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Trends in precipitation extremes during the typhoon season in Taiwan over the last 60 years

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Abstract

The trends of four common climate change indices related to extreme precipitation events during the typhoon season (July–October) from 21 stations in Taiwan are investigated using a robust nonparametric method. Upward trends in precipitation intensity and 5-day total precipitation amounts prevail from 1950 to 2010. Longer drought duration is also noted, in southern Taiwan in particular. Daily precipitation during the typhoon season is further partitioned into typhoon and monsoon rainfall. Precipitation intensity induced by typhoons and monsoon systems has both increased over the last 60 years; these two components collectively contribute to strong upward trend in precipitation intensity.

Keywords: **trends; precipitation extremes; typhoon season; Taiwan**

1. Introduction

There is a growing interest in knowing changes in precipitation and temperature extremes as the climate has become warmer. The changes in extreme events, such as heavy precipitation and associated floods, heat waves, and hurricanes (or typhoons), have attracted a lot of attention because of their devastating consequences on society and economics. Taiwan (Figure 1) stands out prominently among the tropical regions as an area in which precipitation extremes have undergone a dramatic change over the last 50 years or so (e.g. Liu *et al.*, 2009). On average, four or five typhoons pass through the vicinity of Taiwan every year with various degrees of precipitation-related damage (Tu *et al.*, 2009). One recent extreme event is the August 2009 typhoon Morakot which wreaked havoc in Taiwan. This storm produced torrential rain, with the 3-day accumulated rainfall exceeding 2000 mm at many gages in southern Taiwan. Tu *et al.* (2009) also noted an abrupt increase in the typhoon counts near Taiwan and in the East China Sea since 2000. Recently, based on summer rainfall (June–August) and the linear regression method, Chang *et al.* (2012) noted an increasing trend in typhoon rainfall intensity in Taiwan since 1958.

To make a standard of comparison among different regions of the world, a suite of climate change indices was advocated by the Climate Variability and Predictability (CLIVAR) program, a component of the World Climate Research Program under the World Meteorological Organization (WMO). Because climate change indices defined by CLIVAR are widely accepted tools, it is of considerable interest to investigate changes in precipitation extremes in Taiwan using the CLIVAR indices so that the results can be meaningfully compared with other parts of the world (e.g. Frich *et al.*, 2002; Alexander *et al.*, 2006). Unlike Liu *et al.* (2009) and Chang *et al.* (2012) who used different extreme indices, the trends of four commonly used CLIVAR precipitation indices in Taiwan are investigated here using daily observational records since 1950. Instead of the three summer months (June–August), we focus on the typhoon season (July through October) when tropical cyclones are most active in the western North Pacific (Chia and Ropelewski, 2002). Moreover, a robust nonparametric method is used to test for trends because the

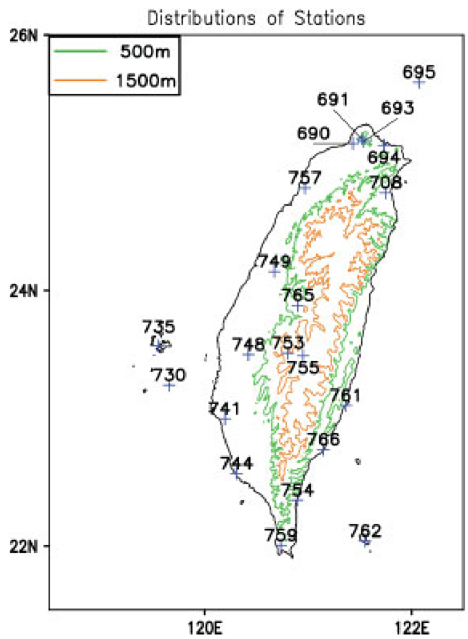

Figure 1. Orientation map for Taiwan. Stations are indicated with numbered site codes that are listed in Table 1.

Table I. Station numbers, names, elevation, and the number of years used. Trend values for SDII and R50 during the typhoon season are also shown.

Site_code	Name of station	Height (m)	Available years	Trend for SDII (mm day^{-1} year^{-1})	Trend for R50 (days year^{-1})
690	Danshui	19	59	0.12[a]	0.03[b]
691	Anbu	825.8	61	0.19[a]	0.05
693	Zhuzihu	607.1	61	0.12	0
694	Keelung	26.7	61	0.08[b]	0.03
695	Penjiayu	101.7	61	0.19[a]	0[b]
708	Ilan	7.2	56	0.1	0
730	Donjidao	43	46	0.25[a]	0.03[a]
735	Penghu	10.7	54	0.08	0
741	Tainan	40.8	48	0.12	0
744	Kaoshiung	2.3	60	0.14[a]	0.02
748	Chiayi	26.9	41	0.28[a]	0.07[b]
749	Taichung	84.04	46	0.03	0.03
753	Alishan	2413.4	61	0.09	0
754	Dawu	8.1	52	0.12	0
755	Yushan	3844.8	59	0.11	0
759	Hengchun	22.1	52	0.07	0
761	Cheng-kung	33.5	52	0.05	0.02
762	Lanyu	324	59	0.05	0
765	Sun Moon Lake	1017.5	60	0.06	0
766	Taitung	9	57	0.13[a]	0.03
757	Hsinchu	32.8	41	0.1	0

[a] 5% significant level.
[b] 10% significant level.

linear regression method is subject to certain assumptions. This paper is organized as follows: Sections 2 and 3 describe the dataset and climate change indices, respectively; Section 4 discusses the method and results are presented in Section 5; and Section 6 provides a summary and discussion.

2. Data

Long-term daily rainfall data from the Central Weather Bureau are available; however, some stations have missing observations or changing locations over time. In order to maintain data quality, some criteria are applied to the climate change indices. This is in reference to those adopted in Griffiths and Bradley (2007), Chu *et al.* (2010a), and others. Table I lists the station names, their elevations, and data length. There are 21 stations with data available for at least 41 years up to 2010, and 7 out of these 21stations even have at least 60 years of data.

Tropical cyclone (TC) best track data archived by the Joint Typhoon Warning Center in Honolulu, Hawaii are used to locate a TC center in the vicinity of Taiwan for all 6-hourly intervals. Here, we consider the maximum surface wind over 34 kt as a TC case. TC thus includes both tropical storms and typhoons.

3. Climate change indices

Four of the 27 indices defined by the WMO/CLIVAR program are used here. The first index is the simple daily intensity index (SDII), which is the average wet-day precipitation intensity. A wet day is taken as a day with daily precipitation $\geq$1 mm. The unit of SDII is millimeter per day. For simplicity, the SDII is also called the precipitation intensity. The R50 is the annual number of days with precipitation $\geq$50 mm and the unit is days. This definition is consistent with the Central Weather Bureau in Taiwan for heavy rainfall events. R5d is the annual maximum consecutive 5-day precipitation amounts, with units in mm, and describes the magnitude of intense precipitation events. The fourth index is the annual maximum number of consecutive dry days (CDD). The CDD defines the duration of excessive dryness, and the unit is days.

4. Methods: nonparametric Mann–Kendall test and Sen's method

The trends of the indices are estimated by the nonparametric rank-based Mann–Kendall test and Sen's method. The former tests whether the trend is increasing or decreasing and estimates the significance of the trend, whereas the latter quantifies the slope of this trend (Chu *et al.*, 2010a; Garza *et al.*, 2012). The slopes of all data pairs are calculated and the median of these slopes is the Sen's estimator of slope. The advantage of these two methods is that missing values are allowed and the data need not conform to any particular parametric distribution. Furthermore, Sen's method is robust against skewed distributions and outliers.

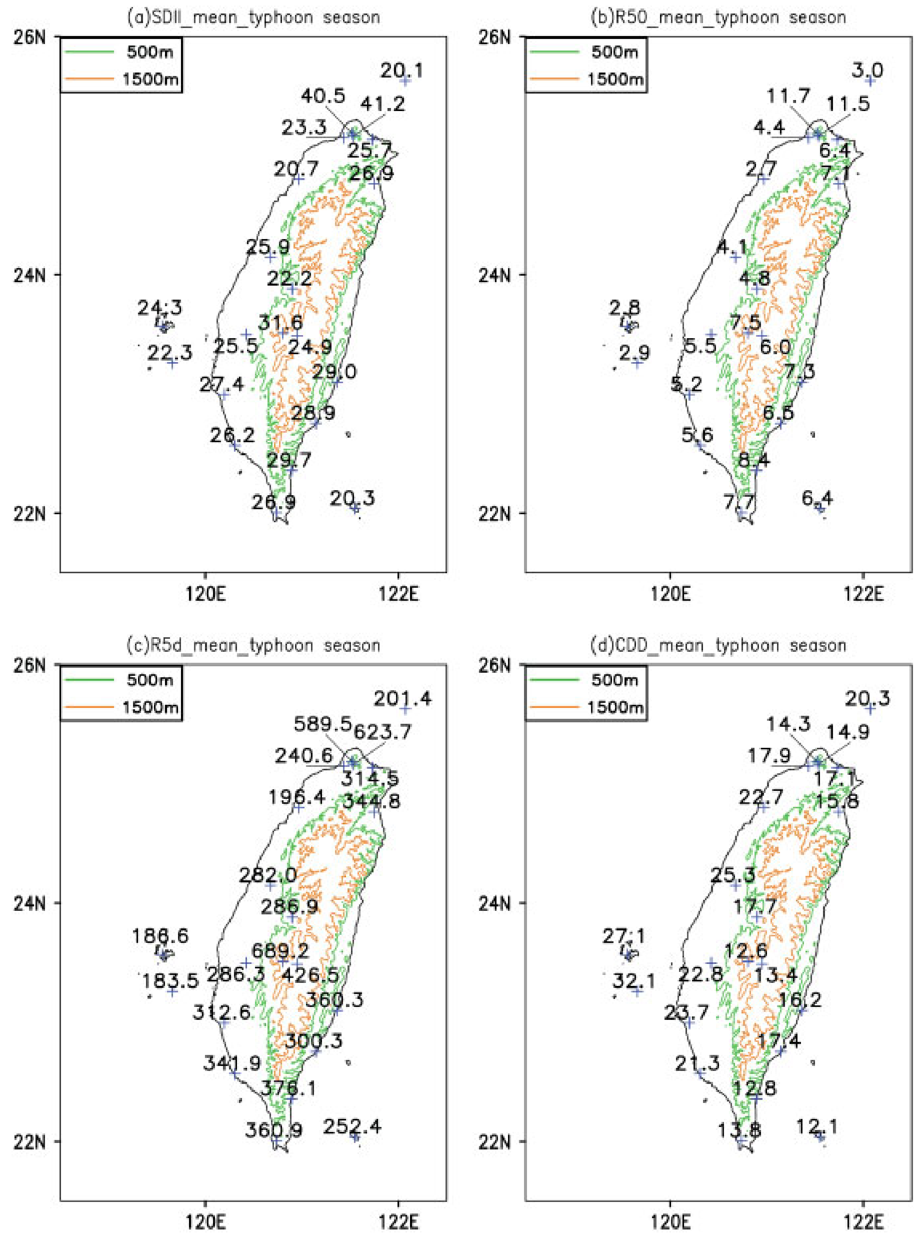

Figure 2. Climatological mean value of (a) SDII, mm day^{-1}; (b) R50, days; (c) R5d, mm; and (d) CDD, days from 1950–2010 for Taiwan.

5. Temporal and spatial characteristics of climate change indices

In this section, we will focus on the temporal and spatial characteristics of climate change indices in Taiwan.

5.1. Spatial patterns of mean and trend in precipitation extremes

The climatological mean values for the four indices are shown in Figure 2. On average, the highest rainfall intensity (Figure 2(a)) is found in the northern, mountainous region, with values slightly >40 mm day^{-1} at Anbu and Zhizihu. This is followed by 31.6 mm day^{-1} for Alishan in the Central Mountain Range (CMR). For the remaining 18 stations, the SDII lies between 20 and 30 mm day^{-1}. For R50 (Figure 2(b)), Anbu and Zhizihu again exhibit the largest number of heavy rainfall days in a year. As expected, the aforementioned three mountain stations also rank high in the consecutive 5-day precipitation amounts (Figure 2(c)). For CDD (Figure 2(d)), the two outer isles—Donjidao and Penghu—and the western plain stations exhibit the highest consecutive dry days.

Figure 3(a) displays the trend pattern for SDII. It is noteworthy that all 21 stations across Taiwan and its outer isles show an increasing trend in precipitation intensity and trends at 7 out of these 21 stations are statistically significant at the 5% level (Table I). Therefore, increasing precipitation intensity during the typhoon season is not a local phenomenon but occurs at the regional level. Moreover, save for Anbu, the other six stations with significant upward trends are not

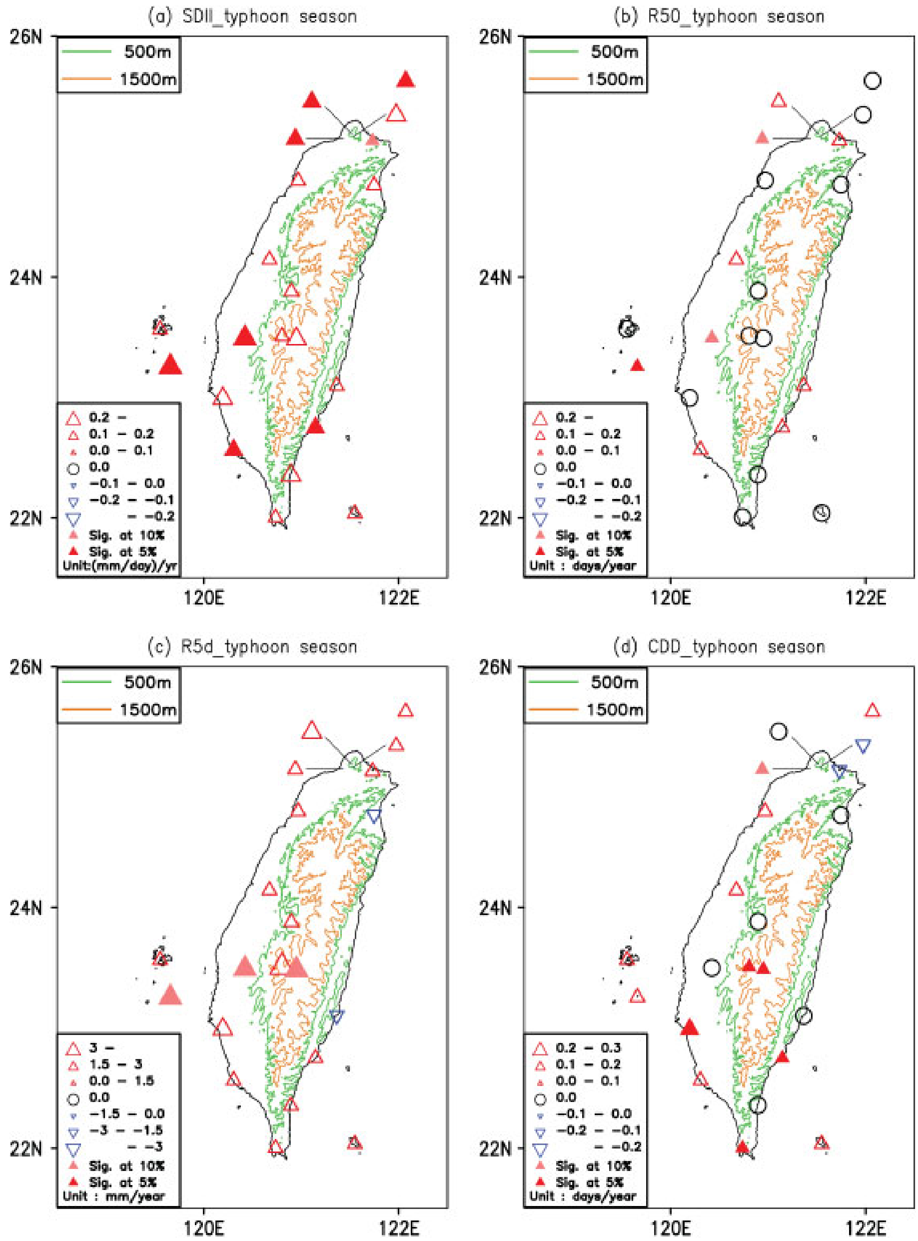

Figure 3. Spatial distribution of the Sen's slopes for (a) SDII, (b) R50, (c) R5d, and (d) CDD from 1950 to 2010. Triangles and circles denote the location of stations. Upward (downward) hollow triangles indicate positive (negative) direction of trends and their size corresponds to the magnitude of trends. Light (solid) filled-in triangles indicate trends significant at the 10% (5%) level.

located at high elevations (Table I). For R50, coastal and lower elevation stations experienced an increasing trend but only one station shows a significant trend at the 5% level (Figure 3(b), Table I).

The pattern of the trend in R5d is marked by positive trends in the entire region (Figure 3(c)), except for two coastal stations in eastern Taiwan (Ilan and Cheng-Kung). Overall, the trend pattern revealed in the maximum consecutive 5-day precipitation (Fig. 3c) is similar to that for precipitation intensity (Figure 3(a)). Changes in the plain stations seem to be more uniform and consistent among the three precipitation-related indices. This is not the case for mountain stations. For example, no significant slope in R50 is noted for stations 753, 755, and 765 (Figure 3(b)), although an upward trend is found in SDII and R5d (Figure 3(a) and (c)). Therefore, increases in precipitation intensity and amounts do not necessarily imply a similar change in the frequency of heavy rainfall events for high-elevation stations. This point will be discussed further in the last section. For CDD (Figure 3(d)), the most pronounced feature is the prevailing upward trend across Taiwan and this trend is most significant in southern Taiwan and at high elevations in the CMR (Alishan and Yushan).

5.2. Trends in typhoon and monsoon rainfall during the typhoon season

Rainfall in Taiwan during the period from July to October is contributed by TCs, mesoscale convective disturbances, or local thunderstorms associated with the diurnal cycle of summer heating patterns embedded in the prevailing southwesterly monsoon (Chen and Chen, 2003; Chen *et al.*, 2007). Chen *et al.* (2004) found that the contribution of typhoon rainfall overwhelms that from convective systems over eastern and northern Taiwan at the height of summer. For southwestern Taiwan which is on the windward side of the southwesterly flows, typhoon rainfall is comparable to that of convective rainfall.

Chen and Chen (2011) partitioned summer rainfall in Taiwan into two components: TC rainfall and seasonal monsoonal rainfall. They defined TC rainfall days as when a TC center is located near Taiwan within 2.5° in latitude and longitude (117.5°E–124.5°E, 19.5°N–27.5°N). The remainder of the rainfall systems that are not associated with TCs is termed as seasonal monsoon rainfall. Adopting Chen and Chen (2011) definition, we will classify a wet day as either caused by TC or monsoon systems. Because most typhoons that have impact on Taiwan within the defined domain are short-lived, we will focus only on the SDII and R50.

For precipitation induced by TCs, the majority of stations in Taiwan are marked by positive trends in SDII (Figure 4(a)), suggestive of increasing precipitation intensity directly caused by TC-related systems. Although high precipitation is expected at high elevations of the CMR (e.g. Alishan) because of

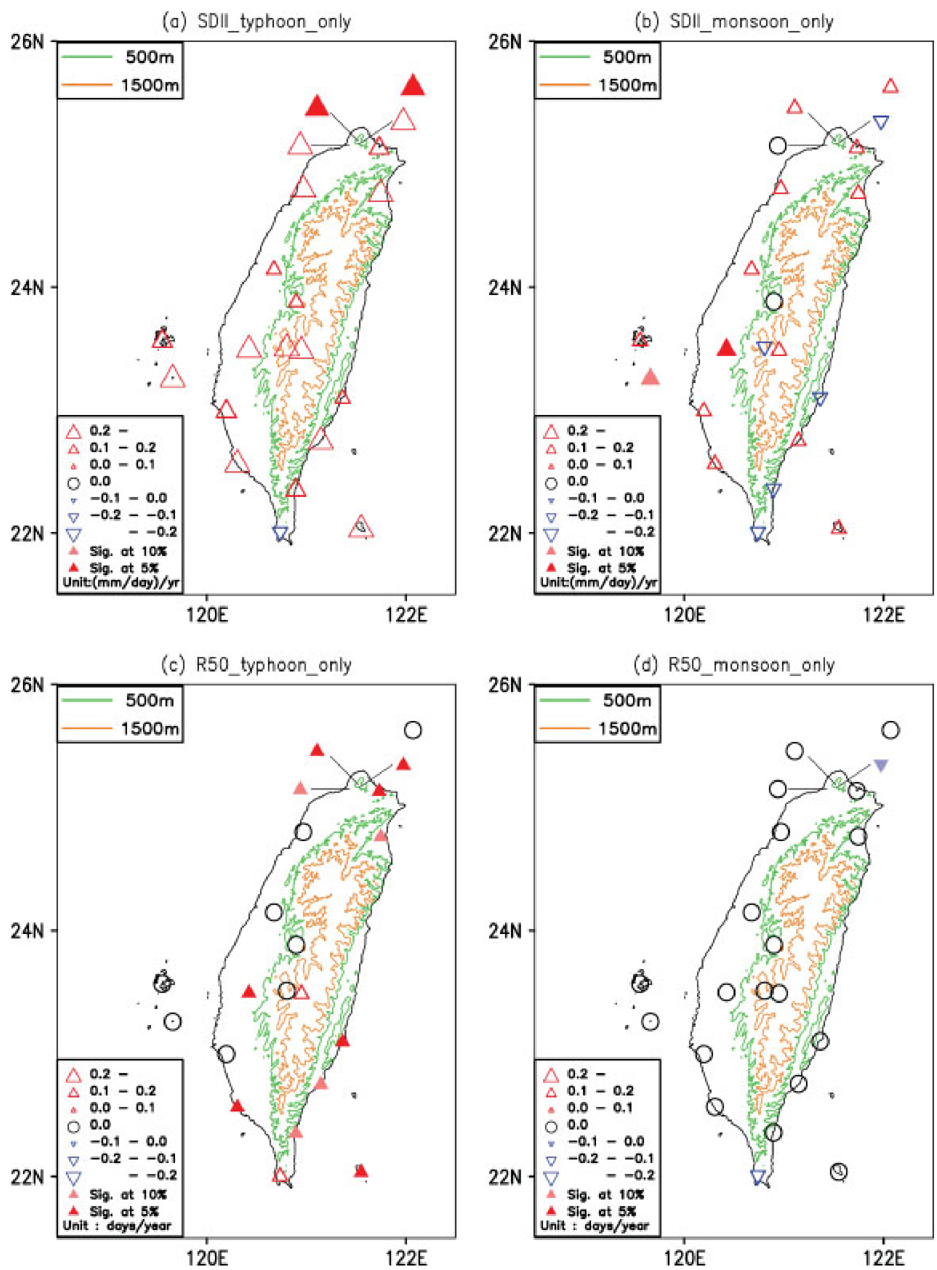

Figure 4. Spatial distribution of the Sen's slopes for (a) SDII and (b) SDII and (c) R50 from typhoon-induced precipitation, and (d) R50 from monsoon-induced precipitation. The period of analysis is July–October from 1950 to 2010. Triangles and circles denote the location of stations. Upward (downward) hollow triangles indicate positive (negative) direction of trends and their size corresponds to the magnitude of trends. Light (solid) filled-in triangles indicate trends significant at the 10% (5%) level.

TC wind and terrain interaction, the upward trend in precipitation intensity induced by TCs is generally not statistically significant. In Figure 4(b), there is also an upward trend in precipitation intensity induced by monsoon systems over the last 60 years. It is likely that the positive contributions made by the two components revealed in Figure 4(a) and (b) enhance the overall signal, rendering a strong and prevailing upward trend in SDII during the typhoon season (Figure 3(a)). For heavy precipitation days (Figure 4(c)), most stations show an increasing trend induced by TCs since 1950. This feature is particularly evident in northern and southeastern Taiwan. Interestingly, there is essentially no change in heavy precipitation days caused by monsoon systems over the last 60 years (Figure 4(d)). Taken together, the increasing trend in heavy precipitation days observed in Figure 3(b) and Table I is rather weak.

6. Summary and discussion

For the first time, this study uses four climate change indices defined by the WMO/CLIVAR to document changes in precipitation extremes during the typhoon season (July–October) in Taiwan from 1950 to 2010. Upward trends are noted for precipitation-related indices (e.g. precipitation intensity) and also for the drought duration index since 1950. This is indicative of more distinct dry–wet conditions during the typhoon season in recent years.

Changes among different precipitation indices are more uniform and consistent for the plain stations. In contrast, the pattern in R50 for the mountain stations (Figure 3(b)) is different from that of SDII and R5D (Figure 3(a) and (c)). It is possible that daily rainfall >50 mm is not an adequate threshold value for defining heavy precipitation events in mountain stations where rainfall is usually high because of the TC wind–terrain interaction. For southern Taiwan, the long-term increase in CDD (Figure 3(d)), and the concurrent increasing precipitation intensity and magnitude (Figure 3(a) and (c)), is troublesome for the region where agriculture is a major economic sector. We also investigate the relative role of TC and non-TC-related precipitation. An increase in precipitation intensity induced by TCs and monsoons is noted (Figure 4(a) and (b)). Heavy rainfall days caused by TCs have also increased but changes caused by southwesterly monsoons are rather flat since 1950 (Figure 4(c) and (d)).

Liu *et al.* (2009) and Shiu *et al.* (2009) found an increase in heavy precipitation (>10 mm/h) in Taiwan for the period 1961–2005 and they suggested this increase is likely associated with global warming because under a warm climate the atmosphere can hold more water vapor. However, the rate of increase in global-mean precipitation, constrained by radiative equilibrium considerations, is much slower than that from global-mean water vapor (∼7% per degree of surface warming). The latter is consistent with expectations from the Clausius–Clapeyron equation (e.g. Held and Soden, 2006; Chou and Chen, 2010). Given the slower rate of observed precipitation increase in response to global warming, the significant upward trend in precipitation intensity (Figure 3(a)) cannot be accounted for only by atmospheric warming. Besides global warming, Chen and Chen (2011) noted the impact of the Pacific decadal oscillation (PDO) on summer (June–August) rainfall trends over Taiwan. Moreover, TC rainfall exhibits an increasing trend in Taiwan during the past 50 years, whereas monsoon rainfall shows a decreasing trend (Chen and Chen, 2011).

Chu *et al.* (2010b) classified historical TC tracks in the western North Pacific into eight types. They noted that a majority of the eight types exhibit an increasing level of storm days, indicative of longer storm duration after the identified shifts. Interestingly, steering flows of TCs have weakened over the subtropical western North Pacific east of Taiwan and translational speeds of storms have decreased since 1950 (Chu *et al.*, 2012). These changes will keep TCs in the main track path longer in their lifetime and likely cause an upward trend in TC induced precipitation in Taiwan (Figure 4(a)). Indeed, the longer duration of storms (Chu *et al.*, 2010b), the slowdown of easterly steering flows, and increasing track frequency (Tu *et al.*, 2009) are also postulated as mechanisms for the increase in TC rainfall intensity affecting Taiwan since 2004 (Chang *et al.*, 2013).

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References

Alexander LV, Zhang X, Peterson TC, Caesar J, Gleason B, Klein Tank AMG, Haylock M, Collins D, Trewin B, Rahimzadeh F, Tagipour A, Rupa Kumar K, Revadekar J, Griffiths G, Vincent L, Stephenson DB, Burn J, Aguilar E, Brunet M, Taylor M, New M, Zhai P, Rusticucci M, Vazquez-Aguirre JL. 2006. Global observed changes in daily climate extremes of temperature and precipitation. *Journal of Geophysical Research* **111**: D05109.

Chang C-P, Lei Y, Sui C-H, Lin X, Ren F. 2012. Tropical cyclone and extreme rainfall trends in East Asian summer monsoon since mid-20th century. *Geophysical Research Letters* **39**: L18702.

Chang C-P, Yang Y-T, Kuo H-C. 2013. Large increasing trend of tropical cyclone rainfall in Taiwan and the role of terrain. *Journal of Climate* **26**: 4138–4147.

Chen CS, Chen Y-L. 2003. The rainfall characteristics of Taiwan. *Monthly Weather Review* **131**: 1323–1341.

Chen CS, Chen Y-L, Chen W-C, Lin P-L. 2007. Statistics of rainfall occurrences in Taiwan. *Weather and Forecasting* **22**: 981–1002.

Chen J-M, Chen H-S. 2011. Interdecadal variability of summer rainfall in Taiwan associated with tropical cyclones and monsoon. *Journal of Climate* **24**: 5786–5798.

Chen C-S, Chen W-C, Tao W-K. 2004. Characteristics of heavy summer rainfall in southwestern Taiwan in relation to orographic effects. *Journal of the Meteorological Society of Japan* **82**: 1521–1543.

Chia H-H, Ropelewski CF. 2002. The interannual variability in the genesis locations of tropical cyclones in the northwest Pacific. *Journal of Climate* **15**: 2934–2944.

Chou C, Chen C-A. 2010. Depth of convection and the weakening of tropical circulation to global warming. *Journal of Climate* **23**: 3019–3030.

Chu P-S, Chen YR, Schroeder TA. 2010a. Changes in precipitation extremes in the Hawaiian Islands in a warming climate. *Journal of Climate* **23**: 4881–4900.

Chu P-S, Zhao X, Kim J-H. 2010b. Regional typhoon activity as revealed by track patterns and climate change. In *Hurricanes and Climate Change*, Elsner JB et al. (eds), Vol. 2. Springer: New York; 137–148.

Chu P-S, Kim J-H, Chen YR. 2012. Have steering flows over the western North Pacific and the South China Sea changed over the last 50 years? *Geophysical Research Letters* **39**: L10704.

Frich P et al. 2002. Observed coherent changes in climatic extremes during the second half of the twentieth century. *Climate Research* **19**: 193–212.

Garza JA, Chu P-S, Norton CW, Schroeder TA. 2012. Changes of the prevailing trade winds over the islands of Hawaii and the North Pacific. *Journal of Geophysical Research* **117**: D11109.

Griffiths ML, Bradley RS. 2007. Variations of twentieth-century temperature and precipitation extreme indicators in the northeast United States. *Journal of Climate* **20**: 5401–5417.

Held IM, Soden BJ. 2006. Robust responses of the hydrological cycle to global warming. *Journal of Climate* **19**: 5686–5699.

Liu SC, Fu C, Shiu C-J, Chen J-P, Wu F. 2009. Temperature dependence of global precipitation extremes. *Geophysical Research Letters* **36**: L17702.

Shiu C-J, Liu SC, Chen J-P. 2009. Diurnally asymmetric trends of temperature, humidity, and precipitation in Taiwan. *Journal of Climate* **22**: 5635–5649.

Tu J-Y, Chou C, Chu P-S. 2009. Abrupt shifts of typhoon activity in the vicinity of Taiwan and its association with the western North Pacific-East Asia climate change. *Journal of Climate* **22**: 3617–3628.

