STATISTICAL CHARACTERISTIC OF HEAVY RAINFALL ASSOCIATED WITH TYPHOONS NEAR TAIWAN BASED ON HIGH-DENSITY AUTOMATIC RAIN GAUGE DATA

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Data from hundreds of automatic rain gauge stations recorded over the past 20 years are shown to effectively represent and assess the rainfall characteristic of typhoon-associated heavy rainfall in Taiwan.

Typhoon-induced rainfall remains one of the most important and challenging issues for both research and forecast operations. In particular, accurate representation of the extreme rainfall is very important for disaster prevention since serious flooding events are generally associated with heavy or extreme rainfall. Taking the typhoon impact in Taiwan as an example, multiple factors can affect the rainfall amount and distribution and give rise to considerable uncertainty in quantitative forecasts of typhoon-induced precipitation (Wu and Kuo 1999). It has been suggested that factors influencing the typhoon-related rainfall in Taiwan include the topographic effect of the Central Mountain Range (e.g., Chang et al. 1993; Wu et al. 2002; Tsai and Lee 2009); interaction between typhoon circulation patterns and the Asian monsoon system, such as the northeasterly winds late in the typhoon season and southwesterly winds in the summer (Wu et al. 2009; Yu and Cheng 2014); impacts from other nearby typhoons (Wu et al. 2010a); and the locations of the typhoons relative to the topography of Taiwan (Wu et al. 2013).

Occasionally, such interactions among the multiple factors above could cause extremely heavy rainfall events. For instance, Typhoon Morakot (2009) lashed southern Taiwan, bringing torrential rainfall, peaking at

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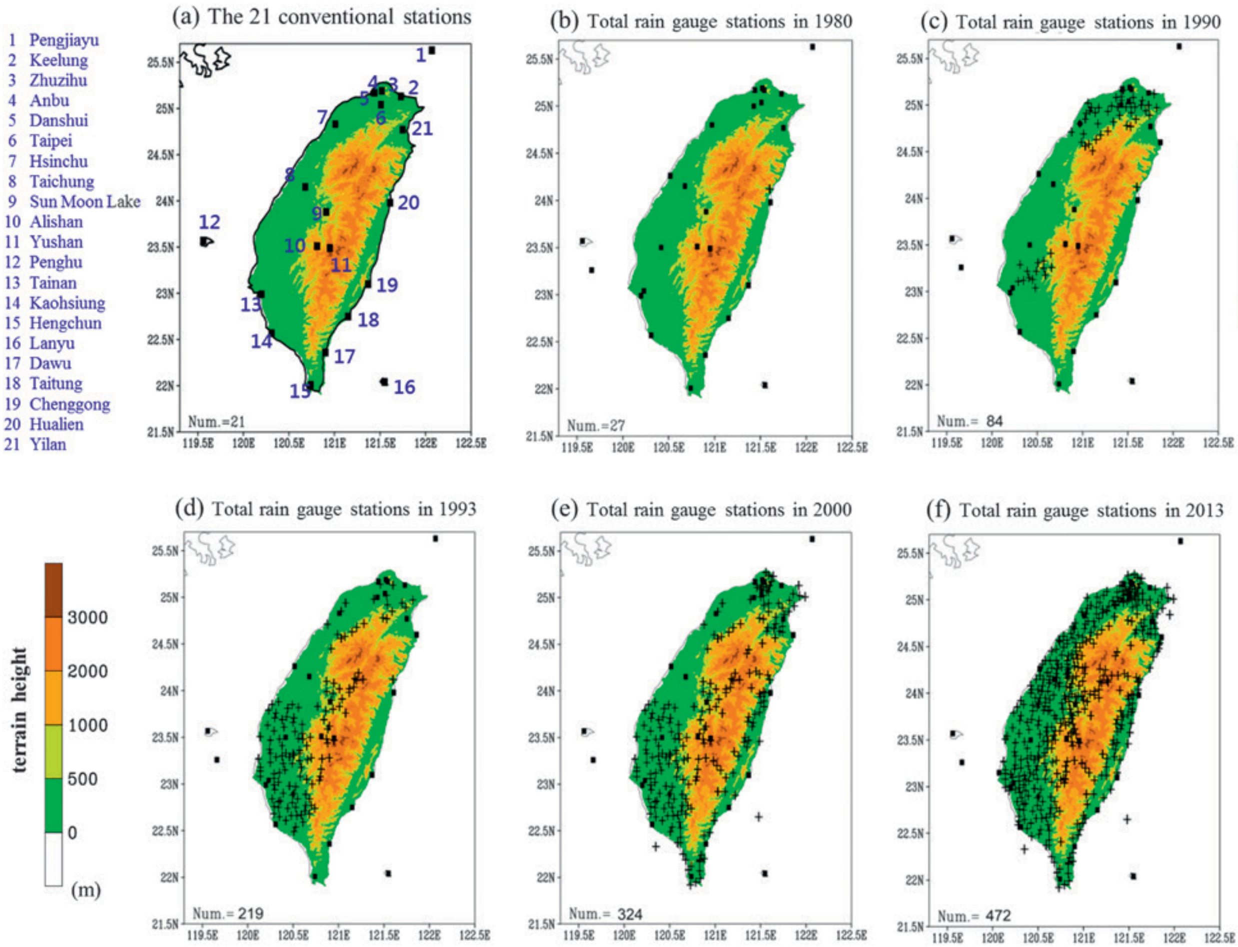


Fig. 1. (a) Locations of the 21 CWB conventional weather stations. Locations of the conventional weather stations (black squares) and automatic rain gauge stations (cross marks) in operation during (b) 1980, (c) 1990, (d) 1993, (e) 2000, and (f) 2013 with conventional stations marked by squares. The total number of stations is shown in the bottom-left corner of each panel. The topography of Taiwan is shaded.

3000 mm in 4 days, that resulted in catastrophic floods and landslides. A number of studies have addressed the physical reasons behind the Morakot-produced heavy rainfall from different scientific perspectives, such as the large-scale moisture convergence, the confluent flow due to interactions between the typhoon's outer circulation pattern and the concurrent southwesterly monsoon, the asymmetric typhoon structure, the slow translation speed, oceanic conditions conducive for typhoon development, and the impact of Typhoon Goni (Ge et al. 2010; Hsu et al. 2010; Wang et al. 2010; Wu et al. 2010b; Yeh et al. 2010; Zhang et al. 2010; Yen et al. 2011; Jou et al. 2012; Wang et al. 2012; Yu and Cheng 2013; Wu 2013). Wu and Yang (2011) coordinated a special issue of the journal *Terrestrial, Atmospheric and Oceanic Sciences* (*TAO*) entitled, "Typhoon Morakot (2009): Observation, Modeling, and Forecasting Applications," which specifically focused on analyses of the different processes discussed above.

In addition to the investigation of a single extreme rainfall case, the long-term characteristics of the typhoon-induced rainfall and their connection to climate change or global warming is another important research topic (Liu et al. 2009; Chang et al. 2013). Chang et al. (2013) used rainfall data from 21 conventional weather stations operated by the Central Weather Bureau (CWB) in Taiwan to examine the rainfall statistics for typhoons that made landfall in Taiwan from 1960 to 2011. They reported that 8 of the top 12 typhoons in terms of total rainfall occurred after 2004. Nevertheless, most conventional stations are distributed along the coast with only three stations (i.e., station numbers 9–11, marked in Fig. 1a) located in the mountainous areas (above 1000 m) of central Taiwan. None of the conventional stations were deployed over the mountainous regions in northern and southern Taiwan, where very intense rainfall has been frequently observed as typhoons

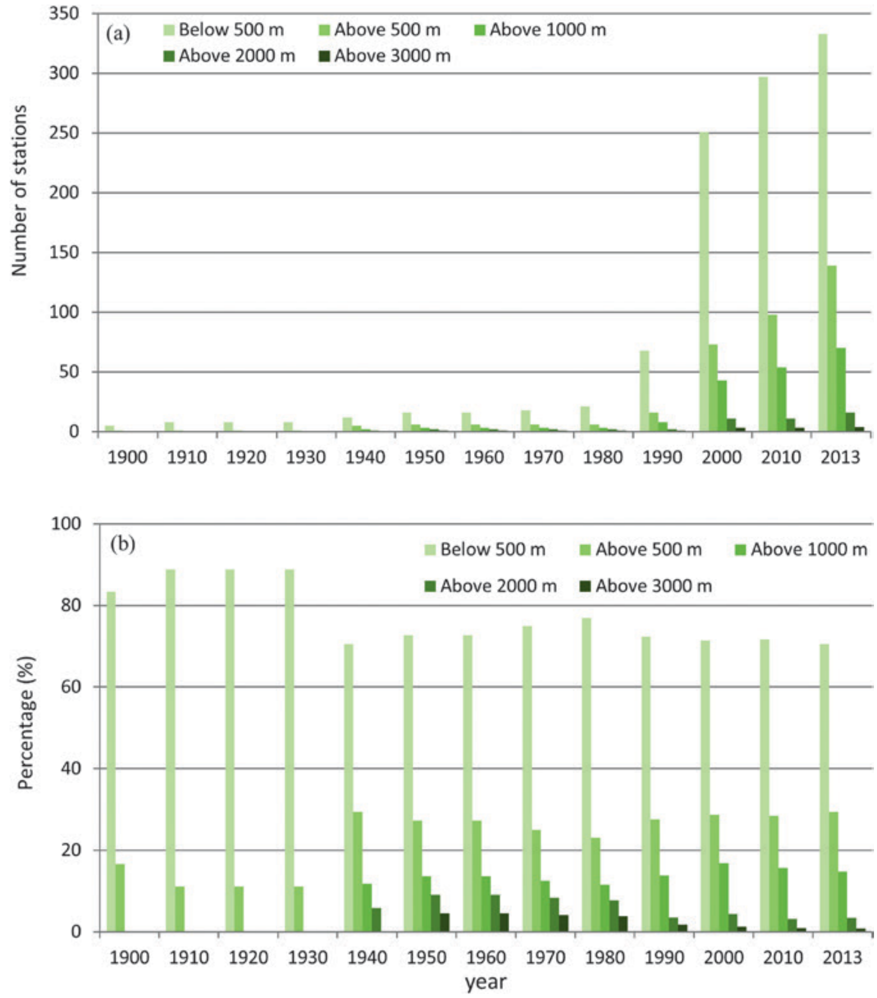


Fig. 2. Temporal variation of (a) the numbers of rain gauge stations and (b) the percentages with respect to the total number of stations. The stations located at different elevations are indicated by different bars.

influence Taiwan (e.g., Yu and Cheng 2008; Yu and Cheng 2014). It is reasonable to presume that the analysis results based on the few conventional stations, which are unevenly distributed, are not adequately representative of the typhoon-induced rainfall in Taiwan.

To address this issue, this study attempts to 1) examine the impact of rainfall data that are recorded at the limited, unevenly distributed conventional stations on the statistical characteristics of the typhoon-associated rainfall near Taiwan, and 2) highlight the importance of using data from a large number of automatic rain gauge stations, which became available starting in the 1990s, to assess the statistical features of the typhoon-related rainfall.

This article is organized as below. The data and methodology are described in the next section, comparisons between the results from the conventional stations and all the available rain gauges are given in the results section, and the final section of the paper offers the concluding remarks.

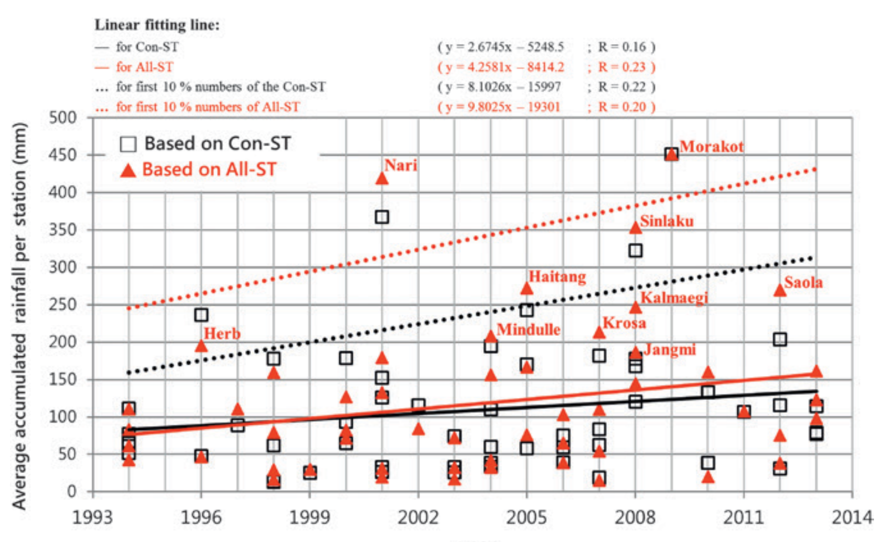


Fig. 3. The average accumulated rainfall amount per station (mm) for a single station calculated based on data from Con-ST (black) and from All-ST (red) for all 53 typhoons. Fitting lines are shown based on data from Con-ST, All-ST, and the top 10% rain gauge stations of Con-ST and All-ST (in terms of respective total rainfall for all 53 typhoons). Names of the top 10 highest ranking typhoons in terms of average rainfall amount based on All-ST are also labeled.

Table 1. List of the analyzed typhoons and their relevant information.

No.	Typhoon (year)	Time of landfall in Taiwan	Impact time in Taiwan			Type of track
			Start[a]	End[b]	Duration (h)	
1	Tim (1994)	1210 UTC 10 Jul	0900 UTC 10 Jul	1900 UTC 10 Jul	11	C
2	Caitlin (1994)	1000 UTC 3 Aug	0600 UTC 3 Aug	2100 UTC 3 Aug	16	C
3	Doug (1994)	X[c]	1300 UTC 7 Aug	0300 UTC 8 Aug	15	Other
4	Gladys (1994)	0300 UTC 1 Sep	2300 UTC 31 Aug	1000 UTC 1 Sep	12	N
5	Gloria (1996)	0800 UTC 26 Jul	2300 UTC 25 Jul	1500 UTC 26 Jul	17	S
6	Herb (1996)	1244 UTC 31 Jul	0900 UTC 31 Jul	0000 UTC 1 Aug	16	N
7	Amber (1997)	1950 UTC 28 Aug	1300 UTC 28 Aug	1000 UTC 29 Aug	22	C
8	Nichole (1998)	1700 UTC 9 Jul	0400 UTC 9 Jul	0000 UTC 10 Jul	21	Other
9	Otto (1998)	0400 UTC 4 Aug	0000 UTC 4 Aug	1300 UTC 4 Aug	14	C
10	Yanni (1998)	X	2100 UTC 27 Aug	2100 UTC 28 Aug	25	Other
11	Zeb (1998)	X	1200 UTC 15 Oct	0700 UTC 16 Oct	20	Other
12	Maggie (1999)	X	1800 UTC 5 Jun	0100 UTC 6 Jun	8	Other
13	Kai-Tak (2000)	0130 UTC 9 Jul	1700 UTC 8 Jul	1100 UTC 9 Jul	19	Other
14	Bilis (2000)	1400 UTC 22 Aug	1200 UTC 22 Aug	2200 UTC 22 Aug	11	S
15	Xangsane (2000)	X	1300 UTC 31 Oct	0500 UTC 1 Nov	17	Other
16	Chebi (2001)	X	2100 UTC 22 Jun	0800 UTC 23 Jun	12	Other
17	Trami (2001)	0930 UTC 11 Jul	2100 UTC 10 Jul	1200 UTC 11 Jul	16	S
18	Toraji (2001)	1610 UTC 29 Jul	1100 UTC 29 Jul	1000 UTC 30 Jul	24	C
19	Nari (2001)	1300 UTC 16 Sep	0400 UTC 16 Sep	0900 UTC 19 Sep	78	Other
20	Lekima (2001)	1030 UTC 26 Sep	2000 UTC 25 Sep	0000 UTC 28 Sep	53	S
21	Nakri (2002)	2100 UTC 9 Jul	0000 UTC 9 Jul	1100 UTC 10 Jul	36	Other
22	Morakot (2003)	1350 UTC 3 Aug	0600 UTC 3 Aug	0200 UTC 4 Aug	21	S
23	Dujuan (2003)	X	1300 UTC 1 Sep	1900 UTC 1 Sep	7	Other
24	Melor (2003)	X	0900 UTC 2 Nov	0400 UTC 3 Nov	20	Other
25	Mindulle (2004)	1440 UTC 1 Jul	2200 UTC 30 Jun	1400 UTC 2 Jul	41	Other
26	Aere (2004)	X	1300 UTC 24 Aug	0600 UTC 25 Aug	18	Other
27	Haima (2004)	X	1500 UTC 11 Sep	1000 UTC 12 Sep	20	Other
28	Nock-Ten (2004)	0230 UTC 25 Oct	1800 UTC 24 Oct	1100 UTC 25 Oct	18	N
29	Nanmadol (2004)	2340 UTC 3 Dec	2000 UTC 3 Dec	0400 UTC 4 Dec	9	S

DATA. Figure 1 shows the locations of the 21 conventional weather stations and the automatic rain gauge measurements from the CWB during some representative years. It is clear that the number of automatic rain gauges has significantly increased since 1990, while the number of rain gauges located below the altitude of 500 m has always accounted for more than 70% of all stations (Fig. 2). In other words, the percentage of the stations located above 500 m has been higher than 20%, but never reached 30%, and those located above 1000 m have accounted for around 10%–15% of the total. Stations at higher elevations (above 2000 or 3000 m) cover even smaller percentages.

Hourly rain gauge data from the conventional weather stations and the automatic rainfall gauges are used to obtain statistics related to precipitation induced by typhoons that have struck Taiwan between 1993 and 2013. In this study, the total accumulated rainfall for each typhoon is obtained during a time period when the typhoon center is within a distance of 100 km from the nearest coastline, similar to the definition in Chang et al. (2013). In addition, an index of the average rainfall amount for a single station during the typhoon's influence is calculated by summing the total accumulated rainfall from all the available rain gauges and dividing it by the number of gauge stations. For convenience, the selected 21

Table 1. Continued.						
			Impact time in Taiwan			
No.	Typhoon (year)	Time of landfall in Taiwan	Start[a]	End[b]	Duration (h)	Type of track
30	Haitang (2005)	0650 UTC 18 Jul	0400 UTC 18 Jul	1100 UTC 19 Jul	32	N
31	Talim (2005)	1700 UTC 31 Aug	1300 UTC 31 Aug	0500 UTC 1 Sep	17	C
32	Longwang (2005)	2110 UTC 1 Oct	1800 UTC 1 Oct	0800 UTC 2 Oct	15	C
33	Bilis (2006)	1420 UTC 13 Jul	0800 UTC 13 Jul	0100 UTC 14 Jul	18	N
34	Kaemi (2006)	1545 UTC 24 Jul	1200 UTC 24 Jul	0400 UTC 25 Jul	17	S
35	Bopha (2006)	1920 UTC 8 Aug	1300 UTC 8 Aug	0200 UTC 9 Aug	14	S
36	Pabuk (2007)	1800 UTC 7 Aug	1200 UTC 7 Aug	2300 UTC 7 Aug	12	S
37	Wutip (2007)	0100 UTC 9 Aug	2000 UTC 8 Aug	0300 UTC 9 Aug	8	C
38	Sepat (2007)	2140 UTC 17 Aug	1800 UTC 17 Aug	1200 UTC 18 Aug	19	C
39	Krosa (2007)	1430 UTC 6 Oct	0300 UTC 6 Oct	0100 UTC 7 Oct	23	N
40	Kalmaegi (2008)	1340 UTC 17 Jul	0600 UTC 17 Jul	0400 UTC 18 Jul	23	N
41	Fung-Wong (2008)	2250 UTC 27 Jul	1700 UTC 27 Jul	1300 UTC 28 Jul	21	C
42	Sinlaku (2008)	1750 UTC 13 Sep	0200 UTC 13 Sep	2200 UTC 14 Sep	45	N
43	Jangmi (2008)	0740 UTC 28 Sep	0400 UTC 28 Sep	0400 UTC 29 Sep	25	N
44	Morakot (2009)	1550 UTC 7 Aug	0500 UTC 7 Aug	0100 UTC 9 Aug	45	N
45	Namtheun (2010)	X	1200 UTC 30 Aug	1100 UTC 31 Aug	24	Other
46	Fanapi (2010)	0040 UTC 19 Sep	2000 UTC 18 Sep	1700 UTC 19 Sep	22	C
47	Nanmadol (2011)	2020 UTC 28 Aug	0600 UTC 28 Aug	1900 UTC 29 Aug	38	S
48	Talim (2012)	X	0900 UTC 20 Jun	1700 UTC 20 Jun	9	Other
49	Saola (2012)	1920 UTC 1 Aug	1500 UTC 1 Aug	1500 UTC 2 Aug	25	N
50	Tembin (2012)	2100 UTC 23 Aug	1300 UTC 23 Aug	0300 UTC 28 Aug	41	S
51	Soulik (2013)	1900 UTC 12 Jul	1600 UTC 12 Jul	0400 UTC 13 Jul	13	N
52	Trami (2013)	X	0600 UTC 21 Aug	1500 UTC 21 Aug	10	Other
53	Kong-Rey (2013)	X	1700 UTC 28 Aug	0600 UTC 29 Aug	14	Other

[a] Starting time is defined as when the typhoon center moves to a location that is within 100 km to the nearest coastline of Taiwan.

[b] Ending time is defined as when the typhoon center departs for a location that is 100 km away from the nearest coastline of Taiwan.

[c] X indicates storm did not make landfall in Taiwan.

conventional weather stations [basically those used in the analysis of Chang et al. (2013)] are referred to as Con-ST, while all rain gauge stations (including both the conventional and automatic gauge stations) are referred to as All-ST.

RESULTS. Fifty-three typhoons struck Taiwan from 1993 to 2013. Among the 12 typhoons with the highest average rainfall amount based on Con-ST data (21 stations; Fig. 1a), 4 occurred before 2004 [Typhoons Herb (1996), Zeb (1998), Xangsane (2000), and Nari (2001)] and the remaining 8 typhoons occurred after 2004, consistent with the results in Chang et al. (2013) based on typhoons from 1960 to 2011. However, if the reference is expanded to include all data from All-ST (about 250–500 stations; Fig. 1), the number of typhoons before 2004 drops to three, yet with a slightly different composition [Typhoons Herb (1996), Toraji (2001),and Nari (2001); Table 1] compared to Con-ST. Figure 3 shows the average accumulated rainfall amount (mm) per station from 53 typhoons within the 21 years studied. The average rainfall amount is calculated using two approaches: based solely on Con-ST or with All-ST. The statistical analysis indicates a slightly increasing, yet statistically insignificant (with a very small correlation coefficient of about 0.2 in Fig. 3), trend in the average rainfall for both Con-ST and All-ST. A clear difference can be found in the fitting lines (dotted lines in Fig. 3) of the average rainfall between the top 10% of Con-ST and All-ST. Although

TABLE 2. The *t* tests for Data-1 and Data-2 of Con-ST and All-ST with *t* values and *p* values for comparison. Data-1 and Data-2 are two 10-yr groups ranging between 1994 and 2003 and 2004 and 2013, respectively.

t test	Avg accumulated rainfall per station between Data-1 and Data-2 from Con-ST	Avg accumulated rainfall per station between Data-1 and Data-2 from All-ST
Data-1 (mm)	93.7	93.0
Data-2 (mm)	122.5	138.8
t value	1.6198	2.3320
p value	0.1256	0.0475

both dashed lines show similar increasing temporal trends, each line has a rather weak linear-regression correlation. The number of typhoon cases with average rainfall exceeding 150 mm appears to be higher after 2004 as compared to those before 2004, as indicated in Chang et al. (2013). For each typhoon case, the mean value of the average rainfall for a single station based on the All-ST data is larger than that based on the Con-ST by about 8 mm.

To further examine the above observations, we divide the data into two 10-yr groups: Data-1 for 1994–2003 and Data-2 for 2004–13. Table 2 shows *t*-test results (Larsen and Marx 1981) for the comparison of Data-1 and Data-2 between Con-ST and All-ST. First, it is found that the *p* value for the comparison of Data-1 and Data-2 from All-ST is less than 0.05. Therefore, a significant difference (at a confidence level of 95%) can be identified between Data-1 and Data-2 for All-ST, while the difference between Data-1 and Data-2 for Con-ST does not pass the significance test (at the 90% confidence level). The above result again highlights the importance of using All-ST data. We also calculate the *p* value of the average accumulated rainfall from stations with the top 10%, 15%, 25%, 50%, and 100% rainfall for Con-ST and All-ST (Table 3). It is found that the *p* value is less than 0.05 for the comparison of the top 10% and 15% groups, indicating a significant difference in average hourly rainfall per station between the top 10% and 15% of both Con-ST and All-ST. This analysis shows that although the average rainfall amount calculated from Con-ST is similar to that from All-ST, Con-ST cannot identify the precipitation extremes (such as the top 10% and 15% rainfall amounts). Hereafter, further analysis based on stations with the top 10% rainfall is conducted to show more statistics related to extreme rainfall.

The top 10% rain gauge stations for the top 10 highest ranking typhoons (hereafter referred to as top 10 typhoons, with each name indicated in both Figs. 3 and 4) in terms of average rainfall amount based on All-ST data are mostly distributed across the mountainous areas of above 1000-m altitude, where only 3 of the 21 conventional stations (Con-ST) are located (cf. Figs. 1 and 4). In addition, most of the top 10 typhoons passed over northern Taiwan (Figs. 4a,c,d,e,f,g,i,j). The relationship between the average accumulated rainfall per station calculated based on All-ST with respect to the duration of each typhoon's influence over Taiwan is displayed in Fig. 5. The positive correlation between the average rainfall and duration is more evident in the assessment for the top 10 typhoons (black), with a correlation coefficient (*R*) of 0.77. Meanwhile, the

TABLE 3. The *t* and *p* values from *t* tests of average accumulated rainfall from the stations with the top 10%, 15%, 25%, 50%, and 100% of rainfall from Con-ST and All-ST.

t test	Avg accumulated rainfall per station from the top 10% of Con-ST and All-ST	Avg accumulated rainfall per station from the top 15% of Con-ST and All-ST	Avg accumulated rainfall per station from the top 25% of Con-ST and All-ST	Avg accumulated rainfall per station from the top 50% of Con-ST and All-ST	Avg accumulated rainfall per station from Con-ST and All-ST
Con-ST (mm)	238.6	242.0	229.3	178.0	109.5
All-ST (mm)	341.0	317.3	261.4	193.2	118.1
t value	2.7893	2.2911	1.1019	0.6812	0.6327
p value	0.0140	0.0405	0.2023	0.3068	0.3205

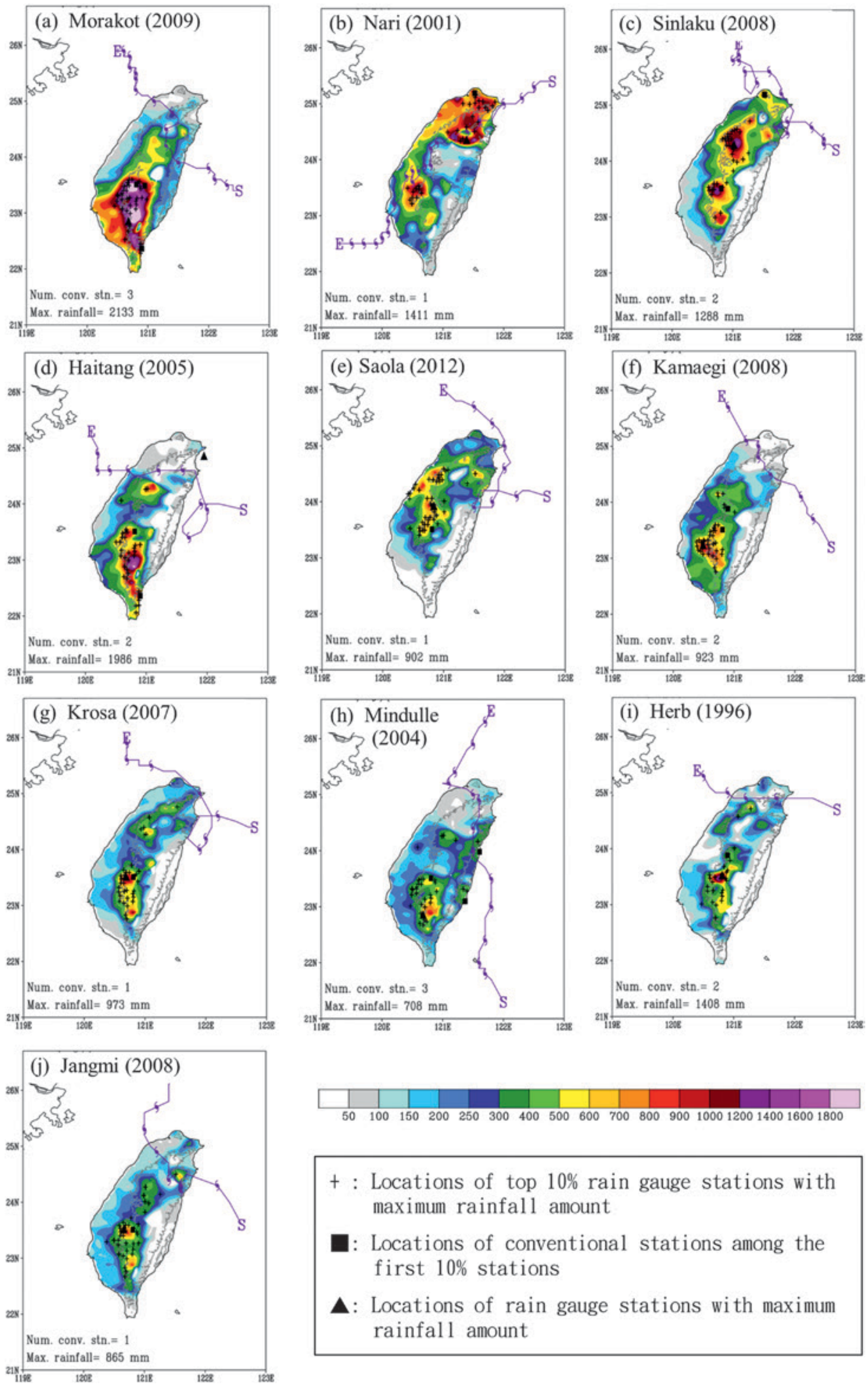


Fig. 4. The distribution of the accumulated rainfall during the typhoons' influence over Taiwan. Only the top 10 typhoons are shown. Locations of the top 10% rain gauge stations in terms of total rainfall amount are marked by crosses, among which the conventional stations are indicated by squares. The best track analyzed by the CWB is shown by typhoon symbols every 3 h. The letters S and E indicate the typhoon positions when the typhoon center approaches to within 100 km of the nearest coastline and at its departure time when the typhoon center is 100 km away from the nearest coastline, respectively. The thick black contour indicates the terrain above 500 m.

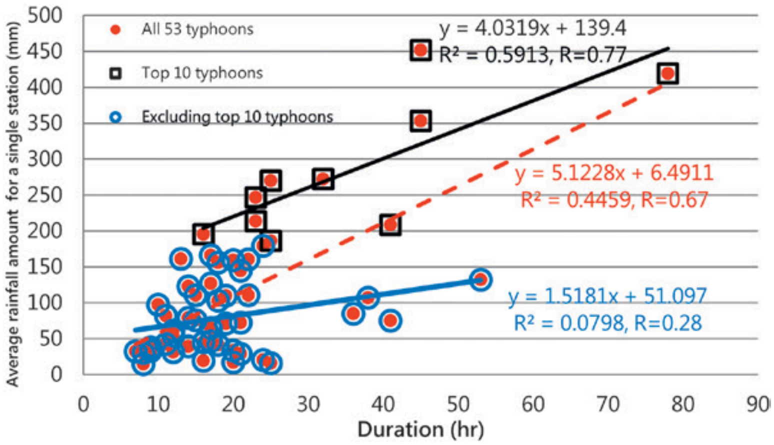


Fig. 5. The average accumulated rainfall amount per station (mm) based on data from All-ST vs the duration for all 53 typhoons (red circles), the top 10 typhoons (black squares), and all typhoons excluding the top 10 typhoons (blue circles) during their time impacting Taiwan. The corresponding linear fitting line and equation are also shown.

correlation coefficient between the average rainfall and the duration time for all 53 typhoons slightly decreases to about 0.67. However, the correlation coefficient drops to 0.28 when the data from the top 10 typhoons are excluded, suggesting that a strong correlation between the average rainfall and the impact duration of a typhoon mainly exists for typhoons with the most pronounced rainfall.

To further understand the statistical difference between the Con-ST and the All-ST results in the mountainous areas, the ratio of rainfall over the mountainous areas to the total rainfall amount is examined. The mean ratios calculated from Con-ST above 3000, 2000, and 1000 m and averaged for all typhoon cases are 8.2%, 18.6%, and 23.7%, respectively (Fig. 6a), while the mean ratios from the All-ST results are strongly reduced to 0.9%, 3.0%, and 9.1% (Fig. 6b). Note that only one (Yushan station) out of the 21 conventional stations is located above an elevation of 3000 m and only another one (Alishan station) is located between the elevations

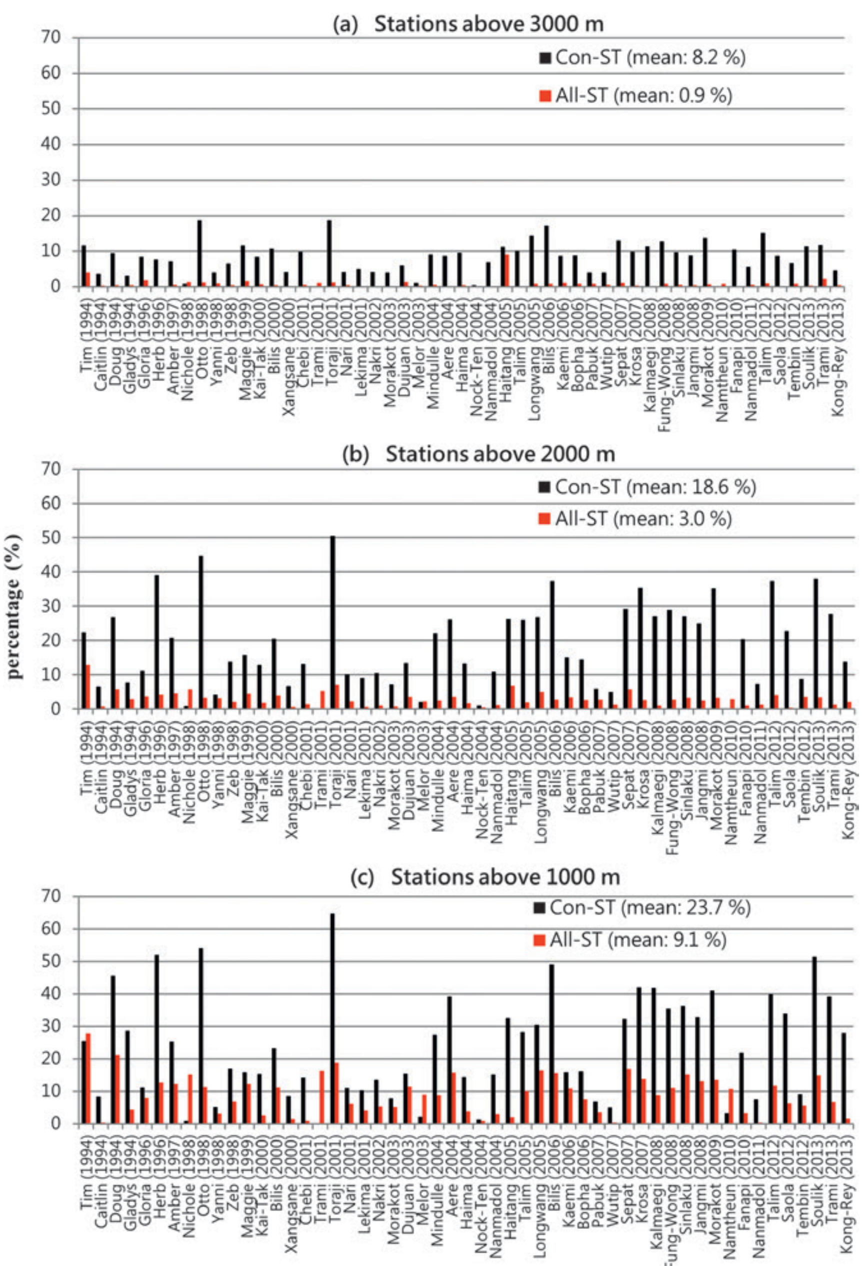
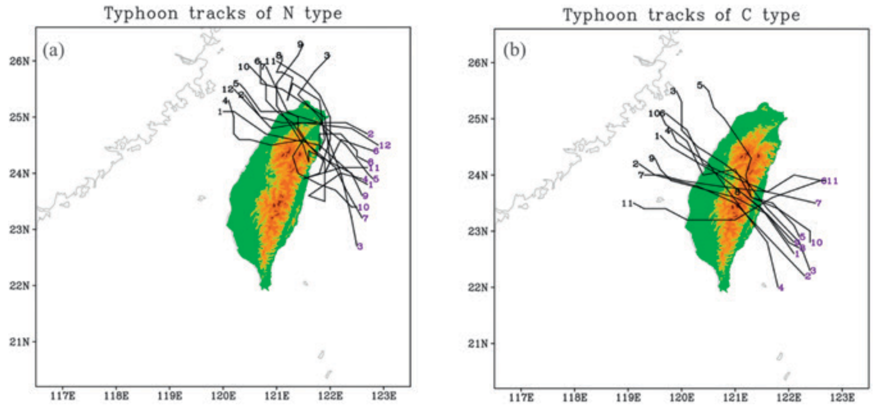
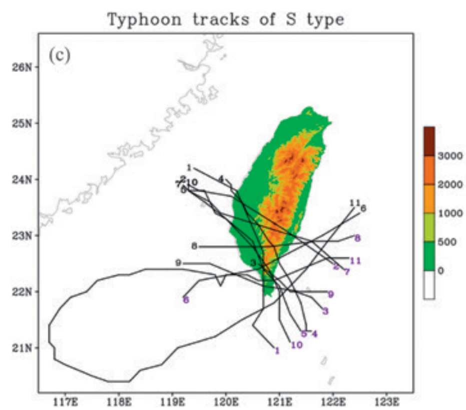


Fig. 6. The percentage of rainfall measured by Con-ST and All-ST above (a) 3000, (b) 2000, and (c) 1000 m, with respect to the total rainfall during each of the 53 typhoons.





case #	N type	C type	S type
1	Gladys (1994)	Tim (1994)	Gloria (1996)
2	Herb (1996)	Cartlin (1994)	Bilis (2000)
3	Nock-Ten (2004)	Amber (1997)	Trami (2001)
4	Haitang (2005)	Otto (1998)	Lekima (2001)
5	Bilis (2006)	Toraji (2001)	Morakot (2003)
6	Krosa (2007)	Talim (2005)	Nanmadol (2004)
7	Kalmaegi (2008)	Longwang (2005)	Kaemi (2006)
8	Sinlaku (2008)	Wutip (2007)	Bopha (2006)
9	Jangmi (2008)	Sepat (2007)	Pabuk (2007)
10	Morakot (2009)	Fung-Wong (2008)	Nanmadol (2011)
11	Saola (2012)	Fanapi (2010)	Tembin (2011)
12	Soulik (2013)		

Fig. 7. The typhoon best tracks analyzed by the CWB for (a) N-, (b) C-, and (c) S-type typhoons. Typhoon tracks indicated start where the typhoon center is within 100 km of the nearest coastline (indicated by purple numbers) when approaching Taiwan and ends where the typhoon center is 100 km away from the nearest coastline (indicated by the black numbers) when departing Taiwan. Table to the bottom right shows the analyzed typhoons with their case numbers.

of 2000 and 3000 m (Fig. 1a). It has been shown that the location of Alishan station is close to one of the heavy precipitation centers during typhoon rainfall events (Wu et al. 2002; Yu and Cheng 2014). Therefore, the percentage of rainfall at higher elevations is most likely overestimated if only the three conventional stations in the mountains are considered, because of their quite limited numbers and their uneven distribution over the mountainous areas. This result suggests that the statistical analyses conducted solely based on Con-ST are unable to represent the partitioning by terrain heights of the rainfall associated with typhoons in Taiwan.

To understand the statistical rainfall features in relation to typhoon tracks, we categorize the landfalling typhoons into three types based on their landfall locations [as in Chang et al. (2013)], namely, around northern Taiwan (N type, landfalling to the north of 23.6°N), across central Taiwan (C type, landfalling between 23.1° and 23.6°N), and over southern Taiwan (S type, landfalling to the south of 23.1°N) (Fig. 7). Figure 8 shows the average hourly rainfall per station of the three track types of typhoons based on the rain gauge data in four different zones

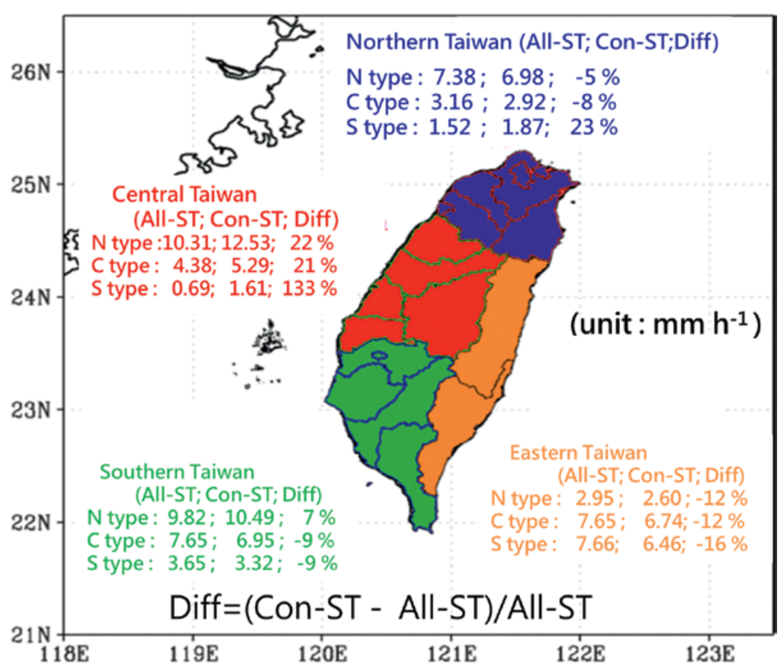


Fig. 8. The average hourly rainfall amount per station (mm h^{-1}) based on data from All-ST and solely on Con-ST located in the four zones of Taiwan, averaged by groups of N-, C-, and S-type typhoons, respectively.

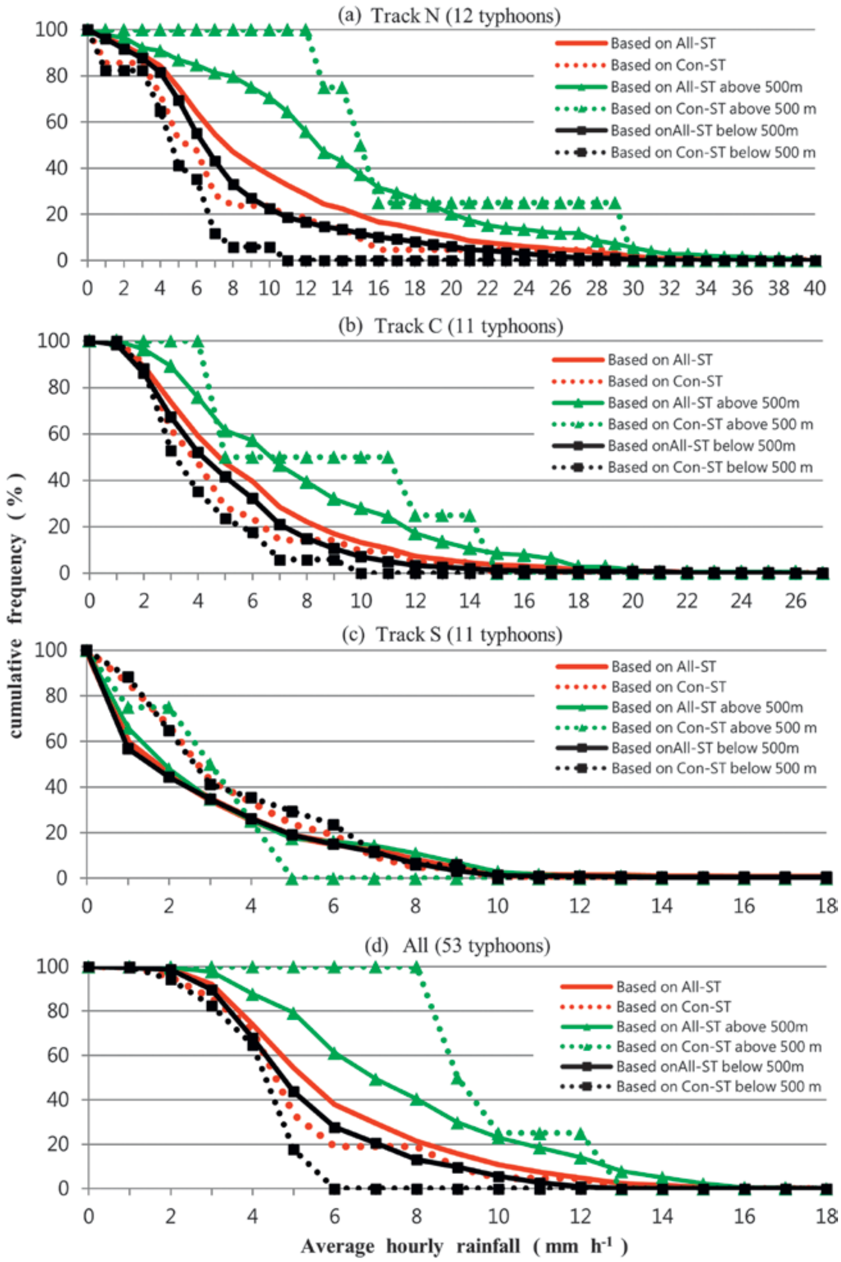


FIG. 9. The cumulative frequency of the average hourly rainfall calculated with rainfall data from Con-ST and All-ST as well as data below or above 500 m for (a) N-, (b) C-, and (c) S-type typhoons, and (d) all 53 typhoons.

of Taiwan. In northern, central, and southern Taiwan, the N-type typhoons produce the largest average hourly rainfall in each portion of Taiwan as compared to those in the other two track types. In particular, the largest average hourly rainfall produced by the N-type typhoons occurs across both central and southern Taiwan, which is more than the hourly rainfall in northern Taiwan, where the storm centers pass by (Fig. 7a). This result is consistent with previous findings (Wu and Kuo 1999) that the cyclonic circulation of the typhoons can interact with the low-level southwesterly flow to strengthen the confluence flow while the convection is further enhanced along the upslope side of the Central Mountain Range of Taiwan, thus leading to the heavy rainfall in central and southern Taiwan. Meanwhile, the smallest average hourly rainfall occurs in eastern Taiwan for the N-type typhoons since it is located to the lee side of the Central Mountain Range as the storm centers pass over northern Taiwan (Wu et al. 2002). As with the results obtained from All-ST, the largest average hourly rainfall of Con-ST produced by the N-type typhoons occurs in central Taiwan with a value of 12.53 mm h^{-1} (Fig. 8). Figure 8 demonstrates that the average rainfall results from Con-ST offer a clear positive bias as compared to the All-ST results in central Taiwan. This is in part due to the fact that the three mountainous rain gauges in Con-ST above 1000-m elevation are all located in central Taiwan (cf. Figs. 1a and 4), thus leading to much higher average hourly rainfall result compared to Con-ST.

To understand the difference in the percentage of stations that measure the rainfall above certain criteria between Con-ST and All-ST, the cumulative frequency (Wu et al. 2002, 2013) of the average hourly rainfall is examined and compared among the three track types (Fig. 9). One common robust feature among the different track types is that the cumulative frequency assessed by data from stations at elevations below 500 m (black lines) is closer to that from stations at all elevations (red lines), while the cumulative frequency assessed by the data from stations above 500 m (mountainous areas) deviates from it. For stations located above 500 m, the cumulative frequency based on the Con-ST dataset is generally higher than that associated with All-ST for the N and C storm types, as well as for all 53 typhoons. In contrast, a higher percentage of the Con-ST data measure the average hourly rainfall below 4 mm h^{-1}, while a smaller percentage of the Con-ST data measure hourly rainfall between 4 and 10 mm h^{-1} (green lines in Fig. 9c). With only 4 conventional stations (out of the total of 21) located above 500 m, the cumulative frequency from the Con-ST dataset in the mountainous areas is likely less representative and biased toward larger rainfall amounts in the N and C types, while stronger (lighter) rainfall events of S type are underestimated (overestimated). Furthermore, from both Con-ST and All-ST the cumulative frequency calculated with data from stations above 500 m is evidently higher in both N and C types as compared to that below 500 m (i.e., the green lines are located well above the red and black lines in Figs. 9a–c). In other words, precipitation induced by typhoons that pass over northern and central Taiwan mostly occurs at higher elevations. This statistical characteristic highlights the importance of topographically forced vertical motions in intensifying rainfall as the N- and C-type typhoons bring strong westerly and/or southwesterly flow that impinges on the mountainous regions of central and southern Taiwan (Wu et al. 2002; Yu and Cheng 2013; Yu and Cheng 2014).

The extreme rainfall amount is shown in Fig. 10 as the accumulated rainfall calculated based on the highest 10% of the accumulated rainfalls during the typhoons. Such extreme rainfall results are underestimated, on average, by 23.3%, 43.5%, and 37.2% in N-, C-, and S-type storms, respectively (Table 4), when only the Con-ST data are used [with only a few exceptions, such as Gladys (1994) and Herb (1996) being the N type, and Wutip (2007) being the C type]. The most significant underestimation occurs in the C type, in which typhoons make landfall in central Taiwan, again implying the critical impact of topography on the extreme rainfall amounts. The added value of the All-ST data in assessing the long-term characteristics or the change in the extreme rainfall amount and the rainfall distribution associated with typhoons and the complicated Taiwan topography are therefore worth noting.

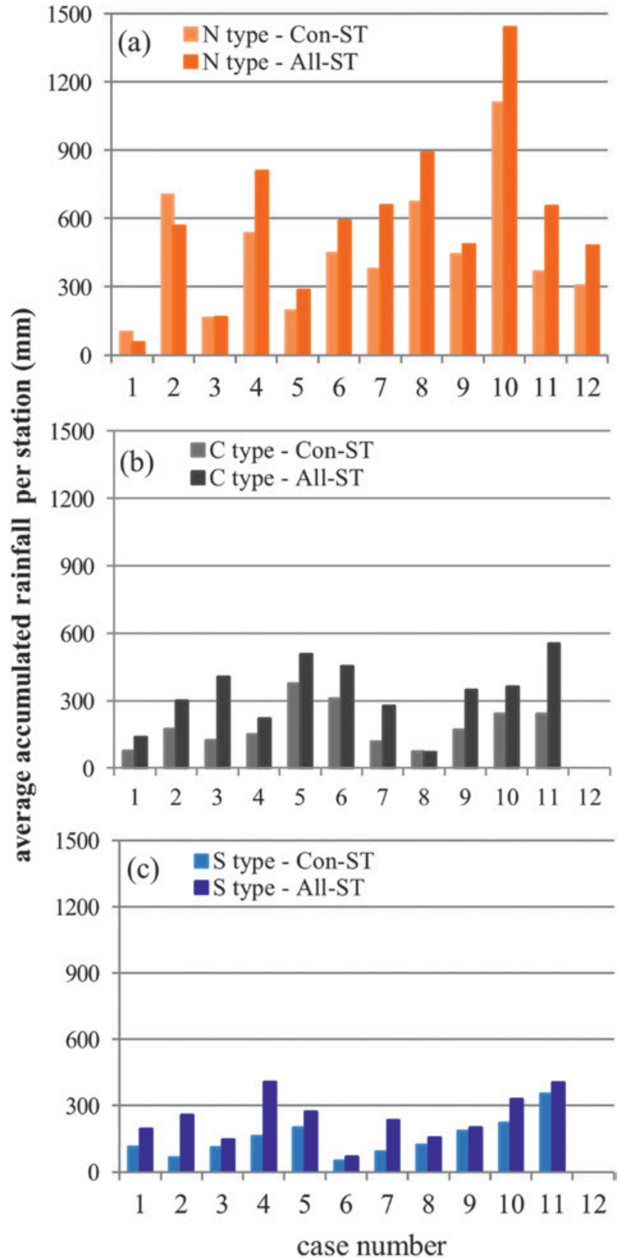


Fig. 10. Average accumulated rainfall per station from the top 10% Con-ST (the lighter color) and All-ST (the darker color) in terms of respective accumulated rainfall during typhoons of (a) N, (b) C, and (c) S types. The names of typhoons corresponding to each case number of each type are indicated in Fig. 7.

SUMMARY. The statistical characteristics of rainfall associated with 53 typhoons from 1993 to 2013 are examined based on the rainfall data from all of the available automatic rain gauges (All-ST) and conventional weather stations (Con-ST) from the CWB of Taiwan. Analyses from both kinds of data indicate a statistically insignificant but slightly increasing trend in the average rainfall amount produced by typhoons during the 21 years of study. In addition, a strong correlation between the average rainfall and the impact duration of a typhoon exists mainly for typhoons with the most pronounced rainfall based on All-ST data. The top 10 typhoons in terms of average rainfall amount from the All-ST dataset are found to pass over northern Taiwan,

Table 4. The extreme rainfall assessed by the stations with the top 10% accumulated rainfall in each corresponding typhoon.

	N type		C type		S type	
Type of typhoon best track (as categorized in Fig. 7)	All-ST	Con-ST	All-ST	Con-ST	All-ST	Con-ST
Avg hourly rainfall per station from the top 10% of stations in terms of respective accumulated rainfall during each typhoon (mm)	589.9	451.9	330.5	186.8	243.0	152.5
Difference (%): (All-ST – Con-ST)/All-ST × 100%	23.3%		43.5%		37.2%	

which leads to larger rainfall over the mountainous regions of central and southwestern Taiwan.

Although the average rainfall amount assessed by Con-ST is statistically similar to that evaluated by data from All-ST, the rainfall data of the Con-ST cannot accurately capture the main features of both precipitation extremes and the rainfall distribution, especially for the mountainous areas. The uneven distribution and very sparse numbers of Con-ST stations over the mountainous regions (only three stations are located above an elevation of 1000 m) are likely to cause such biases in the interpretation of rainfall patterns at higher elevations where major typhoon-induced extreme rainfall tends to occur. Under such circumstance, the rainfall measured by Con-ST over the mountains is relatively overestimated, and the cumulative frequency calculated is less representative. Accordingly, analyses of statistical rainfall features solely based on the Con-ST dataset, as adopted in some previous studies, may be at risk of bias to a certain degree in depicting the long-term statistical characteristics.

The top 10% rain gauge stations for the top 10 typhoons in terms of average rainfall amounts based on the All-ST data are mostly distributed over the mountainous areas. In addition, the cumulative frequency for rain gauge stations above 500 m is higher than that for rain gauge stations below 500 m, indicating the important role of topography in affecting the rainfall distribution and amount. In all, this study highlights the value of the use of the high-density rain gauge data, especially over the mountainous areas, in identifying representative statistics of the typhoon-induced rainfall in Taiwan.

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