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

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(Manuscript received 23 July 2012, in final form 7 November 2012)

ABSTRACT

Taiwan, which is in the middle of one of the most active of the western North Pacific Ocean's tropical cyclone (TC) zones, experienced a dramatic increase in typhoon-related rainfall in the beginning of the twenty-first century. This record-breaking increase has led to suggestions that it is the manifestation of the effects of global warming. With rainfall significantly influenced by its steep terrain, Taiwan offers a natural laboratory to study the role that terrain effects may play in the climate change of TC rainfall. Here, it is shown that most of the recently observed large increases in typhoon-related rainfall are the result of slow-moving TCs and the location of their tracks relative to the meso-α-scale terrain. In addition, stronger interaction between the typhoon circulation and southwest monsoon wind surges after the typhoon center moves into the Taiwan Strait may cause a long-term trend of increasing typhoon rainfall intensity, which is not observed before the typhoon center exits Taiwan. The variation in the location of the track cannot be related to the effects of global warming on western North Pacific TC tracks reported in the literature. The weaker steering flow and the stronger monsoon–TC interaction are consistent with the recently discovered 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, 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

The increased water vapor capacity and thermodynamic energy potential associated with global warming has led to considerable interest in its possible impacts on tropical cyclone (TC) trends. Several observational studies (Kim et al. 2006; Lau et al. 2008; Lau and Zhou 2012) suggest an increasing trend in TC rainfall and intensity in various regions. Modeling studies also suggest that TC intensity and precipitation may increase with global warming, although the frequency may decrease and considerable variability exists among different basins (Knutson et al. 2010).

Taiwan, which is situated in one of the main paths of western North Pacific Ocean's TCs, has experienced a series of TCs with extraordinary amounts of rainfall since the late 1990s. In addition to an increase in the number of TCs, 9 of the top 12 typhoons in terms of total rainfall since hourly rainfall observations started in 1960 have occurred in the twenty-first 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; Hendricks et al. 2011), which caused huge economic and life losses and became the first natural disaster in Taiwan that actually triggered a change of government. Whether the heavy rainfall associated with these heavy rainfall typhoons is an impact of global warming, and in particular whether global warming–enhanced water vapor capacity caused a positive interaction between water vapor supply and TC that led to the observed large increasing trend of heavy rainfall, is the subject of intense debate (Hsu et al. 2011; Chang et al. 2012).

The terrain of Taiwan is dominated by the Central Mountain Range, which has a significant effect on TC

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DOI: 10.1175/JCLI-D-12-00463.1

TABLE 1. The 12 typhoons in 1960–2011 with total rainfall over Taiwan exceeding 3500 mm during the three phases, ranked according to total rainfall amount. The eight since 2004 are highlighted in boldface.

Rank	Year	Typhoon name	PR (h)	OL (h)	EX (h)	Total duration (h)	Rainfall (mm)	Type of track
1	**2009**	**Morakot**	**12**	**15**	**18**	**45**	**8996**	**CWB 3 (C)**
2	2001	Nari	10	51	14	75	8108	CWB Special
3	**2008**	**Sinlaku**	**16**	**10**	**22**	**48**	**8105**	**CWB 2 (N)**
4	**2005**	**Haitang**	**11**	**9**	**12**	**32**	**5589**	**CWB 3 (C)**
5	1996	Herb	5	7	4	16	4836	CWB 2 (N)
6	1989	Sarah	5	20	13	38	4655	CWB 3 (C)
7	1960	Shirley	3	11	10	24	4637	CWB 2 (N)
8	**2007**	**Krosa**	**12**	**1**	**10**	**23**	**3936**	**CWB 2 (N)**
9	**2004**	**Mindulle**	**16**	**18**	**7**	**41**	**3856**	**CWB 6**
10	**2008**	**Jangmi**	**4**	**13**	**8**	**25**	**3800**	**CWB 2 (N)**
11	**2008**	**Kalmaegi**	**8**	**10**	**5**	**23**	**3763**	**CWB 2 (N)**
12	**2005**	**Talim**	**4**	**9**	**4**	**17**	**3526**	**CWB 3 (C)**

structure and rainfall (Chang et al. 1993; Ge et al. 2010). In this paper, the role that terrain plays in the TC rainfall is investigated by analyzing typhoons that made landfall during 1960–2011. The objective is to gain insight into the mechanisms involved in the apparent large increase of Taiwan TC rainfall in the recent decades.

2. Data and method

The database includes 84 typhoons that made landfall in Taiwan during 1960–2011. Hourly rainfall records from 21 rain gauge stations (Fig. 1a) are averaged to produce one value each hour. All stations are manually operated with no missing observations. Three of the stations, Taipei, Hsinchu, and Tainan, were relocated in the 1990s. The temporary relocation between 1992 and 1997 of the Taipei station within the same street block and nearly identical physical environment should have negligible effects under typical heavy rainfall situations, so only the relocations of Hsinchu and Tainan may cause concern. To ensure that these relocations do not materially affect the conclusions of this study, we conducted two experiments to estimate the probable range of errors in our results. One experiment used only the other 19 stations for the island-wide average rainfall. The other experiment used a larger set of data, 25 stations that were available since 1977, to compute the island-wide average after 1977 after a validation procedure. The procedure compared the 21- and 25-station averages during an overlapping period of 1977–90, before the relocation of the three stations started. The correlation between the two averages exceeds 0.99 in all cases. The 25-station average is then adjusted to give the same mean averages and standard deviations. For both the 19-station and the mixed 21-/25-station experiments, all numerical values vary by 11% or less from the 21-station results shown in Figs. 2–4 below.

Whereas the Taiwan Central Weather Bureau (CWB) categorizes all typhoons into nine types of tracks, the focus here is on the three leading types that directly cross the island and whose maximum width is 144 km: the northern type (N; CWB category 2; 26 cases; Fig. 1b), central type (C; CWB category 3; 23 cases; Fig. 1c), and southern type (S; CWB category 4; 14 cases; Fig. 1d). While all three tracks have a southeast–northwest orientation, the N and C types have a more northward component than the S type, which has a more westward component. The average separation between tracks of the northern and central types and between those of the central and southern types is about 100 km, which is about one-half of the length of the Central Mountain Range. The remaining 21 cases are spread over six less frequent track categories. Examples of the 925-hPa streamlines for each of the three types based on the European Centre for Medium-Range Weather Forecasts (ECMWF)–Tropical Ocean and Global Atmosphere (TOGA) Global Advanced Analysis are shown in Fig. 1e.

Typhoon tracks analyzed postoperationally are used to estimate the starting and ending times of each typhoon as it passes through three track phases. The first is the prelanding phase (PR) that starts when the typhoon center moves to within 100 km of the nearest coastline point and ends when the center makes landfall. The overland phase (OL) starts at the end of the PR phase and ends when the typhoon center exits the coast. Finally, the exit phase (EX) starts at the end of the OL phase and ends when the typhoon center reaches 100 km away from the nearest coastline. These phases are defined from the postoperational tracks produced by the Typhoon Reanalysis Project using aircraft, satellite, and radar fixes by CWB until 1997, and then continued by National Taiwan University starting in 1998 with satellite and radar fixes. The sums of the hourly rainfall

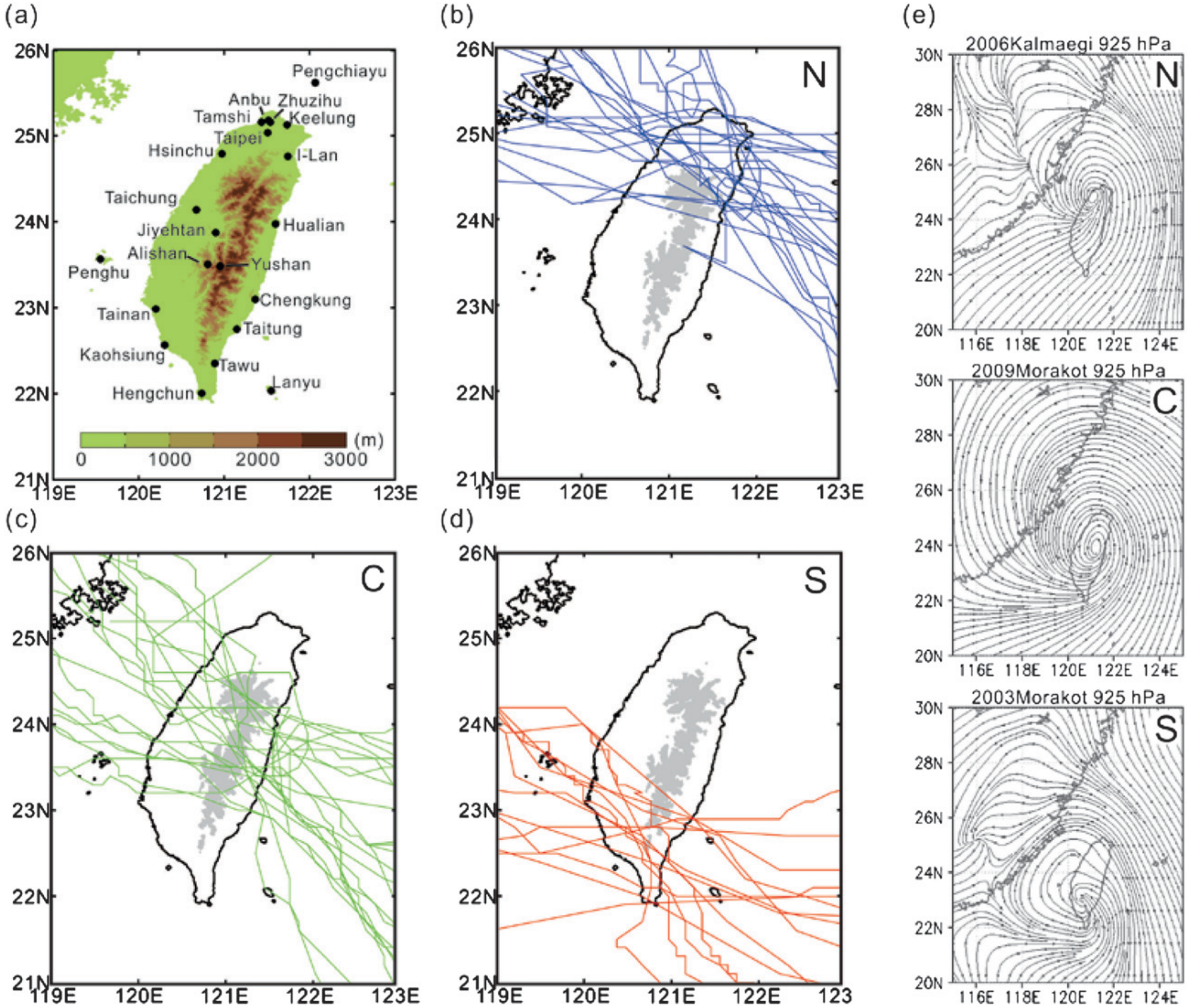

FIG. 1. (a) Taiwan's topography and rainfall stations. (b) The northern (N)-type tracks. (c) The central (C)-type tracks. (d) The southern (S)-type tracks. (e) Examples of 925-hPa streamlines for the three types of tracks: (top) N—Typhoon Kalmaegi (2006), (middle) C—Typhoon Morakot (2009), and (bottom) S—Typhoon Morakot (2003).

during each of the three phases and the total rainfall for each typhoon constitute the database that is used to analyze the variations of rainfall over the 52 years.

Because rainfall within typhoons is asymmetric with respect to the distance from the center and the direction of movement, different tracks may lead to different rain intensities at different locations on the island. However, the terrain's influence is so dominant in Taiwan that this effect is secondary. Chang et al. (1993) have shown that the detailed horizontal structure of typhoons based on the surface station network over Taiwan depends mainly on the center's location and has almost no relationship with the track and movement direction. This is also the conclusion of CWB operational forecasters whose empirical rainfall forecast model is entirely based on the center location and size of a typhoon (Dr. T.-C. Yeh, CWB, 2010, personal communication).

3. Rainfall intensities for the prelanding, overland, and exit phases

A scatterplot of the accumulated rain amount versus the duration of the corresponding typhoon is shown in Fig. 2a for the prelanding phase. The linear fits are separately computed for the N, C, and S types and the All type (all nine types of tracks with a total of 84 cases). When all typhoons are considered, the variation of rainfall intensity is far more scattered (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. All

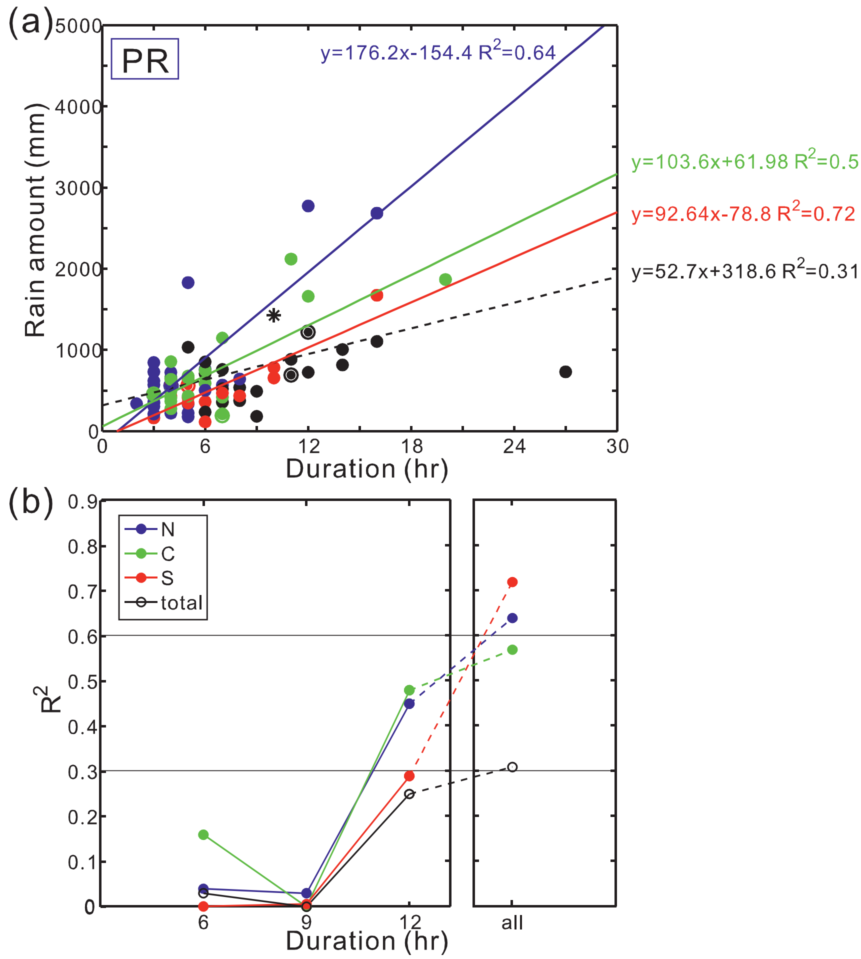

FIG. 2. (a) Rainfall amount vs duration during PR. Blue, green, and red dots mark typhoons of N-, C-, and S-type tracks, respectively. Black dots mark typhoons of the other six types of tracks that made landfall in Taiwan during 1960–2011. Circled dots indicate two overlapping data points (i.e., having the same rainfall amount and duration). The asterisk indicates Typhoon Nari (2001), an unusual case that broke the record of overland duration. The linear fitting lines and equations for the N, C, and S types are blue, green, and red, respectively. The linear fitting line and equation for all 84 typhoons in the nine types of tracks (not just the other six types) are black. (b) The coefficient of determination (i.e., R^2) for typhoons with prelanding durations up to 6, 9, and 12 h, and all cases.

coefficients pass the 99% significance level with the Student's *t* test. This large variation is mainly caused by the large differences in the mean rainfall intensities among the three types (Table 2, column 1), which is highest for the N [1960 mm $(12\ \mathrm{h})^{-1}$], followed by the C [1305 mm $(12\ \mathrm{h})^{-1}$] and the S type [1033 mm $(12\ \mathrm{h})^{-1}$]. These results indicate that when the typhoons are stratified according to these types of tracks, the rainfall intensity during the prelanding 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.

These differences among the types of tracks can be explained by the interaction of the TC circulation with the terrain (Fig. 1). During the most active period of the typhoon season (June–September), Taiwan is under the influence of the East Asian summer monsoon (EASM) so the quadrant of the TC with southwesterly winds will have an enhanced moisture flux. The moisture flux convergence resulting from interaction between these southwesterly winds and the mountain range produces more rainfall and mesoscale convective systems than do the winds in other quadrants. Prior to landfall, a typhoon situated to the north will have the most exposure of westerly and southwesterly winds against the terrain, but this exposure will be decreased if the typhoon is farther south.

Within each type of track, linear fittings are also computed for all typhoons with rainfall durations up to 6, 9, and 12 h. During the prelanding phase, the

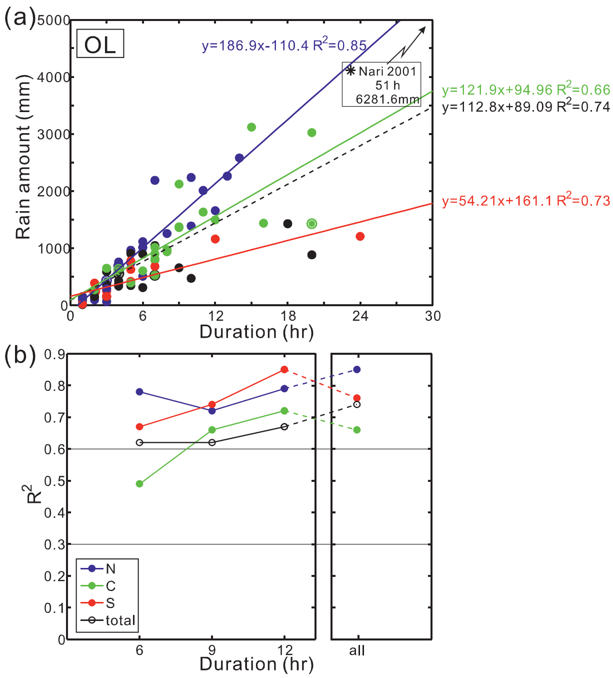

FIG. 3. As in Fig. 2, but for OL.

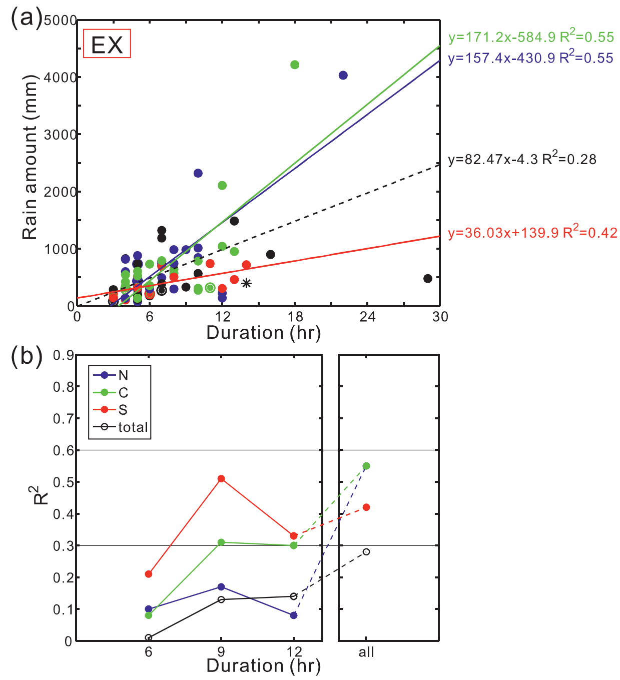

FIG. 4. As in Fig. 2, but for EX.

coefficients of determination (Fig. 2b) demonstrate 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; significance level 99%) than for the S (R^2 = 0.29; significance level 95%) and All (R^2 = 0.25; significance level 99%) types. These results suggest that starting from 12 h after a typhoon is within 100 km of the coast, the wind–terrain interaction has a modulating effect on rainfall intensity that constrains its variations. However, this modulation effect is delayed for a typhoon of the S-type track, which is attributed to the smaller wind–terrain interaction.

For the overland phase (Fig. 3), the rainfall intensities for the three types of tracks are all clustered within tight ranges starting with the 6-h duration. This short duration is consistent with the expectation that the largest terrain effect should be in this phase because the typhoon centers are over land. This maximum terrain effect regulating the TC rainfall intensity is also verified by the fact that the final coefficients of determination are the highest among the three phases for every type of track, and particularly the All-type track with a value of 0.74 that is much larger than the corresponding values of around 0.3 during the prelanding and exit phases.

During the overland phase, the rainfall intensity (Table 2, column 2) again is highest for the N [2132 mm $(12\ \mathrm{h})^{-1}$], followed by the C [1558 mm $(12\ \mathrm{h})^{-1}$], and then the S type [812 mm $(12\ \mathrm{h})^{-1}$]. The N and C types have higher intensities than the corresponding rainfall intensities during the prelanding phase because the maximum wind–terrain interaction occurs while the center is over land, even though the TC intensity typically weakens over land. The larger rainfall intensities are also consistent with the streamflow in Fig. 1e, with westerly and southwesterly winds interacting with terrain over the entire western coast of Taiwan for the N type and over the southern half of the coast for the C type. The wind–terrain interaction is the smallest for the S type, which actually has lower rainfall intensity over land than for the prelanding phase. Rain amounts for the All type are substantially distorted by inclusion of the unusual Typhoon Nari (2001), which produced a record-breaking 6282 mm rainfall in 51 h as it moved southward over nearly the entire length of the mountainous island.

For the exit phase (Fig. 4), the modulating effect of the terrain on the rainfall becomes smaller relative 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). The S-type typhoons, which have the

TABLE 2. The 12-h rainfall intensity for the three types of tracks during the three phases.

Type of track	PR (mm)	OL (mm)	EX (mm)
N	1960	2132	1458
C	1305	1558	1467
S	1033	812	572

smallest terrain modulation effect on rainfall intensity, 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 S types also have significantly lower rainfall intensity during the exit phase [1458 and 572 mm $(12\ h)^{-1}$, respectively] than the other two phases. The rainfall intensity for the C type [1467 mm $(12\ h)^{-1}$] is only slightly reduced from the peak value during the overland phase, and matches the rainfall intensity of the N type. This continued high rainfall intensity for the central track is caused by the typhoon center being in the middle of the Taiwan Strait during the exit phase (Fig. 1c). As a result the C-type typhoon circulation still has a robust wind–terrain interaction, and also has a stronger interaction with the southwest monsoon winds originating from the South China Sea than does the N type, which is moving in a northwestward direction away from the South China Sea (Fig. 1a).

4. Decadal changes

The above results suggest that when stratified according to the type of track the rainfall intensity of typhoons crossing Taiwan has not changed greatly since 1960, especially during the prelanding and over land phases when the scattering for each of the leading types of tracks is quite small as indicated by coefficients of determination around or larger than 0.6. This suggests that the possibility that the recent increase in typhoon rainfall may be mainly caused by two factors: 1) a slowdown of the typhoon's movement so more rainfall is produced from the longer duration over Taiwan, and 2) a shift in the TC tracks such that the TC circulation–terrain effect leads to more rainfall. For example, the slow translation speed of Typhoon Morakot (2009) has been reported as an important factor for its record-breaking rainfall (Lee et al. 2011). Indeed, eight of the nine heavy rainfall typhoons in the twenty-first century were slow-moving storms with a total duration ranging from slightly above to more than double the 22-h average for all 84 typhoons (Table 1). Among these 9 typhoons, 7 are of either the N- or C-type tracks, and none was the S type. The two others are of less frequent types of tracks with very long durations, including Typhoon Nari (2001) that produced the second highest total rainfall. Typhoon Nari is considered to be an exceptional case because of its extraordinarily slow and very rare southward movement that lasted 51 h over land, which is more than double the duration of the second longest one in Table 1—Typhoon Sarah of 1989, which was a C-type track that lasted 20 h over land.

Excluding Typhoon Nari (2001), the other eight heavy rainfall typhoons in the twenty-first century all occurred

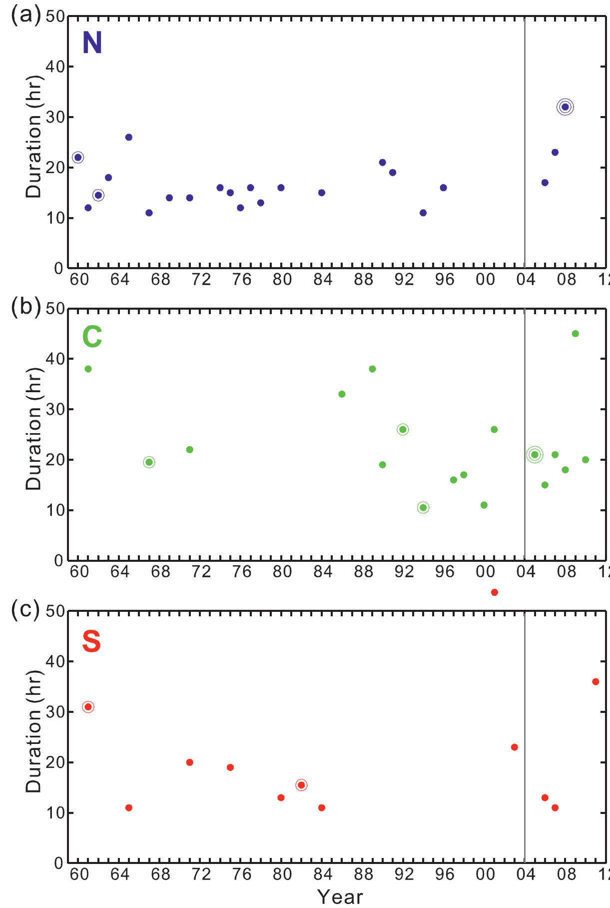

FIG. 5. Time series of the average duration of typhoons from 1960 to 2011 for the (a) northern (N)-, (b) central (C)-, and (c) southern (S)-type typhoon tracks. The thin vertical line inside each panel denotes year 2004. A dot with one circle indicates two typhoons and a dot with two circles indicate three typhoons.

during or after 2004 (in boldface, Table 1). The time series of typhoon occurrences and durations for the N-, C-, and S-type tracks are shown in Fig. 5, with the 52-yr period divided at 2004. The frequencies, both absolute and relative (as a percentage of the N, C, and S total), and durations of typhoons of the three types of tracks before and since 2004 are also compared in Table 3. When a year has more than one typhoon of the same type, the average duration is used. For all three types, the number of typhoons per year increased after 2004, with the C type having the largest increase. As a result, the total number of TCs of all-type tracks making landfall in Taiwan also 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 EASM region (Chang et al. 2012) since the mid-twentieth century,

TABLE 3. The frequency (number of typhoons with the percentage of the total in parentheses) and duration (h) of the three types of tracks before and after 2004.

	1960–2003	2004–11
Frequency		
N	21 (44.6%)	5 (31.3%)
C	15 (31.9%)	8 (50.0%)
S	11 (23.4%)	3 (18.8%)
Duration		
N	15.9	24.0
C	23.9	23.3
S	21.7	20.0

and also the century trend of decreasing number of landfalling typhoons on Taiwan (Lee and Chia 2008).

For the N-type track, which has the highest rainfall intensity overall, the relative frequency with respect to the total of the three leading type tracks has decreased by 30%, but this is more than compensated by an increase of duration by 51%. For the C type, which has the second highest rainfall intensity overall, the duration has been nearly unchanged, but the relative frequency increased by 57%. The C type produces substantially more intense rainfall than the S type, especially during the exit phase when the C-type rainfall intensity is the highest among all three types and is almost 3 times that of the S type. The S type has the lowest rainfall intensity, and its relative frequency and duration have both decreased by 20% and 10%, respectively.

The conclusion from these statistics is that the large increase of typhoon rainfall intensity since 2004 is related to changes in both track distribution and duration. The increase is attributed mainly to an increase in the relative frequency of the C-type typhoons, an increase in the duration of the N-type typhoons, and a decrease in both the relative frequency and duration of the S-type typhoons.

To examine possible decadal changes, the time series of typhoon rainfall intensity for the three phases for all 84 cases is plotted in Fig. 6. When a season has multiple TCs, the average rainfall intensity is used for that year. If only the weak-to-medium–intensity TCs (categories 1–3) are included (Fig. 6a), the PR and OL series have interannual and interdecadal variations, but a 52-yr trend is not obvious. However, it is quite conspicuous that the EX time series has an increasing trend in addition to the interannual and decadal variations. This trend is verified by comparing the averages of each year's rainfall intensity between the first 26 years (1960–85) and the last 26 years (1986–2011). While the changes in the average rainfall intensity for the prelanding phase (from 112.5 to 110.1 mm h^{-1}) and the overland phase (from 128.7 to 129.0 mm h^{-1}) are both negligible, the exit phase has a relatively large increase from 78.2 to 92.9 mm h^{-1} (19%), although it is far below the 95% significance level because of the large interannual and decadal variations. It is interesting to note that this increasing trend is entirely related to typhoons that occurred in the last decade.[1] If all TCs (categories 1–5) are included (Fig. 6b), the results are very similar.

These rainfall statistics are a strong indication that the effect of the wind–terrain interaction may constrain the potential influence of climate change on typhoon rainfall intensity in Taiwan. That is, very small long-term trends are detected in the prelanding and overland phases when the typhoon–terrain interaction is strong and are more important in contributing to the heavy rainfall. The trend is positive in the exit phase after the typhoon leaves Taiwan. The Taiwan Strait and regions southwest of Taiwan are in the path of major southwesterly surges during the EASM. These moist monsoon surges are a primary mechanism bringing heavy rainfall to Taiwan (Johnson 2006). The surges may be especially strengthened when interacting with a TC, and the resulting heavy rainfall often leads to major floods as in the case of Typhoon Morakot (2009) (Wu et al. 2011; Chien and Kuo 2011). In the exit phase, the western and southwestern sides of the typhoon circulation come into closer contact with the southwest monsoon winds. Because the terrain effect may not be as strong, it is possible that increased interaction with the monsoon and the resultant additional moisture supply may play a role in the positive trend of typhoon rainfall intensity during the exit phase.

This positive trend for the exit phase cannot be attributed to an increase in the TC intensity (Fig. 6). The exit-phase trend when strong typhoons (categories 4–5) are included is slightly larger than when they are excluded (21% versus 19% without strong typhoons), but the number of strong typhoons actually decreased over the 52 years. This may seem counterintuitive because it is generally accepted that strong TCs produce more intense rainfall. It is possible that this result may be influenced by the 21-station rainfall average that covers an area larger than the scale of the radius of maximum winds, while the heaviest rainfall that may be related to TC intensity occurs on this scale. It is also possible that the strong terrain effect weakens the relationship between rainfall intensity and TC intensity.

[1] The increasing rate nearly doubles if the averages of the two 26-yr periods are performed on the rainfall intensity of individual typhoons rather than each year's average rainfall intensity, because multiple typhoons occurred in the same year in the early part of the first period and the later part of the second period. But the rate is still statistically insignificant.

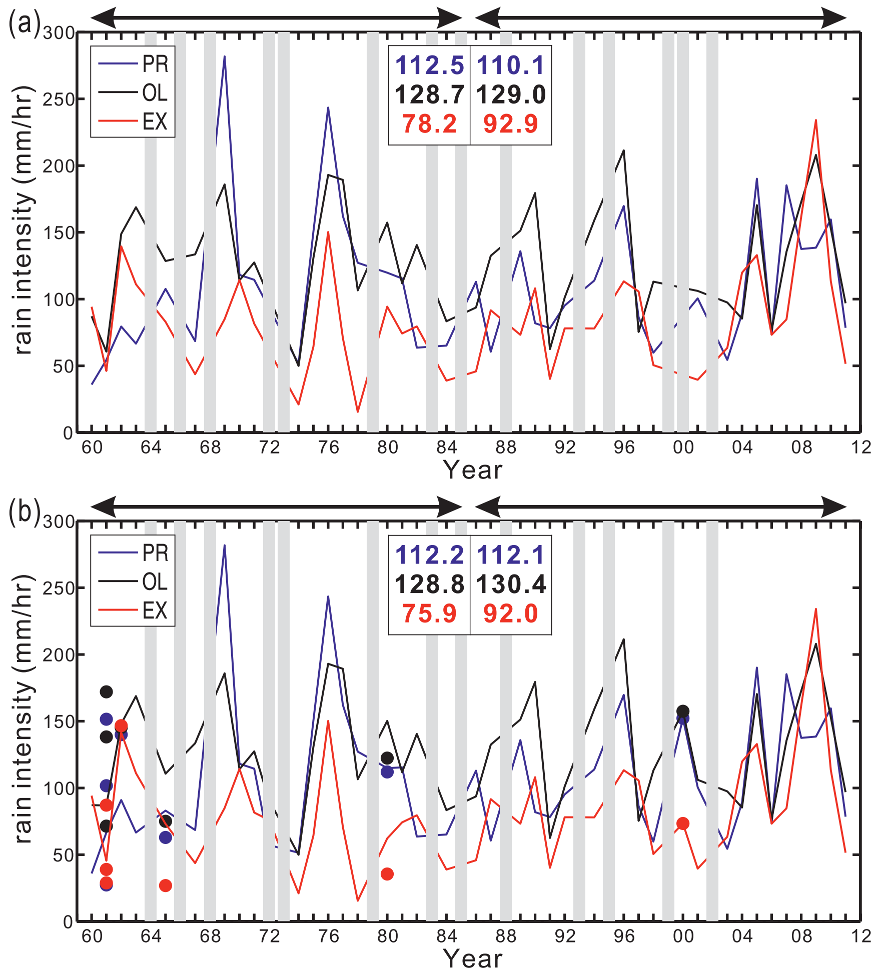

FIG. 6. (a) Time series of rainfall intensity from 1960 to 2011 for the PR (blue), OL (black), and EX (red) phases for weak- and medium-intensity (category 1–3) typhoons. Gray vertical columns indicate years with no typhoons of the three leading types of tracks. The table inside the panel lists the average yearly rainfall intensities of the three phases during the (left) first (1960–85) and (right) second half (1986–2011) of the 52-yr period. The two subperiods are indicated by double ended arrows above the panel. (b) As in (a), but for strong-type (categories 4 and 5) typhoons. The rainfall intensity of each strong typhoon is indicated by the respective colored dots.

5. Discussion and concluding remarks

This analysis has demonstrated that typhoon rainfall intensity in Taiwan is strongly regulated by 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 constraints during these two phases, the long-term trend of rainfall intensity is negligible. Thus, the large increases in typhoon rainfall, and the apparent increase in rainfall intensity but not in TC intensity, during recent decades are attributed to the changes in duration and relative track frequencies of recent typhoons that have crossed the island. The relative frequency of the northern track typhoons, which have the most extensive wind–terrain interaction and largest rainfall intensity, has been slightly reduced but the duration has been increased. The relative frequency of the central track typhoons, which also have extensive wind–terrain interaction and have large rainfall intensity particularly in the exit phase, has been increased substantially. Typhoons on the southern track have the smallest wind–terrain interaction and rainfall intensity. Both their relative frequency and duration have been decreased.

Tu et al. (2009), Chou et al. (2010), and Wang et al. (2011) have suggested that changes in western Pacific sea surface temperatures associated with global warming may have caused more typhoons to move in a northward direction toward midlatitude East Asia rather than westward to the South China Sea. However, changes in the relative frequencies among the three types of tracks in this study are unlikely to be related to global warming, 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 being biased toward the north, and these three types are all within the East Asian domain discussed by Tu et al. (2009), Chou et al. (2010), and Wang et al. (2011).

The increase in duration 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 in both the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis and the 40-yr ECMWF Re-Analysis (ERA-40). Although this would be consistent with the increase of the 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) landfalling typhoons. A slower steering flow will slow down all three types of tracks, but the effect may be largest on the N type because of this topographic locking effect. A slower-moving northern typhoon will have more time to experience a positive feedback mechanism, in the sense that more prolonged precipitation and latent heat release in the windward side of the southern Taiwan mountains will result in further speed reductions. A similar effect involving the interaction of the Typhoon Morakot (2009) circulation with the southwest monsoon winds near southwestern Taiwan was shown by C.-C. Wang et al. (2012) to contribute to a slow translation speed on a C-type track.

The only long-term trend in typhoon rainfall intensity detected between the first and second halves of the 1960–2011 study period was during the exit phase, when the TC circulation interacts strongly with the monsoon's southwesterlies while experiencing less terrain effects. B. Wang et al. (2012; 2012, manuscript submitted to *Climate Dyn.*) found from satellite rainfall and ERA-40 wind data that the Northern Hemisphere subtropical monsoon and the Hadley and Walker circulations have had a coherent increasing trend since the late 1970s. Over East Asia the subtropical westerlies penetrate farther eastward into the western part of the western North Pacific, about 20° longitude past Taiwan. An increasing subtropical monsoon trend offers a plausible explanation for the increasing trend of exit-phase typhoon rainfall, because 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.

The results of B. Wang et al. (2012; 2012, manuscript submitted to *Climate Dyn.*) are contradictory to theoretical and model studies of global warming effects (Held and Soden 2006; Vecchi et al. 2006), which project a weakening of monsoon and tropical circulations. Using coupled model experiments, they attributed the main cause of the strengthening of monsoon and tropical circulations to natural variations associated with multidecadal variations of the Mega-El Niño–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 are larger than the anthropogenic effects during the recent decades that have been predicted in the global warming model studies.

While the possibility that increased water vapor capacity from global warming may have some role in the recently large increase of typhoon rainfall in Taiwan cannot be ruled out, we are not aware of any research on global warming effects that can explain the changes in typhoon tracks and durations observed in this study. The slowdown of the steering flow and the increased interaction with southwest monsoon winds may even be contrary to some modeling studies of the effects of global warming. It is also clear that the recent increase in typhoon-related rainfall in Taiwan cannot be attributed to a positive feedback between global warming–related water vapor supply and typhoon intensity. That is, the frequency of strong typhoons affecting Taiwan has actually decreased from 5 in the first 26 years of this study to just 1 during the last 26 years. Furthermore, no strong typhoon has made landfall in Taiwan since the beginning of the twenty-first century, and yet 9 of the 12 largest rainfall amounts associated with typhoons have occurred during this period.

Acknowledgments. This research is sponsored by National Science Council (NSC), Taipei, Taiwan, under Grants NSC 101-2111-M-002-010. We thank Dr. Yongui Lei for discussions of the statistical tests and Professor Russ Elsberry for reading the manuscript. Three anonymous reviewers made valuable suggestions to improve the clarity of the analysis and description.

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