Chapter 20

Large Increasing Trend of Tropical Cyclone Rainfall in Taiwan and the Roles of Terrain and Southwest Monsoon

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Since the beginning of the 21st century Taiwan has experienced a dramatic increase in typhoon-related rainfall. Some investigators suggested that they are the manifestation of global warming effects. However, an analysis of typhoon rainfall intensity with respect to typhoon tracks in different landfall phases relative to the Central Mountain Range indicates this is unlikely the cause. Rather, most of the recently observed large increase in typhoon rainfall in the pre-landing and overland phases is the result of slower moving tropical cyclones (TCs) and their tracks relative to the high mountains. A positive feedback mechanism in which the convective heating pattern forced by topography acts to slow down the TC motion, which is most efficient for the slowly-moving northern-track storms. Another factor contributing to increased TC-related rainfall is the interaction between the typhoon circulation and southwest monsoon wind surges. This factor is most important after the typhoon center exits Taiwan and led to the increase of both typhoon rainfall intensity and rainfall amount in the new century. Both the slower TC motion and the increased monsoon interaction are consistent with the recently observed multidecadal trend of intensifying subtropical monsoon and tropical circulations, which is contrary to some theoretical and model projections of global warming. There is also no evidence of a positive feedback between global warming-related water vapor supply and TC intensity in the typhoon rainfall increase, as the number of strong landfalling TCs has decreased significantly since 1960 and the recent heavy rainfall typhoons are all of weak to medium intensity.

1. Introduction

Taiwan, which is situated in one of the main paths of western North Pacific tropical cyclones (TCs), has experienced a series of TCs with extraordinary amount of rainfall since the late 1990s. As of 2012, nine of the top 12 typhoons in total rainfall since hourly rainfall observations started in 1960 have occurred in the 21st century (Table 1). The most extreme case is the record-breaking Typhoon Morakot in 2009 (Ge *et al.* 2010; Lee *et al.* 2011; Chien and Kuo 2011, Wu *et al.* 2011) that caused huge economic and life losses, and became the first natural disaster in Taiwan that directly triggered a change of government. Whether the heavy rainfall of these typhoons is an impact of global warming is the subject of intense debate (Hsu *et al.* 2011; Chang *et al.* 2012). Here we review recent analyses that show it would be a mistake to attribute the apparently large increasing trends of TC rainfall in Taiwan in the recent decades to anthropogenic global warming.

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Table 1. The twelve typhoons in 1960–2011 with total rainfall over Taiwan exceeding 3500 mm during the three phases. The eight since 2004 are highlighted in boldface. (Adapted from Chang *et al.* 2013.)

Rank	Year	Typhoon Name	Rainfall (mm)	Central Weather Bureau Track type
1	**2009**	**Morakot**	**8996**	**CWB 3 (C)**
2	2001	Nari	8108	CWB Special
3	**2008**	**Sinlaku**	**8105**	**CWB 2 (N)**
4	**2005**	**Haitang**	**5589**	**CWB 3 (C)**
5	1996	Herb	4836	CWB 2 (N)
6	1989	Sarah	4655	CWB 3 (C)
7	1960	Shirley	4637	CWB 2 (N)
8	**2007**	**Krosa**	**3936**	**CWB 2 (N)**
9	**2004**	**Mindulle**	**3856**	**CWB 6**
10	**2008**	**Jangmi**	**3800**	**CWB 2 (N)**
11	**2008**	**Kalmaegi**	**3763**	**CWB 2 (N)**
12	**2005**	**Talim**	**3526**	**CWB 3 (C)**

2. The Roles of Terrain and Southwest Monsoon

Chang *et al.* (2013) examined hourly rainfall averaged over 21 stations in Taiwan (Fig. 1a) for the 84 typhoons that made landfall during 1960–2011. They focused on the three main leading track types that directly cross Taiwan whose maximum width is 144 km: Northern type (N, 26 cases, Fig. 1b); Central type (C, 23 cases, Fig. 1c); and Southern type (S, 14 cases, Fig. 1d). The average separation between tracks of the North and Central types and that of the Central and South types are both about 100 km, which is about one half of the length of the Central Mountain Range (CMR). The remaining 21 cases are spread over six less frequent track categories. Examples of the 925 hPa streamlines for each of the three main types are shown in Fig. 1e.

A most important factor on the amount of typhoon rainfall is the terrain effect of the CMR. From Fig. 1, it is clear the circulations of the three track types give rise to different degrees of wind-terrain interactions on the western slope of the CMR. The terrain effect is strongest for the N type and weakest for the S type. The track of each landfall typhoon can be separated into three different phases of its life history: the pre-landing (PR) phase that starts when the typhoon center moves to within 100 km from the nearest coastline point; followed by the overland phase (OL) that starts when the center makes landfall; and the exit phase (EX) that starts when the center exits the coast and ends when the center reaches 100 km away from the nearest coastline.

The first question to be answered is whether the large increase in TC rainfall implies a significant trend of rainfall intensity in the past decades. This can be examining a scatter plot of the accumulated rain amount versus the duration of that typhoon for the different track types during each phase.

Figure 2a shows the plots for the pre-landing case for the N, C, and S track types separately, and for the All track type (all nine track types with a total of 84 cases). When all typhoons are considered, the variation of rainfall intensity is far more scattered with a coefficient of determination $R^2 = 0.31$ than those of the individual N ($R^2 = 0.64$), C ($R^2 = 0.57$), and S ($R^2 = 0.72$) types. This large variation is mainly due to the large differences in the mean rainfall intensities among the three types (Table 2), which is highest for the N type (1960 mm/12 h), followed by the C type (1305 mm/12 h) and the S type (1033 mm/12 h). Prior to landfall, a typhoon situated to the north will have the most exposure of westerly and southwesterly winds against the terrain therefore its rainfall will be the largest, but this exposure will decrease if the typhoon is farther south. These results indicate that when the typhoons are stratified according to these track types, the rainfall intensity during the pre-landing phase changes over a far smaller range over the 52 years than might be inferred from the long-term rainfall time series of all typhoons. So the impression of a significant trend from combining all TCs could be misleading.

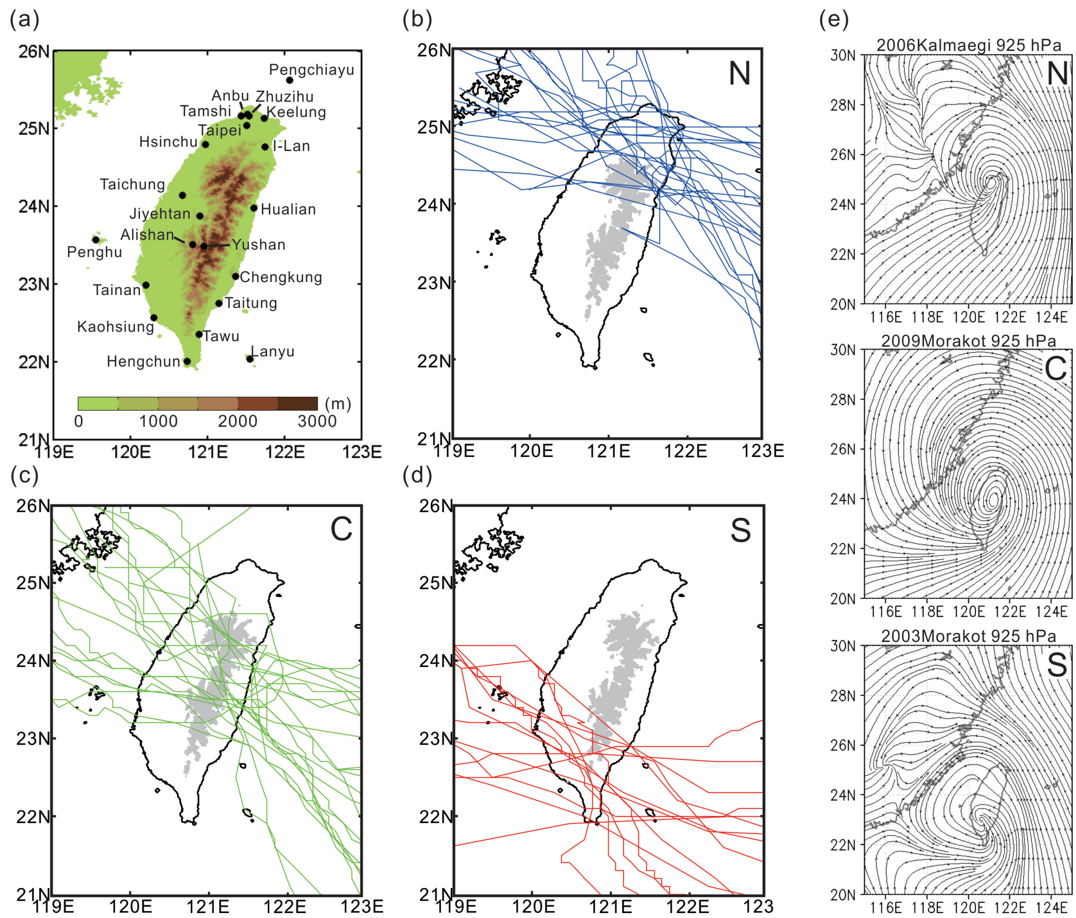

Fig. 1. (a) Taiwan topography and rainfall stations. (b)–(d) The northern (N), central (C) and southern type (S) tracks. (e) Examples of 925 hPa streamlines based on the European Centre for Medium-range Weather Forecasts–TOGA Global Advanced Analysis for the three track types. (Chang *et al.* 2013, courtesy of American Meteorological Society)

Additional insight may be gained when linear fittings are computed for rainfall durations up to six, nine, and 12 hours. During the pre-landing phase the coefficients of determination (Fig. 2b) show that clustering of rainfall intensity over 12 h becomes evident earlier for the N and C types ($R^2 = 0.47$ and 0.49 at 12 h, respectively) than for the S ($R^2 = 0.29$) and All ($R^2 = 0.25$) types. These results suggest that starting from 12 hours after a typhoon is within 100 km of the coast, the wind-terrain interaction has a modulating effect on the rainfall intensity that constrains its variations. However, this modulation effect is delayed for the S type, which is attributed to its smaller wind-terrain interaction. The decrease of the terrain effect to the south is consistent with the decrease of rain intensity from the N type to the S type in Table 2.

During the overland phase, the rainfall intensity (Table 2) again is highest for the N type, followed by the C type, and lowest for the S type. The N and C types have higher intensities than the corresponding rainfall intensities during the pre-landing phase because the maximum wind-terrain interaction occurs while the center is

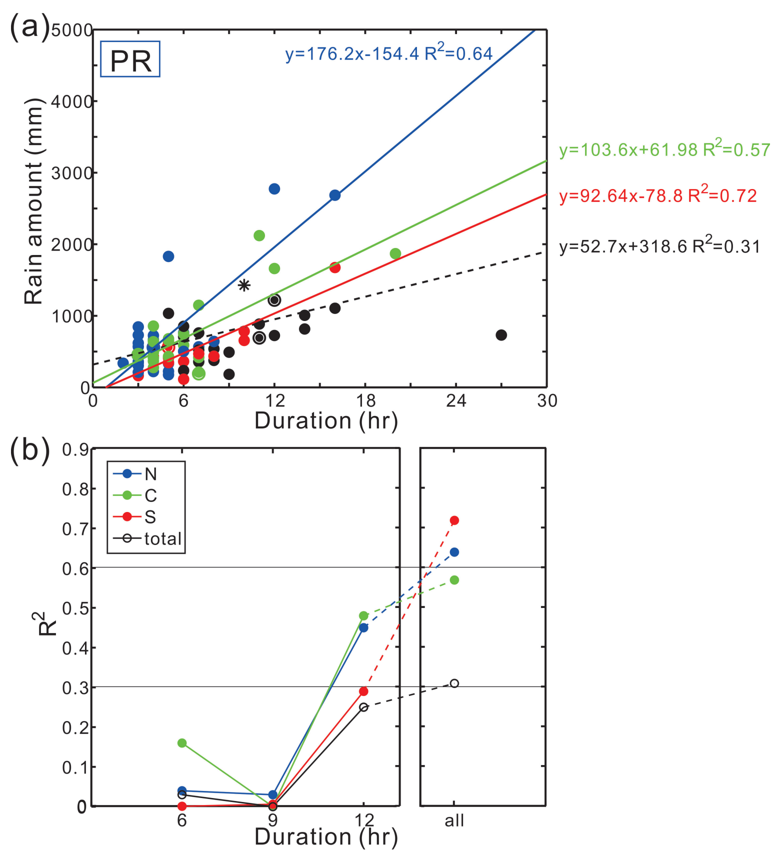

Fig. 2. (a) Rainfall versus duration during the pre-landing phase. Blue, green, and red dots mark the N, C, and S track types, respectively. Black dots mark landfall typhoons of the other six track types. Circled dots indicate two overlapping data points. The star symbol indicates the unusual case Typhoon Nari (2001). The linear fitting lines and formulas for the N, C, S types are colored in blue, green, and red. The linear fitting line and formula for the All type, which includes all 84 typhoons in the nine track types (not just the other six types), are colored in black. (b) The coefficient of determination (R^2). (Chang *et al.* 2013, courtesy of American Meteorological Society)

Table 2. The 12-hour rainfall intensity (mm) for the three track types during the pre-landing (PR), overland (OL) and exit (EX) phases (Chang *et al.* 2013, courtesy of American Meteorological Society.)

Phase track type	PR	OL	EX
N	1960	2132	1458
C	1305	1558	1467
S	1033	812	572

over land, even though the TC intensity typically weakens over land. Figure 1e shows westerly and southwesterly winds interacting with the terrain over the entire western coast of Taiwan for the N type and over the southern half of the coast for the C type. On the other hand, the S type has lower rainfall intensity than for the pre-landing phase due to a smaller wind-terrain interaction. Rain amounts for the All type are substantially distorted by inclusion of the Typhoon Nari (2001), which has a rare southward track over nearly the entire length of the island and a record-breaking rainfall of 6282 mm over 51 hours.

The strong terrain control on rain intensity is also reflected in the fact that all three types as well as the All track type have high R^2 values throughout the overland phase, and the values are the highest among the three phases

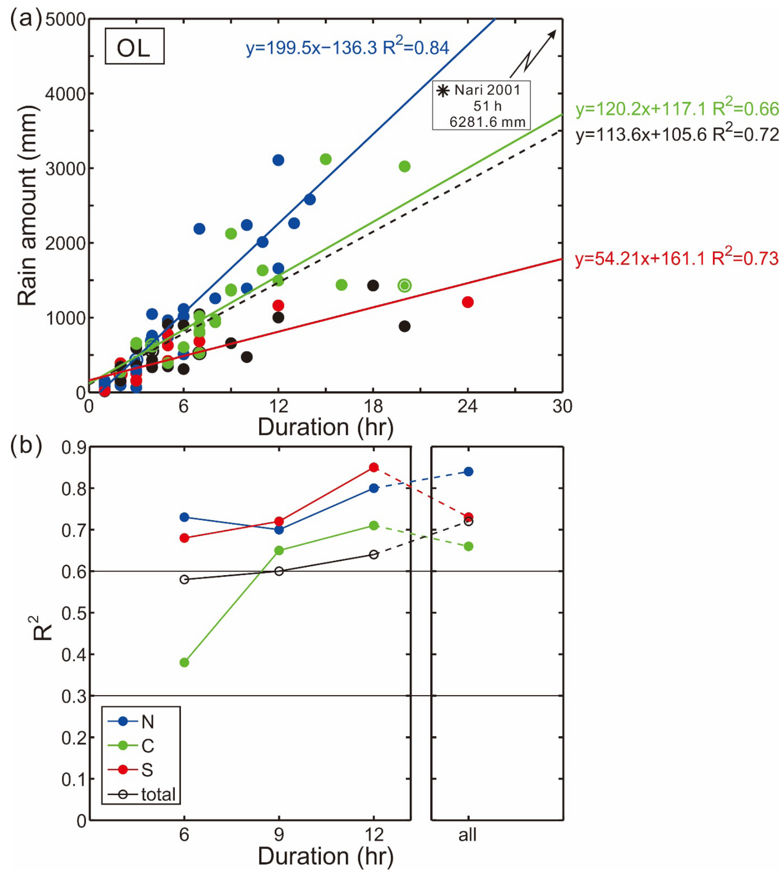

Fig. 3. Same as Fig. 2 except for the overland phase. (Chang *et al.* 2013, courtesy of American Meteorological Society)

for all track types (Fig. 3). It appears that the strong terrain effect and the abundant moisture supply from the South China Sea may have caused the TC rain intensity to approach the maximum limit for each type, so the rain intensity during the overland phase for each type has even less variations than the pre-landing phase.

There are some exception cases where a typhoon has more rainfall during the pre-landing phase than the overland phase (Su *et al.* 2012). Figure 4 shows these PR-rainfall-dominated tracks, which all possess a looping pattern. The looping tracks prolong the duration of TCs and thus produce large rainfall. These tracks tend to occur in the north side of the east coast, suggesting that the topographic stretching effect of flow across the mountain (Kuo *et al.* 2001) or the mountain channeling effect (Jian and Wu 2008) may be important.

For the exit phase (Fig. 5), the modulating effect of the terrain on the rainfall becomes smaller compared to the previous two phases. The largest decrease in the coefficient of determination is for the S type ($R^2 = 0.42$ versus 0.72 for PR and 0.73 for OL), which have the smallest terrain modulation effect on rainfall intensity. These TCs are moving farther away into the South China Sea during the exit phase (Fig. 1d) and thus the terrain effect is even more diminished. As indicated in Table 2, the N and the S types also have significantly lower rainfall intensity in the exit phase than during the other two

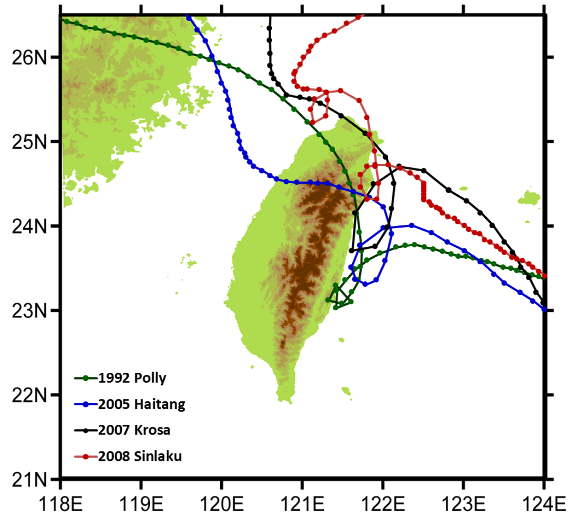

Fig. 4. Tracks of four pre-landing rainfall dominated typhoons from CWB hourly typhoon track data. The dots are the positions every three hours. (Su *et al.* 2012, courtesy of Meteorological Society of Japan)

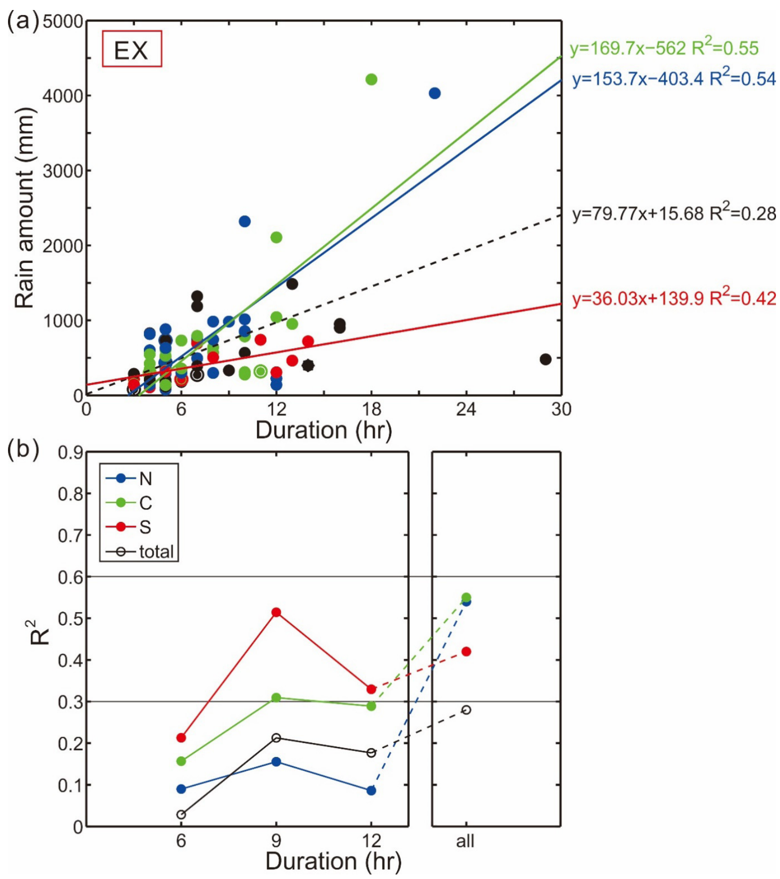

Fig. 5. Same as Fig. 2 except for the exit phase. (Chang *et al.* 2013, courtesy of American Meteorological Society)

phases. On the other hand, the rainfall intensity for the C type during the exit phase is only slightly reduced from the peak value achieved during the overland phase, and it matches the rainfall intensity of the N type. This continued high rainfall intensity for the central track is due to the typhoon center being in the middle of the Taiwan Strait during the exit phase (Fig. 1c). As a result rainfall in the C type typhoons is supported by two mechanisms. On the one hand their circulation still has a robust wind-terrain interaction. On the other hand there is a stronger interaction with the moist southwest monsoon winds originating from the South China Sea that contributes to enhanced wind-terrain interaction. The N type storms receive less such contribution because it moves northwestward away from the South China Sea (Fig. 1a).

A most dramatic example of the effect of the interaction of the southwest monsoon flow with the TC circulation and the terrain is Typhoon Morakot (2009), which led to torrential rainfall in southern Taiwan during the exit phase. Figure 6 shows the 925 hPa water vapor flux and the wind vectors for Typhoon Morakot (2009) during the exit phase. A convergent zone in the Taiwan Strait is caused by the typhoon northwesterly flow and the monsoon southwesterly flow, the origin of the latter can be traced back to the Bay of Bengal.

Table 3 shows the correlations of the typhoon rainfall amount (upper panel), and the rainfall intensity (lower panel), with two moisture flux indexes of the exit phase during the southwest monsoon season (JJA) of 1960–2012. The correlations with the duration of the exit phase are also shown. The indexes, computed from the Japanese 55-year Reanalysis data, are the southwest monsoon water vapor flux (SWF) and the total monsoon water vapor flux (TSWF) at 925 hPa in the region 16.25°N–22.5°N, 110°E–120°E, the domain used by as Pan *et al.* (2013) to cover the upstream inflow of southwest monsoon adequately. The SWF is the average moisture flux over the region during the exit phase and the TSWF is the product of SWF and the exit phase duration. Because of the very moist air over the warm sea surface, the SWF is mainly determined by the wind speed and is not sensitive to either the moisture content or the choice of the depth of the moisture layer within 1000–700 hPa.

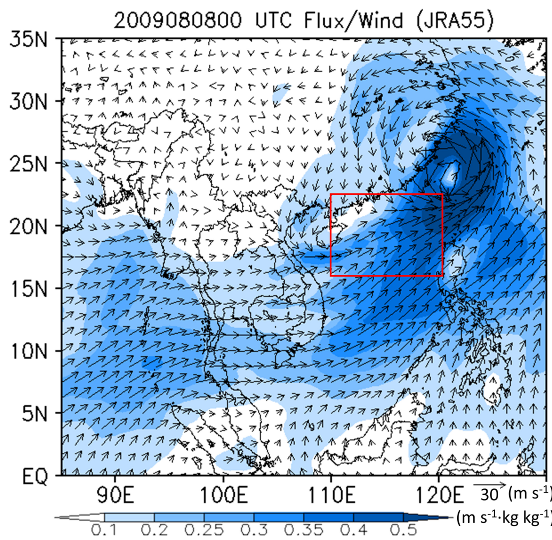

Fig. 6. Typhoon Morakot (2009) 925 hPa average wind vector (vector, $\mathrm{m\,s^{-1}}$) and average water vapor flux (shaded, $\mathrm{m\,s^{-1}}$) during exit period. The small rectangular (16.25–22.5°N, 110.0–120.0°E) is the region for computing the southwest monsoon water vapor flux (SWF).

Table 3. The correlations of the typhoon rainfall amount (upper panel), and the rainfall intensity (lower panel), with the southwest monsoon water vapor flux (SWF), the total monsoon water vapor flux (TSWF), and duration, during the exit phase.

	TSWF	SWF	Duration
Typhoon rainfall (mm)			
All	0.85	0.58	0.57
N + C	0.91	0.69	0.66
N	0.62	0.50	0.14
C	0.97	0.91	0.85
S	0.75	0.74	0.70
Typhoon rainfall intensity (mm $\mathrm{hr^{-1}}$)			
All	0.47	0.62	0.00
N + C	0.55	0.66	0.14
N	0.42	0.59	0.30
C	0.77	0.79	0.60
S	0.00	0.57	0.26

The largest correlation with rainfall amount is from TSWF, with correlations 0.85 for All type, 0.91 for the C and N types together, and 0.97 for the C type. These values are higher than the correlations with SWF or the duration individually, which is not the case in the overland phase (not shown). So while the rainfall amount in the overland phase is controlled mainly by the duration because of the strong terrain effect, the rainfall amount in the exit phase is controlled by both the duration and SWF.

The largest correlation with the rainfall intensity is from SWF, 0.62 for All type, 0.55 for the C and N types together, and a much larger 0.79 correlation for the C type. The larger C type correlation with the SWF than that of the N type is expected as the C type tracks are closer to the South China Sea. The winds in its southwest sector converge with the monsoon wind to produce a strengthened interaction with the CMR. The low SWF correlation for the S type may be due to the fact that being further away from Taiwan the circulation of the S type TCs is less likely to converge with the southwest monsoon wind and move together towards the CMR. Furthermore, the S type is the only track type that does not have duration longer than 14 hours in the exit phase (Fig. 5a).

3. Decadal Changes

Excluding Typhoon Nari (2001), the other eight heavy rainfall typhoons between 2000–2011 all occurred in or after 2004 (boldfaced in Table 1). Table 4 compares the frequencies and durations of typhoons of the three track types before and since 2004. When a year has more than one typhoon of the same type, the average duration is used. Overall, the averaged total number of TCs of all track types making landfall in Taiwan each year increased during recent decades. But this increasing trend in Taiwan does not reflect global or basin scale changes, as it is opposite to the decreasing trends of both the western North Pacific TCs (Lau and Zhou 2012) and TCs affecting the East Asian summer monsoon region (Chang *et al.* 2012) since middle-20th century, and also the century-trend of decreasing number of landfalling typhoons on Taiwan (Lee and Chia 2008).

Table 4. The frequency and duration of the N, C, and S typhoons before and after 2004, and the frequency of the three tracks typhoons before and after 1986. (Adapted from Chang *et al.* 2013.)

Frequency	1960–2003	2004–2011
N	21	5
C	15	8
S	11	3
Duration (hour)		
N	15.9	24.0
C	23.9	23.3
S	21.7	20.0

The bulk of the increase of rainfall since 2004 was due to Types N and C. During the 44 years before 2004, N type typhoons occurred about once every two years, C type typhoons occurred about once every three years, and S type typhoons occurred about once every four years. For all three types, the number of typhoons per year increased after 2004, but the increase is minimum for the N and S types each of which has one extra typhoon over the eight-year period. On the other hand, the C type had a drastic increase from averaging one every three years to one every year, a 300% increase. While the frequency for the N type did not increase much, its average duration increased 51%. Since the N type has the highest rainfall intensity and the C type has the second highest rainfall intensity (and highest intensity during the exit phase), the longer-duration N type typhoons and the more frequent C type typhoons since 2004 are the key reasons for the large increase in rainfall and rainfall intensity. The S type, on the other hand, has the lowest rainfall intensity, and its average duration has decreased by 10%.

The increase in the duration of the N type TCs may be related to a change of the large-scale easterly steering flow. Chu *et al.* (2012) reported a slowing trend between 1959 and 2009 of the steering flow in the subtropical western North Pacific east of Taiwan and the South China Sea. Although this would be consistent with the increase of average duration of typhoons, most of the slowing down in this study was for the N type typhoons among the three leading tracks. The explanation may lie in the location of the maximum terrain interaction, which is in southern Taiwan behind the N type track in which the typhoons move in a prevailing northwestward direction. Hsu *et al.* (2013) used mesoscale model simulations to demonstrate that the topographically locked convection acts to slow down (speed up) the northern (southern) landfall typhoons. A slower steering flow will slow down all three track types, but the effect is largest on the N type due to this topographic locking effect during the pre-landing and overland phases. A slower-moving northern typhoon will have more time to experience a positive feedback mechanism, in the sense more prolonged precipitation and latent heat release in the windward side of the southern Taiwan mountains will result in further speed reductions.

Table 5 shows that although the rainfall amount per typhoon or per year increases substantially from the first half to the second half of the 52 years for all three phases, the average rainfall intensity did not change much during the pre-landing and the overland phases. These results are a strong indication that the effect of the wind-terrain interaction may constrain potential climate changes of typhoon rainfall intensity in Taiwan. That is, long-term trends are small in the pre-landing and overland phases when the typhoon-terrain interaction is strong and important in contributing to the heavy rainfall. However, during the exit phase the rainfall intensity has an increasing trend. This increase cannot be explained by the terrain effect associated with track and duration changes. It also cannot be attributed to an increase in the TC intensity because the number of strong typhoons actually decreased over the 52 years. Su *et al.* (2012) have also shown that Taiwan the amount of rainfall has poor correlation with the TC intensity. The possible implication of this multidecadal increase in rainfall intensity during the exit phase will be discussed in the next section.

4. Discussion and Concluding Remarks

The analysis of the 52-year data shows that typhoon rainfall intensity in Taiwan is strongly regulated by the terrain effects, particularly as the typhoon approaches Taiwan from the east and during the period its center is over land. Because of the strong terrain effect during these two phases, the long-term trend of rainfall intensity is small. On the other hand, there is increase in the typhoon rainfall amount for all phases, and this may be caused by two factors. The first is a change in the TC tracks. The slowdown of the northern track storms and the increase of the frequency of the central track storm both contribute to an increase in rainfall. The second is the strengthening of the southwest monsoon so that the TC circulation-monsoon-terrain interaction effect leads to more rainfall. This

Table 5. The average rainfall amount per TC, rainfall amount per year and rainfall intensity of the three phases during the first (1960–1985) and second half (1986–2011) of the 52-yr period.

	1960–1985 (41 TCs)			1986–2011 (43 TCs)		
	mm TC^{-1}	mm yr^{-1}	mm hr^{-1}	mm TC^{-1}	mm yr^{-1}	mm hr^{-1}
PR	563.1	888.0	112.2	831.9	1375.8	112.1
OL	632.2	1003.2	128.8	1131	1870.5	130.4
EX	496.8	783.4	75.9	749.1	1238.9	92.0

factor contributes significantly to an increasing trend of rainfall intensity during the exit phase. Table 5 also shows a very small effect on the overland phase. An updated analysis including data up to 2015 shows that the increasing trend for the over-land phase (not shown) has continued, suggesting that the strengthening of the southwest monsoon has began to contribute to the increasing rainfall intensity in the over-land phase as well.

Tu *et al.* (2009), Chou *et al.* (2010) and Wang *et al.* (2011) have suggested that changes in western Pacific SST associated with global warming may have caused more typhoons to move northward toward midlatitude East Asia rather than westward to the South China Sea. However, changes in the frequencies among the three track types in this study are unlikely related to this process, because the separation distances between the tracks are only around 100 km. Furthermore, the shift of tracks has been from northern and southern types to the central type, rather than have been biased toward the north, and these three types are all within the East Asia domain in these previous studies.

The largest long-term trend in typhoon rainfall intensity detected was during the exit phase, when the TC circulation interacts strongly with the monsoon southwesterlies while experiencing less terrain effects. Wang *et al.* (2013) found from ERA-40 reanalysis wind data that the Northern Hemisphere subtropical monsoon and the Hadley and Walker circulations have a coherent increasing trend since the late 1970s. Over East Asia the subtropical westerlies penetrates more eastward into the western part of the western North Pacific, about 20 degrees longitude past Taiwan. An increasing subtropical monsoon trend offers a plausible explanation for the increasing trend of exit phase typhoon rainfall, since the typhoon-monsoon interaction will be enhanced. Increased subtropical westerlies over East Asia would also be consistent with the slowing down of the easterly steering flow and typhoon movement during the recent decades.

These results suggest that the main reasons for the increase in typhoon rainfall in Taiwan cannot be attributed to global warming. Using coupled-model experiments, Wang *et al.*'s (2013) attributed the main cause of the strengthening of the monsoon and tropical circulations to natural variations associated with multi-decadal variations of the Mega-El Nino Southern Oscillation (ENSO) and the Atlantic Multidecadal Oscillation (AMO). They concluded that the impacts of the Mega-ENSO and AMO are so strong that they would be larger than the anthropogenic effects during the recent decades that have been predicted in the global warming model studies. The increase in typhoon-related rainfall in Taiwan also cannot be attributed to a positive feedback between global warming-related water vapor supply and typhoon intensity, because on the one hand the rainfall intensity and typhoon intensity is poorly correlated, and also the frequency of strong typhoons affecting Taiwan has actually decreased over the last half century.

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