TI 2013-006/III
Tinbergen Institute Discussion Paper

Statistical Modelling of Extreme Rainfall in Taiwan

Lan-Fen Chu[1]
Michael McAleer[2]
Ching-Chung Chang[3]

[1] *National Science and Technology Center for Disaster Reduction (NCDR), Taiwan;*
[2] *Erasmus School of Economics, Erasmus University Rotterdam, Econometric and Tinbergen Institutes, Kyoto University, Japan, and Complutense University of Madrid ;*
[3] *Academia Sinica, Taiwan.*

Tinbergen Institute is the graduate school and research institute in economics of Erasmus University Rotterdam, the University of Amsterdam and VU University Amsterdam.

More TI discussion papers can be downloaded at http://www.tinbergen.nl

Tinbergen Institute has two locations:

Tinbergen Institute Amsterdam
Gustav Mahlerplein 117
1082 MS Amsterdam
The Netherlands
Tel.: +31(0)20 525 1600

Tinbergen Institute Rotterdam
Burg. Oudlaan 50
3062 PA Rotterdam
The Netherlands
Tel.: +31(0)10 408 8900
Fax: +31(0)10 408 9031

Duisenberg school of finance is a collaboration of the Dutch financial sector and universities, with the ambition to support innovative research and offer top quality academic education in core areas of finance.

DSF research papers can be downloaded at: http://www.dsf.nl/

Duisenberg school of finance
Gustav Mahlerplein 117
1082 MS Amsterdam
The Netherlands
Tel.: +31(0)20 525 8579

Statistical Modelling of Extreme Rainfall in Taiwan*

Lan-Fen Chu

National Science and Technology Center for Disaster Reduction
Taiwan

Michael McAleer

Econometric Institute
Erasmus School of Economics
Erasmus University Rotterdam
and
Tinbergen Institute
The Netherlands
and
Institute of Economic Research
Kyoto University
Japan
and
Department of Quantitative Economics
Complutense University of Madrid
Spain

Ching-Chung Chang

Institute of Economics
Academia Sinica
Taiwan

December 2012

***** For financial support, the first and third authors are grateful to the Taiwan Climate Change Projection and Information Platform Project (NSC 100-2621-M-492-001), and the second author wishes to acknowledge the Australian research Council, National science Council, Taiwan, and the Japan Society for the promotion of Science.

Abstract

In this paper, the annual maximum daily rainfall data from 1961 to 2010 are modelled for 18 stations in Taiwan. We fit the rainfall data with stationary and non-stationary generalized extreme value distributions (GEV), and estimate their future behaviour based on the best fitting model. The non-stationary model means that the parameter of location of the GEV distribution is formulated as linear and quadratic functions of time to detect temporal trends in the maximum rainfall. Future behavior refers to the return level and the return period of the extreme rainfall. The 10, 20, 50 and 100-years return levels and their 95% confidence intervals of the return levels stationary models are provided. The return period is calculated based on the record-high (ranked 1st) extreme rainfall brought by the top 10 typhoons for each station in Taiwan. The estimates show that non-stationary model with increasing trend is suitable for the Kaohsiung, Hengchun, Taitung and Dawu stations. The Kaohsing and Hengchun stations have greater trends than the other two stations, showing that the positive trend extreme rainfall in the southern region is greater than in the eastern region of Taiwan. In addition, the Keelung, Anbu, Zhuzihu, Tamsui, Yilan, Taipei, Hsinchu, Taichung, Alishan, Yushan and Tainan stations are fitted well with the Gumbel distribution, while the Sun Moon Lake, Hualien and Chenggong stations are fitted well with the GEV distribution.

Keywords: Extreme theory, Extreme rainfall, Return level, Typhoon.

1. Introduction

Extreme rainfall events are a primary cause of flooding hazards worldwide. Not surprisingly, considerable attention has been paid to the modelling of extreme rainfall to help prevent flooding hazards, and for analysing water-related structures, agriculture, and monitoring climate changes.

Taiwan is a small island East-Asia. An average of 3.5 typhoons strike Taiwan each year, often in summer and autumn, and cause significant damage, especially in highly concentrated population and property areas. Taking Typhoon Morakot as an example, it struck Taiwan from 7-9 August 2009 with abundant rainfall, reaching 2,777mm, and surpassing the historical record of Typhoon Herb, which brought rainfall of 1,736mm (Ge et al., 2010; Hong et al., 2010). The extremely heavy rainfall triggered severe flooding (the worst during the past 50 years) and enormous mudslides throughout southern Taiwan, leading to around 700 deaths and roughly NT$110 billion in property damage (Chu et al., 2011).

IPCC Fourth Assessment Report (2007) has indicated that extreme events may become more frequent and severe because of climate change. Taiwan’s 2011 Scientific Report (Hsu et al., 2001) indicated that in the last 40 years, intense rainfall typhoons (the top 10% of typhoons according to their rainfall) often caused severe disasters to Taiwan (e.g., Typhoons Morakot, Herb, and Nari). Chia and Lee (2008) indicated more typhoons affected Taiwan after 1990 than between 1961-1989, and increased sharply around 2000 (Tu et al., 2009). Such an indication of increasing frequency and intensity of rainfall means that Taiwan will face a higher probability of huge damage from extreme rainfall in the future. Thus, understanding the patterns of extreme rainfall and their future behaviour is of increasingly importance in Taiwan.

Several researchers have studied useful applications of generalized extreme theory (GEV) for rainfall data from different parts of the world, including Nguyen et al. (1998, 2002) for Canada; Koutsoyiannis and Baloutsos (2000) for Greece; Ferro (1993) and Parida (1999) for India; Cannarozzo et al. (1995), Aronica et al. (2002) and Crisci et al. (2002) for Italy; Elnaqa and Abuzeid (1993) for Jordan; Zalina et al. (2002) for Malaysia; Miroslava (1991, 1992) for Belgrade; Withers and Nadarajah (2000) for New Zealand; Feng and Hu (2007) for China; Miroslava (1991, 1992) for Yugoslavia; Nadarajah and Choi (2005), and Park et al. (2010), for Korea; Nadarajah

(2005) for West Central Florida; and Abbas et al. (2010) for Pakistan. These findings highlight the urgency and to model extreme rainfall using the generalized extreme value distribution.

In Taiwan, some researchers have analyzed extreme climate by using the general circulation model (GCM) scenarios provided in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Downscaling both dynamic and statistical efforts provides information on a finer scale relative to the data produced by GCMs, such as GCM project climate parameters at a resolution of 250 km^2; downscaled models provide projections at 50 km^2. However, this method is usually costly and requires considerable computer resources, and is difficult for a researcher with a financial deficit to simulate climate variation. Although downscaling can show relationships between small- and large-scale variables to overcome the drawbacks of the GCM method, it still cannot reflect the diverse topography in Taiwan, which has a full range of climate zones.

This paper contributes to scientific research in climate change by using statistical analysis, as well as analysing extreme rainfall by using the generalized extreme value distribution.

The purpose of this paper is to use statistical methods to find the most appropriate distribution of annual maximum daily rainfall data, and estimate their future behaviour based on the best fitting model. We fit the rainfall data with stationary and non-stationary generalized extreme value distributions (GEV), and estimate their future behaviour based on the best fitting model. The non-stationary model means that the parameter of location of the GEV distribution is formulated as a linear and quadratic function of time to detect temporal trends in the maximum rainfall. We also compute the 10, 20, 50 and 100-year return levels of extreme rainfall and their 95% confidence intervals of the return levels of the stationary models. The return period is calculated based on the record-high (ranked 1st) extreme rainfall brought by the top 10 typhoons for each station in Taiwan.

The remainder of this paper is organized as follows. Section 2 presents the statistical description of the data. Section 3 introduces the statistical methodology. Section 4 discusses the estimation results, and the return period record-high extreme rainfall typhoons in Taiwan. Section 5 provides some concluding comments.

2. Statistical Description of the Data

Annual daily maximum daily rainfall (mm) is defined as extreme rainfall, which is a well-known definition for block-maxima method (Gumbel, 1958). The original data consisted of daily rainfall records from 1960 to 2010, which were provided by the Central Weather Bureau, Taiwan. Figure 1 profiles the geographical locations of the 18 stations in Taiwan. In this paper, Taiwan is divided into four regions, namely the northern, central, southern and eastern regions. The northern region of Taiwan includes the Keelung, Anbu, Zuhzihu, Tamsui, Taipei, Hsinchu and Yilan stations; the central region includes the Taichung, Sun Moon Lake, Alishan and Yushan stations; the southern region includes the Tainan, Kaohsiung, and Hengchun stations; and the eastern region includes the Hualien, Chenggong, Taitung and Dawu stations.

Table 1 gives the location, latitude, longitude, station numbers, and the summary statistics of the 18 stations. The table shows that the biggest extreme rainfall appeared in the Alishan and Zhuzihhu stations, and the highest variation of extreme rainfall appeared in the Yushan station. Figure 2 shows the box-plot of the 18 stations for the underlying data. The higher values and several outliers indicate that the data tend to have a long-tailed behaviour for rainfall data, thereby suggesting that the normal distribution does not conform well to the observations. Therefore, our interest lies in the statistical modelling of the extreme values in rainfall in order to capture the tail behaviour in the data.

3. Methodology

Generalized extreme values (GEV) are based on the Gumbel, Fréchet and Weibull distributions. It was developed by Jenkinson (1955), who combined the above three distributions (see Hosking et al., 1985; Galambos, 1987). In this paper, we fit stationary and non-stationary models for GEV for the 18 stations in Taiwan. Stationary GEV means that the location parameter is constant and independent of time, while non-stationary GEV means that the location parameter varies over time in terms of the linear and quadratic functional forms.

The cumulative distribution function (cdf) of GEV is given as:

$$\mathrm{GEV}_0 : F(x) = \exp\{-[1 + \xi((x-u)/\sigma)]^\wedge(-1/\xi)\},$$

$$1+\frac{\xi(x-\mu)}{\sigma}>0 \tag{1}$$

where $\mu, \sigma > 0$, μ is a location parameter, σ is a scale parameter, and ξ is a shape parameter governing the tail behaviour of the distribution. The Gumbel distribution is defined for $\xi = 0$ in (1) as:

$$\mathrm{Gum}_0 \therefore F(x) = \exp\left\{-exp\left[-(\frac{x-u}{\sigma})\right]\right\}, -\infty < x < \infty \tag{2}$$

The sub-families defined by $\xi > 0$ and $\xi < 0$ correspond to the Fréchet family and the Weibull family, respectively. The maximum likelihood method was used to fit equations (1) and (2) to the data, and maximization was performed using a quasi-Newton iterative algorithm. We follow the same statistical methods as Nadarajah (2005), Feng et al. (2007), and Park et al. (2007). Consequently, some description throughout this paper is similar to that given in the cited papers.

Assuming independence of the data, the likelihood function is the product of the assumed densities for the observations $x_1, x_2 \dots, x_n$. For the GEV_0 model, we have:

$$\mathrm{L}(\mathrm{u}, \sigma, \xi) = \frac{1}{\sigma^{\mathrm{n}}}\prod_{\mathrm{i}=1}^{\mathrm{n}}(1+\xi(\frac{x_{\mathrm{i}}-\mu}{\sigma}))^{-(\frac{1}{\xi}+1)} \times exp\left\{-\sum_{\mathrm{i}=1}^{\mathrm{n}}(1+\xi\left(\frac{x_{\mathrm{i}}-\mu}{\sigma}\right))^{-1/\xi}\right\} \tag{3}$$

provided that

$$1+\xi\frac{x_i-\mu}{\sigma}>0 \quad \text{for} \quad i=1,\dots,n. \tag{4}$$

The estimates of μ, σ and ξ, denoted as $\hat{\mu}$, $\hat{\sigma}$ and $\hat{\xi}$, respectively, are taken to be those values that maximize the likelihood function, *L*. The basic model fitted was GEV (to be referred to as GEV_0), with constant μ, σ and ξ. Nadarajah and Choi (2007) indicated that sometimes the Gumbel distribution leads to as good a fit as GEV, so we also fit these data with constant μ and σ (to be referred to as Gum_0). The Gum_0 model is a sub-model of GEV_0, so that a standard way of determining the best fitting model is the likelihood ratio (LR) test.

If *Li* is the maximum likelihood value for model *i*, and *Lj* is the maximum likelihood value for model *j,* then under the null hypothesis, the LR test statistic given by λ = -2 log(*Lj* / *Li*) is asymptotically distributed as a chi-square variable with *v* degrees for freedom, where *v* is the difference in the number of parameters between models *i* and *j*. Thus, at the 5% significance level, model *j* is statistically preferred to model *i* if $\lambda = -2 \log(Lj / Li) > x^2(0.95)$. In practice, because annual maxima lack complete independence, this is likely to be interpreted conservatively (Nadarajah, 2005).

In order to investigate the existence of a trend in extreme rainfall over time, we apply the following variations of models GEV_0 and Gum_0:

$$\mathrm{GEV}_1\text{:}\ \mu = a + b \times (\text{Year} - t_0 + 1,\ \sigma = \text{constant},\ \xi = \text{constant}, \tag{5}$$

a four-parameter model with μ allowed to vary linearly over time, and "constant" means that the parameter is not time dependent and is subject to estimation;

$$\mathrm{Gum}_1\text{:}\ \mu = a + b \times (\text{Year} - t_0 + 1),\ \sigma = \text{constant},\ \xi = 0, \tag{6}$$

a three-parameter model, where μ varies over time;

$$\begin{aligned}\mathrm{GEV}_2\text{:}\ \mu &= a + b \times (\text{Year} - t_0 + 1) \times c(\text{Year} - t_0 + 1)^2\\ \sigma &= \text{constant},\ \xi = \text{constant},\end{aligned} \tag{7}$$

a five-parameter model, where μ varies over time in terms of quadratic form; and

$$\begin{aligned}\mathrm{Gum}_2\text{:}\ \mu &= a + b \times (\text{Year} - t_0 + 1) \times c(\text{Year} - t_0 + 1)^2,\\ \sigma &= \text{constant},\ \xi = 0,\end{aligned} \tag{8}$$

a four-parameter model, where μ varies quadraticially over time.

Thus, we use a non-stationary extreme value model to reflect the context of climate change. In all four models, t_0 denotes the year the records started. A similar technique has been used by many researchers, including Katz et al. (2002), Nadarajah and Choi (2007), Feng et al. (2007), Park et al. (2010), and Sugahara et al. (2009).

When the best models for the data have been determined, the interest of this paper is to derive the return levels for rainfall. The T-year return level, say x_T, is the level exceeded on average only once every T years (Coles, 2001). If model GEV_0 is assumed, then by inverting $F(x_T) = 1 - 1/T$, we can obtain the following expression for the GEV distribution:

$$x_T = \mu - \frac{\sigma}{\xi}\{1 - [-\log(1 - \frac{1}{T})]\}^{-\xi} \tag{9}$$

If model Gum_0 is assumed, then the corresponding expression is given by:

$$x_T = \mu - \sigma \log\{-\log\left(1 - \frac{1}{T}\right)\} \tag{10}$$

By substituting the estimates ($\hat{\mu}$, $\hat{\sigma}$, $\hat{\xi}$) into x_T, we can obtain the maximum likelihood estimates of the return level.

4. Empirical Results

4.1 Estimates

The best fitting models are shown in Table 2, including the estimates and the corresponding standard errors (SE), which are computed by the delta method. As the estimator of $\hat{b}$ is the change in extreme rainfall from one year to the next, a positive sign for $\hat{b}$ suggests the non-stationary Gumbel distribution exhibits an increasing trend for the Kaohsiung, Hengchun, Taitung and Dawu stations. In other words, more than 22% of the stations have had a linear trend over the past 51 years.

As for the increasing degree of extreme rainfall, the Kaohsiung and Hengchun stations are greater than the Taitung and Dawu stations, suggesting that extreme rainfall in the southern part of Taiwan is greater than in the eastern part of Taiwan. In addition, the Sun Moon Lake, Hualien and Chenggong stations are suitable for GEV distribution, while the Keelung, Anbu, Zhuzihu, Tamsui, Yilan, Taipei, Hsinchu, Taichung, Alishan, and Yushan stations are fitted well using the Gumbel distribution. The empirical results suggest that the Gumbel distribution can profile the patterns of extreme rainfall better than the GEV distribution for 18 stations, the percentage of which accounts for a rather high 78% of all stations.

Table 3 summarizes the estimates of the return levels for T = 10, 20, 50 and 100 years for locations where a stationary model was selected. The estimates and the associated 95% confidence intervals of the return levels are also provided. In terms of 10-year return levels, there are six stations (Anbu, Zhuzihu, Sun Moon Lake, Alishan, Yushan, and Chenggong) that are greater than 350mm, surpassing the threshold of the extremely torrential rainfall, as defined by the CWB in Taiwan[1]. For 20-year return level, the Yilan and Hualien stations have rainfall that is greater than 350 mm. For the rainfall of the 50-year return level, the Keelung, Tamsui, Taipei, and Taichung stations are also grouped into torrential rainfall. For the rainfall of the 100-year return level, the extreme rainfall for all stations in this paper will exceed the threshold of 350mm.

The goodness of fit of these models is examined by the quantile (Q-Q plot) and density plots (P-P plot). Taking the Taichung station as an example, the diagnostic plots for Taichung Station (Gum_0) are shown in Figure 3, which were drawn by using Cole's R program (Coles, 2001). The P-P and Q-Q plots are consistent with the histograms of the data. Therefore, we can say that the Gum_0 model can provide an adequate profile of the extreme rainfall in the Taichung station.

4.2 Return periods for record-high extreme rainfall of typhoons in Taiwan

The estimated results from return level can help to answer questions regarding the rarity of extreme rainfall of some severe typhoons. As typhoons have different impacts on each station, let us take the Morakot Typhoon as an example. It struck Taiwan from 6-10 August, and brought the most extreme rainfall that has ever been recorded in history. One record-high 1,166 mm accumulated rainfall day occurred on 7 August was measured at Alishan station but, on the same day, the maximum accumulated rainfall from the Taichung and Tainan stations were only 2 mm and

[1] When the daily rainfall is greater than 50, 130, 200 and 350 mm, the rainfall will accord with the definitions of heavy rainfall, extremely heavy rainfall, torrential rainfall, and extremely torrential rainfall, respectively.

5mm, respectively. Therefore, in this section, we rank extreme rainfall from 1st to 10th according to record-high rainfall brought by typhoons for the top 10 events for each station, and estimate the return period of the highest.

Table 4 lists the rainfall for the top 10 typhoons for each station in Taiwan. It shows that the Lynn Typhoon (1987) brought record-high rainfall for the Keelung (301mm), Zhuzihu (1,136mm) , Danhui (314mm) and Hualien (246mm) stations; the Nari Typhoon (2001) brought record-high rainfall for the Taipei (425mm) and Hsinchu (397mm) stations; the Mindule Typhoon (2004) brought record-high rainfall for the Chengong (352mm) station; the Sinlaku Typhoon (2008) brought record-high rainfall for the Yilan (356mm) and Sun Moon Lake (472mm) stations; and the Morakot Typhoon (2009) brought record-high rainfall for the Anbu (272mm), Tainan (524mm), Taichung (347mm), Alishan (1,166mm) and Yushan (709mm) stations.

Therefore, the Lynn, Nari, Mindulle, Sinlaku, and Morakot Typhoons are regarded as extreme events for the corresponding stations to estimate their return period. The estimates show the return period of the Anbu, Hualien and Chenggong stations are 2, 2.5 and 8.3 years, respectively, given the same rainfall of 272 mm of the Morakot Typhoon, 246 mm of the Lynn typhoon, and 352 mm of the Mindulle Typhoon. The return period of the Sun Moon Lake, Keelung, Yilan, Tamsui, and Taichung stations are 14.1, 15, 17, 18, and 22 years, respectively, with 472 mm of the Sinlaku Typhoon, 301mm of the Lynn Typhoon, 356mm of the Sinlaku Typhoon, 314 mm of the Lynn Typhoon, and 347mm of the Morakot Typhoon, respectively. The return period of the Alishan, Hisinchu, Taipei, Tainan, Zhuzihu and Yushan stations are 80, 144, 168, 216, 358, and 702 years, respectively, with 1,166 mm of the Morakot Typhoon, 397mm of the Nari Typhoon , 425mm of the Nari Typhoon, 524 mm of the Morakot Typhoon, 1,136mm of the Lynn Typhoon, and 709mm of the Morakot Typhoon, respectively.

5. Conclusion

There were two purposes to this paper. First, we analyzed the pattern of annual daily maximum rainfall based on a statistical method of generalized extreme value theory for 18 stations throughout Taiwan. In addition, the corresponding 95% confidence intervals of the return levels of the best fitting models were provided. Second, we estimated the future behaviour of the best fitting models, such as the 10, 20, 50 and 100-year return levels, and the return periods for the record-high (ranked

1^{st}) extreme rainfall brought by the top 10 typhoons for each station in Taiwan. These estimates not only help us to determine the return levels of extreme rainfall, but also to understand how often such rare events might occur in the future, given limited data, and to provide a useful reference for policy-decision makers.

It is evident that 22% of stations are suitable for the non-stationary distribution, and 78% of stations are suitable for stationary models. As for the non-stationary models, the Kaohsiung, Hengchun, Taitung and Dawu stations are fitted well with an increasing trend and the Gumbel distribution, which indicated that the increasing trend of the Kaohsiung and Hengchun stations was greater than for the Taitung and Dawu stations, suggesting that extreme rainfall in the southern part of Taiwan was greater than in the eastern part of Taiwan. As for the stationary models, the Keelung, Anbu, Zhuzihu, Tamsui, Yilan, Taipei, Hsinchu, Taichung, Alishan, Yushan and Tainan stations were fitted well using the Gumbel distribution, while the Sun Moon Lake, Hualien and Chenggong stations were fitted well using the GEV distribution.

Based on the best fitting and stationary models, we have provided 10, 20, 50 and 100-year return levels of extreme rainfall. The estimates indicated that, given 10-year return level (for the years 2020), the return levels of daily extreme rainfall of the Anbu, Zhuzihu, Sun Moon Lake, Alishan, Yusahn, and Chenggong stations were greater than 350mm, reaching a warning line of extremely torrential rainfall, as defined by the CWB in Taiwan. For the 20-year return levels (for the years 2030) of extreme rainfall, the Yilan and Tainan stations were regarded as having extreme rainfall over a warning line. In summary, more than 50% of all stations will likely have extremely torrential rainfall during the next 20 years.

The 1^{st} extreme rainfall brought by the top 10 typhoons for each station in Taiwan was used to estimate the return period of such a rare event. It is evident that the return periods for such a rare event for the Keelung, Anbu, Tamsui, Yilan, Sun Moon Lake, Hualien and Chenggong stations are less than 20 years, and even in the Taichung station, the return period is 22 years. This has important implications for policy makers for designing flood prevention plans, and in anticipating future severe rainfall and the associated consequences of severe flooding.

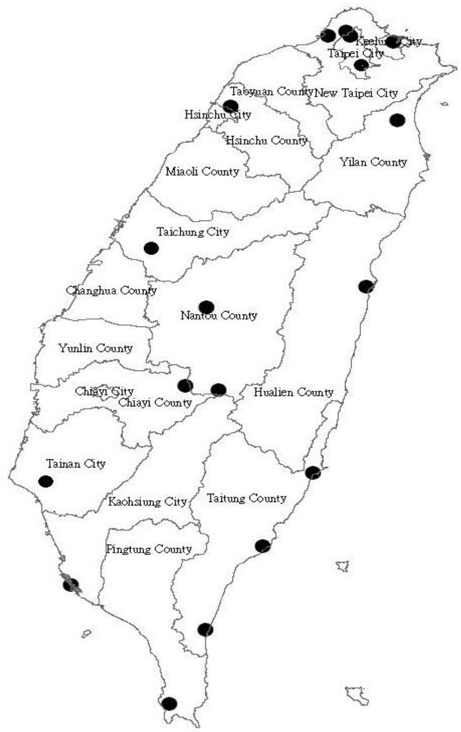

Figure 1

Locations of stations in Taiwan

Table 1
Location, latitude, longitude, station numbers, and summary statistics

Location		Station Number	Latitude	Longitude	Min	Max	Mean	Std. Dev.
Northern Region	Keelung	46694	25°08'	121°43'	78.4	637.6	191.7	109.0
	Anbu	46691	25°11'	121°31'	101.5	351.3	195.6	63.5
	Zhuzihhu	46693	25°09'	121°32'	103.0	749.5	355.1	162.4
	Tamsui	46690	25°09'	121°26'	107.6	1136.0	377.9	188.2
	Yilan	46708	24°45'	121°44'	68.3	389.5	180.4	75.3
	Taipei	46692	25°02'	121°30'	99.8	460.5	217.0	86.5
	Hsinchu	46757	24°49'	121°00'	34.0	425.2	167.0	77.1
Central Region	Taichung	46794	24°08'	120°40'	74.7	397.0	175.1	74.9
	Sun Moon Lake	46765	23°52'	120°53'	71.5	476.9	185.9	89.3
	Alishan	46753	23°30'	120°48'	78.0	558.8	230.5	122.7
	Yushan	46755	23°29'	120°57'	129.0	1166.0	484.4	227.2
Sothern Region	Tainan	46741	22°20'	120°18'	63.1	523.5	204.1	81.87
	Kaohsiung	46744	22°34'	120°18'	139.5	709.2	277.6	105.6
	Hengchun	46759	22°00'	120°44'	50.0	621.5	229.0	119.8
Eastern Region	Hualien	46699	23°58'	121°36'	64.1	430.5	223.6	89.4
	Chenggong	46761	23°05'	121°21'	68.0	428.5	230.8	86.9
	Taitung	46766	22°45'	121°08'	112.4	591.0	246.0	101.3
	Dawu	46754	22°21'	120°53'	91.6	484.0	228.6	87.0

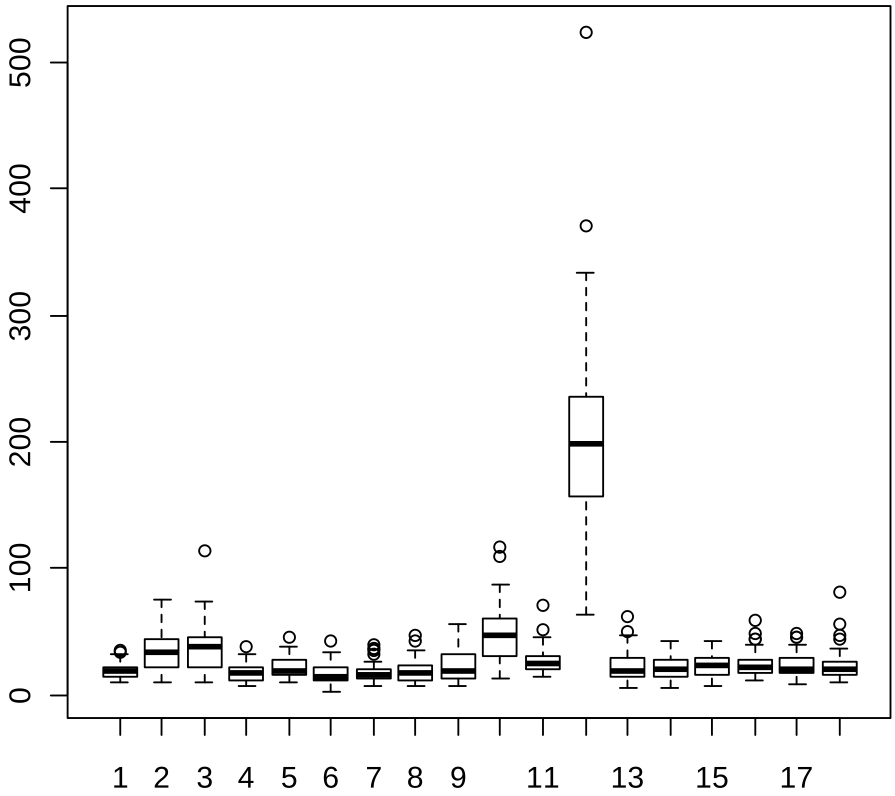

Figure 2
Box-plot of 18 stations

Table 2
Best fitting models and parameter estimates

Location	Model	$\hat{a}$(SE)	$\hat{b}$(SE)	$\hat{c}$(SE)	$\hat{\sigma}$(SE)	$\hat{\xi}$(SE)	K-S test
Keelung	Gum_0	166.35 (7.40)			50.15 (5.58)		0.7794
Anbu	Gum_0	279.51 (19.26)			130.45 (14.49)		0.8687
Zhuzihu	Gum_0	294.70 (21.08)			142.99 (15.78)		0.672
Tamsui	Gum_0	145.71 (8.70)			59.05 (6.62)		0.9004
Yilan	Gum_0	178.20 (9.39)			63.85 (7.30)		0.5566
Taipei	Gum_0	133.04 (8.39)			57.06 (6.34)		0.7542
Hsinchu	Gum_0	143.58 (7.47)			51.01 (5.75)		0.8742
Taichung	Gum_0	146.55 (9.58)			65.16 (7.40)		0.9694
Sun Moon Lake	GEV_0	160.67 (13.71)			76.17 (11.90)	0.32 (0.20)	0.3191
Alishan	Gum_0	380.80 (26.45)			179.25 (19.77)		0.7773
Yushan	Gum_0	233.18 (10.66)			72.63 (8.22)		0.7886
Tainan	Gum_0	167.40 (9.81)			66.41 (7.03)		0.8876
Kaohsiung	Gum_1	137.11 (23.17)	84.41 (47.66)		83.30 (9.43)		
Hengchun	Gum_1	151.71 (18.68)	64.85 (32.23)		69.13 (7.72)		
Hualien	GEV_0	197.55 (12.79)			80.99 (9.17)	-0.20 (0.11)	0.9995
Chenggong	GEV_0	196.22 (9.61)			60.62 (7.68)	0.20 (0.11)	0.8936
Taitung	Gum_1	166.67 (16.48)	51.34 (28.18)		61.36 (6.81)		
Dawu	Gum_1	168.96 (18.84)	27.48 (34.82)		60.99 (7.61)	0.22 (0.10)	
Note: The numbers in parentheses are standard errors.							

Table 3
Return levels estimates for 10, 20, 50, 100-years

	10-year	20-year	50-year	100-year
Keelung	279 (162,396)	315 (198,433)	362 (244,480)	397 (279,515)
Anbu	573 (455,691)	667 (549,784)	788 (670,906)	879 (762,997)
Zhuzihu	616 (498,734)	719 (601,836)	852 (735,970)	952 (834,1070)
Tamsui	278 (161,396)	321 (203,438)	376 (258,493)	417 (299,534)
Yilan	321 (204,439)	367 (250,485)	427 (309,544)	471 (354,589)
Taipei	261 (143,379)	302 (184,420)	355 (238,473)	395 (277,513)
Hsinchu	258 (140,375)	295 (177,412)	342 (255,460)	378 (260,495)
Taichung	293 (175,410)	340 (222,457)	400 (283,518)	446 (328,563)
Sun Moon Lake	412 (328,593)	539 (398, 888)	753 (482,1498)	962 (577,2190)
Alishan	784 (666,901)	913 (795,1030)	1080 (962,1197)	1205 (1087,1322)
Yushan	396 (272,518)	448 (331,566)	516 (399,634)	576 (449,684)
Tainan	317 (128,505)	365 (175,553)	426 (238,615)	472 (284,661)
Hualien	343 (312,391)	377 (343,442)	415 (374,506)	438 (391,554)
Chenggong	370 (318,472)	445 (367,612)	561 (432,863)	664 (481,1114)
Note: The numbers in parentheses are the 95% confidence interval.				

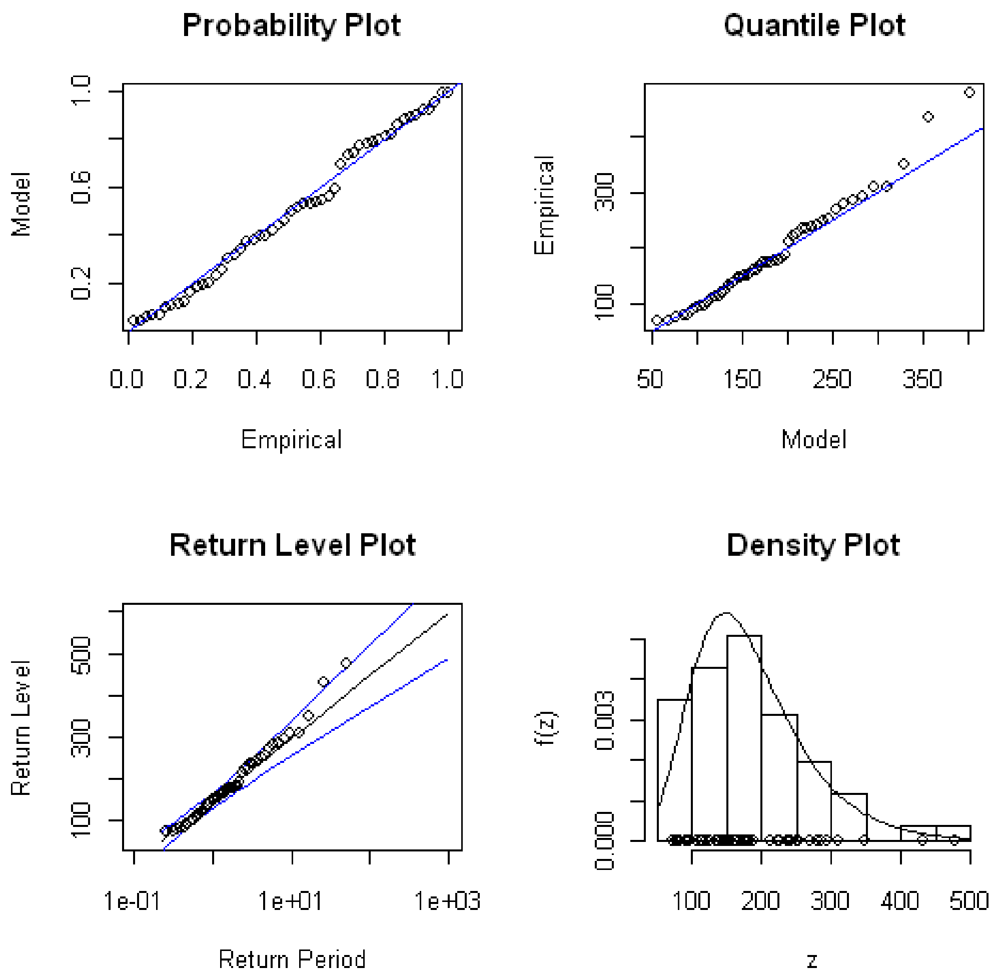

Figure 3
Diagnostic plots for Taichung Station (Gum_0) for annual maximum daily rainfall (return level plots give the return level estimates and 95% confidence intervals)

Table 4
Top 10 rainfalls for each station

Year	Event	Keelun g	Anbu	Zhuzi-hu	Dan-hui	Yilan	Tainan	Taipei	Hsin-chu	Tai-hung	Sun Moon Lake	Ali-han	Yus-han	Hua-lien	Cheng-gong
1963	Gloria	294	35	385	271	86	73	332	348	243	447	874	320	33	3
1987	Lynn	**301**	13	**1136**	**314**	129	26	222	73	7	14	53	112	**246**	278
1996	Herb	168	156	439	210	274	102	203	237	269	454	1095	448	135	52
1997	Amber	217	14	115	73	191	22	0	57	63	79	224	98	243	183
2001	Nari	270	206	685	255	182	226	**425**	**397**	309	50	319	219	71	37
2004	Mindulle	74	165	141	111	55	224	89	109	268	231	556	307	186	**352**
2004	Aere	127	53	508	138	232	52	192	196	205	294	415	387	11	1
2005	Haitang	38	0	15	10	0	0	7	2	0	2	0	2	0	13
2008	Sinlaku	178	22	448	242	**356**	114	283	127	214	**472**	425	419	37	28
2009	Morakot	79	**272**	230	96	35	**524**	50	94	**347**	280	**1166**	**709**	59	102
Return Period		15	2	35858	18	17	216	168	144	22	14.1	80	702	2.5	8.3

Note: Bold entries denote the highest rainfalls.

References

Aronica, G., Cannarozzo, M., and Noto, L., 2002. Investigating the changes in extreme rainfall series recorded in an urbanised area, Water Science and Technology, 45, 49-54.

Cannarozzo, M., Dasaro, F., and Ferro, V., 1995, Regional rainfall and flood frequency-analysis for Sicily using the 2-component extreme-value distribution, Hydrological Sciences Journal, 40, 19-42.

Coles, 2001, An Introduction to Statistical Modeling of Extreme Values, Springer Series in Statistics, Springer Verlag, London.

Feng, S., Nadarajah, S., and Hu, Q., 2007, Modeling annual extreme precipitation in China using the generalized extreme value distribution, Journal of Meteorological Society of Japan, 85, 599–613.

Galambos J., 1987, The Asymptotic Theory of Extreme Order Statistics, 2nd ed., Melbourne, Florida, Krieger.

Ge, X., Li, T., Zhang, S., and Peng, M., 2010, What causes the extremely heavy rainfall in Taiwan during Typhoon Morakot (2009)? Atmospheric Science Letters, 11, 46-50, doi: 10.1002/asl.255.

Gumbel, E.J., 1985, Statistics of Extremes, Columbia University Press, New York.

Hong, C.C., Lee, M.Y., Hsu, H.H., and Kuo, J.L., 2010, Role of submonthly disturbance and 40-50 day ISO on the extreme rainfall event associated with Typhoon Morakot (2009) in Southern Taiwan, Geophysical Research Letters, 37, L08805, doi: 10.1029/2010GL042761.

Hosking, J.R.M., and Wallis, J.R., 1987, Parameter and quantile estimation for the generalized Pareto distribution, Technometrics, 29(3), 339-349.

Hsu, H.-H., Chou, C., Wu, Y.-C., Lu, M.-M., Chen, C.-T., and Chen, Y.-M., 2011, Climate Change in Taiwan: Scientific Report 2011, National Science Council, Taipei, Taiwan, ROC, 67pp.

Jenkinson, A.F., 1995, The frequency distribution of the annual maximum (or minimum) values of meteorological elements, Quarterly Journal of the Royal Meteorological Society, 81, 158-171.

Katz, R.W., Parlang, M.B., and Naveau, P., 2002, Statistics of extremes in hydrology, Advances in Water Resources, 25, 1287-1304.

Koutsoyiannis, D., and Baloutsos, G., 2000, Analysis of a long record of annual maximum rainfall in Athens, Greece, and design rainfall inferences, Natural Hazards, 22, 29-48.

Miroslava, U., 1991, The extreme value distribution of 5-min rainfall data Belgrade, Theoretical and Applied Climatology, 44, 223-228.

Miroslava, U.., 1992, The extreme value distribution of rainfall data at Belgrade, Yugoslavia, Atmosfera, 5, 47-56.

Nadarajah, S., 2005, Extremes of daily rainfall in West Central Florida, Climatic Change, 69, 325-342.

Nadarajah, S., and Choi, D., 2007, Maximum daily rainfall in South Korea, Journal of Earth System Science, 116, 311-320.

Park, J.-S., Kang, H.-S., Lee, Y.-S., and Kim, M.-K., 2010, Changes in extreme daily rainfall in South Korea, International Journal of Climatology.

Whithers, C.S., and Nadarajah, S., 2000, Evidence of trend in return levels for daily rainfall in New Zealand, Journal of Hydrology, 39(2), 155-166.

Zalina, M.D., Desa, M.N.M., Nguyen, V.T.V., and Kassim, A.H.M., 2002, Selecting a probability distribution for extreme rainfall series in Malaysia, Water Science and Technology, 45, 63-68.