributions, there is a consistent increasing trend in ER, with the possible exception of fall. Typhoon season has by far the largest increases. Comparing TC-associated ER and non-TC-associated ER, we find that the former accounts for almost all of Taiwan's ER, using the annual extreme threshold. Furthermore, TC-associated ER accounts for most of the annual ER increase. Therefore, TCs are the driving force of the increase in extreme rainfall.

The six location-based track types – N, C, S, North, South, and Reverse South – have different ER distributions that are based on their location relative to the island. Storms with a more northerly latitude near the island tend to produce more ER in the north, over north-
and west-facing mountain slopes. Storms with a more southerly latitude near the island tend to produce more ER in the east, due to orographic ascent over east-facing mountain slopes. C-type TCs, passing over the center of the island, have a more even, bimodal ER distribution. N-type and C-type TCs produce the most ER, followed by S-type TCs and then the non-landfalling types.

N- and C-type TCs have the largest ER increases, followed by S-type TCs. This is due to a decrease in N-type and S-type TC speed and an increase in C-type TC frequency. South-type ER has actually decreased, possibly because of a decrease in South-type TC intensity. North-type ER has had smaller, less statistically significant decreases, while Reverse South-type ER has increased despite the recent drop-off in this track type. Though there has been an increase in east-coast landfalling TCs since 2000, as observed by Chang et al (2013), there is no statistically significant trend in frequency over the study period 1960 - 2015. The same goes for TC activity within the entire domain 18 – 29.5 N, 116 – 126 E. While activity was increased in 1990 – 2010 versus 1970 – 1990, there is no statistically significant trend.

We also defined three extreme track types in order to see the changes in particularly impactful or unusual TCs. Rain-type TCs – or those that produce the largest island-mean rainfall – have large, statistically significant increasing ER trends over the study period. However, as a percentage of Rain-type ER, these trends are smaller than, for example, C-type ER trends as a percentage of C-type ER. Curved-type TCs – or those with the largest track irregularities near Taiwan – have increased drastically in frequency since 2000. This increase is statistically significant, and drives a large, statistically significant increase in Curved-type ER. This finding was strengthened by looking at a similar category made up of
TCs with the longest track length near Taiwan, which also had statistically significant frequency increases. Apparently, meandering or kinked tracks are becoming more common.

Finally, many of the TCs we analyzed had a rainfall maximum over inland Yilan County, near the end of the Yilan Plain. These systems were combined into the Yilan-type tracks, which produce very large ER in that small region and little elsewhere. The unifying feature of these TCs is that they induce east-northeasterly flow over the island. This wind funnels into the Yilan Plain, a low-lying region that cuts into the northeastern CMR and is oriented perfectly to capture east-northeasterly flow. As the wind funnels into the plain, it converges and ascends, creating a region of enhanced precipitation. Due to a northward shift in mean latitude since 2000, these TCs also have a (smaller) increasing trend in annual ER.

Future work will hinge on creating large-scale and storm-centered composites of the track types in order capture TC characteristics and trends in more detail. Without composites, it is difficult to know which and how many factors are contributing to the changes in ER from a given track type. We may add more track types, or broader track types, such as re-curving TCs. The inter-decadal variability we have seen in various track types might also be linked to changes in indices such as ENSO or PDO. Another topic for future research is ER in other seasons, which has been analyzed only briefly here. Sorting cold-season or Mei-Yu ER by weather type might yield more insight into the non-TC-associated ER increase, which is considerable as a percentage of non-TC-associated ER.

While this study quantifies variability in track types, it does not explain it. By linking the observed changes in track types to changes in large-scale flow regimes, we could make projections about future TC activity based on the behavior of these regimes in climate
models. Because of the localized, topography-dependent nature of TC wind and rainfall in Taiwan, simulating changes in track types would provide valuable information about changing TC impacts.
References


Chen, J M, Li T and Shih C F 2010 Tropical cyclone- and monsoon-induced rainfall variability in Taiwan J. Clim. 23, 4107–20


