Statistics of Heavy Rainfall Occurrences in Taiwan

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ABSTRACT

The seasonal variations of heavy rainfall days over Taiwan are analyzed using 6-yr (1997–2002) hourly rainfall data from about 360 rainfall stations, including high-spatial-resolution Automatic Rainfall and Meteorological Telemetry System stations and 25 conventional stations. The seasonal variations and spatial variations of nontyphoon and typhoon heavy rainfall occurrences (i.e., the number of rainfall stations with rainfall rate >15 mm h^{-1} and daily accumulation >50 mm) are also analyzed. From mid-May to early October, with abundant moisture, potential instability, and the presence of mountainous terrain, nontyphoon heavy rainfall days are frequent (>60%), but only a few stations recorded extremely heavy rainfall (>130 mm day^{-1}) during the passage of synoptic disturbances or the drifting of mesoscale convective systems inland. During the mei-yu season, especially in early June, these events are more widespread than in other seasons. The orographic effects are important in determining the spatial distribution of heavy rainfall occurrences with a pronounced afternoon maximum, especially during the summer months under the southwesterly monsoon flow. After the summer–autumn transition, heavy rainfall days are most frequent over northeastern Taiwan under the northeasterly monsoon flow. Extremely heavy rainfall events (>130 mm day^{-1}) are infrequent during the winter months because of stable atmospheric stratification with a low moisture content. Typhoon heavy rainfall events start in early May and become more frequent in late summer and early autumn. During the analysis period, heavy rainfall occurrences are widespread and dominated by extremely heavy rainfall events (>130 mm day^{-1}) on the windward slopes of the storm circulations. The spatial distribution of typhoon heavy rainfall occurrences depends on the typhoon track with very little diurnal variation.

1. Introduction

Even though monsoons are planetary-scale circulations, monsoon rainfalls are frequently localized in nature because of the terrain and local winds (Ramage 1971; Watanabe and Ogura 1987; Ogura and Yoshizaki 1988; Akaeda et al. 1995; Li et al. 1997; Yeh and Chen 1998; Chen 2000, and others). The Central Mountain Range (CMR) runs through Taiwan in a nearly north–south direction at an average height of about 2 km and with peaks near 4 km (Fig. 1). With steep terrain and narrow basins, heavy rainfall events frequently lead to flooding. During May–June, rainfall in Taiwan is frequently affected by the passage of mei-yu fronts (Yeh and Chen 1998). Furthermore, during the main rainy seasons (mei-yu and summer) (Chen and Chen 2003), localized extremely heavy rainfall (>130 mm day^{-1}) over the mountainous regions frequently results in flooding and landslides (M.-L. Lin et al. 2002). During the period of 1961–82, the annual weather-related economic losses due to typhoons and other heavy rainfall events in Taiwan were about 2.8 billion New Taiwan dollars (approximately $86 million U.S.) with more

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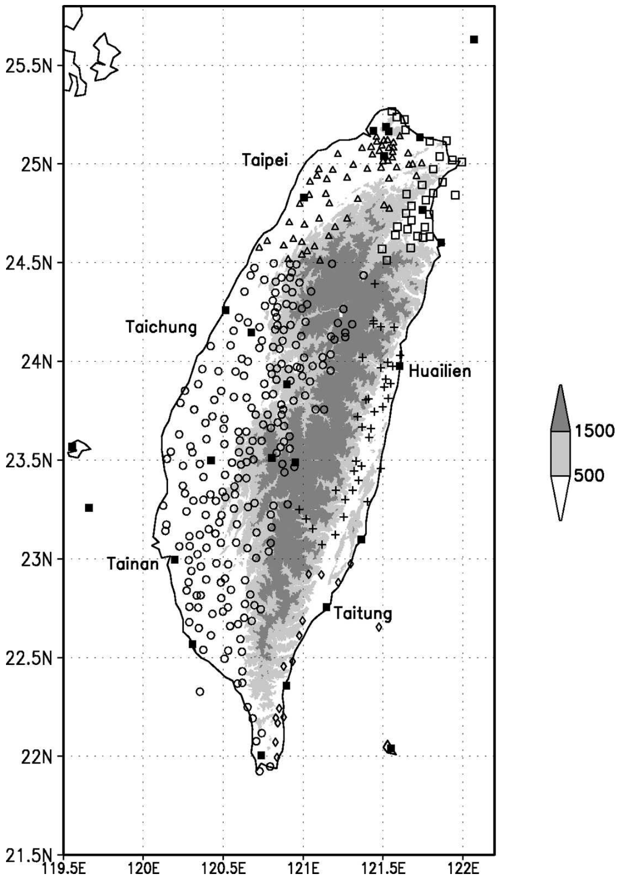

FIG. 1. Topography of Taiwan shown by grayscale at 500 and 1500 m. ARMTS rainfall stations in western (open circles), northern (open triangles), northeastern (open squares), eastern (crosses), and southeastern (open diamonds) Taiwan. The conventional stations are represented by solid squares.

than 100 casualties (Shieh 1986). Most of the previous studies on heavy rainfall events over Taiwan are based on case studies, especially on the roles of synoptic, mesoscale, and local-scale processes as well as the orographic effects on the development of heavy rainfall (e.g., Wang et al. 1990; Akaeda et al. 1995; Li et al. 1997; Teng et al. 2000; Yeh and Chen 2002; Y.-L. Lin et al. 2002; Chiao and Lin 2003, and others). In this study, we compile statistics of heavy rainfall events using the dense rain gauge network deployed in recent years.

The rainfall characteristics of Taiwan throughout the annual cycle were investigated by Chen and Chen (2003) using 38-yr rainfall data (1961–98) from 25 conventional stations and 5-yr hourly rainfall data (1994–98) from 249 Automatic Rainfall and Meteorological Telemetry System (ARMTS) stations (Chen et al. 1999). They found that the rainfall distribution in Taiwan is strongly influenced by the low-level wind direction associated with the east Asian monsoons. Furthermore, the seasonal variations in rainfall amount (light precipitation versus heavy precipitation) and type (stratiform versus convective precipitation) are also dependent on the thermodynamic stratification and the availability of low-level moisture. Besides the seasonal variations, the rainfall characteristics of Taiwan also exhibit diurnal variations (Chen et al. 1999; Kerns 2003). During the 1987 mei-yu season, the surface airflow had pronounced diurnal variations (Chen and Li 1995) with an afternoon rainfall maximum on the windward slopes and mountainous areas (Yeh and Chen 1998; Johnson and Bresch 1991).

With the completion of ARMTS around the island after 1997 (Fig. 1), rainfall data from routine observations and ARMTS stations are now available to forecasters in real time. As a result, flash flood and landslide alerts in near–real time have become feasible. In the past, diurnal variations of heavy rainfall events over the western side of the CMR during the mei-yu season were studied by Chen and Lin (1997) and Chen and Chang (2002). However, the study of the heavy rainfall statistics for the entire island of Taiwan during the mei-yu season and other rainfall regimes is lacking. With the presence of steep terrain, the occurrences of heavy rainfall events have large spatial variations related to terrain and local winds. Furthermore, because of the seasonal changes in environmental flows over Taiwan related to the planetary-scale east Asian monsoon circulations, there are large seasonal changes in the locations and occurrences of heavy rainfall events. Aside from monsoon circulations, tropical storms are frequent during May–October bringing in excessive rainfall with heavy property damage and losses. Compiling seasonal and spatial variations of heavy rainfall events in Taiwan would provide forecasters with valuable information on the likelihood that heavy rainfall might occur at a given location for different rainfall regimes (Brooks and Stensrud 2000; Schumacher and Johnson 2006) and on the regions that are more vulnerable than others to flash flooding and landslides (M.-L. Lin et al. 2002) at a particular time of the year. The orographic effects on the heavy rainfall distributions and the effects of the diurnal heating cycle on heavy rainfall occurrences will also be investigated.

2. Data analyses

In this study, heavy rainfall days are defined as days in which one or more rain gauges record an hourly rainfall rate that exceeds 15 mm h^{-1} at least once and in which the daily rainfall amount is greater than 50 mm (Wang et al. 1985). The number of heavy rainfall occurrences for a heavy rainfall day is defined as the number of stations that exceed both the rainfall rate and accumulation criteria. To adopt the criteria of heavy rainfall (50 mm day^{-1}) used by the forecasters of the Central Weather Bureau (CWB) of Taiwan, to consider the potential threat of large rainfall accumulation (>130 mm day^{-1}) for landslides (M.-L. Lin et al. 2002), and to refine the classification of heavy rainfall, we divide the heavy rainfall occurrences into three mutually exclusive groups defined by the daily rainfall accumulation of each occurrence. These three groups are group A, group B, and group C, with daily rainfall accumulations of 50–90, 90–130, and exceeding 130 mm, respectively (Wang et al. 1985). Group C heavy rainfall events for each rainy season are also analyzed.

Because the mei-yu season over Taiwan is between mid-May and mid-June, and the autumn rainfall regime starts around mid-September (Chen and Chen 2003), the seasonal variation of heavy rainfall days is analyzed bimonthly. The period from 1997 to 2002 is analyzed using hourly rainfall data from around 360[1] rainfall stations, including 25 conventional stations and all ARMTS stations. The average gauge spacing is about 10 km. For each half-month period, the number of heavy rainfall occurrences for each group is analyzed. Considering the complex terrain and the nonuniformity of the rainfall stations around Taiwan, Yeh and Chen (1998) analyzed rainfall characteristics in seven subregions during the 1987 mei-yu season from 85 hourly rainfall stations. They found that hourly rainfall accumulations and hourly rainfall incidences are significantly different among these subregions. Because of the enhancement of rainfall intensity on the windward side of the Central Mountain Range under the monsoon flow that varies during the annual cycle and the nonuniformity of ARMTS network, five subregions around Taiwan are used to examine the heavy rainfall characteristics in each subdomain under different prevailing winds. The total number of rainfall stations in the western (south of 24.5°N), northern (north of 24.5°N), northeastern (north of 24.5°N, east of the CMR, and along the northern coasts), eastern (between 24.5° and 23°N), and southeastern (south of 23°N) Taiwan subregions are about 219, 55, 31, 35, and 20, respectively (see Fig. 1).

Tipping-bucket rain gauges are installed in ARMTS. The data are recorded at 1-min intervals with a resolution of 0.5 mm. The data are transmitted by the SATELLINE-3AS Epic UHF radio communication system from rainfall stations to relay stations and from relay stations to conventional stations (Fig. 1). Data are transmitted from conventional stations to the CWB by frame relay cable line with 512-kB speed. The most common error is that some rainfall amounts in one report may be unreasonably high because of wireless transmission errors. The data are checked automatically to determine whether each report is below some empirical value at each station. The empirical value for each station is the maximum rainfall rate of the past 10 yr. If the data are beyond the empirical value, then a manual check is needed.

Recently, Lu and Chen (2005) analyzed the 54-yr (1951–2004) strong rainfall events (hourly rainfall rate exceeding 20 mm h^{-1}) in northern (Taipei), western (Taichung and Tainan), and eastern Taiwan (Hualien and Taitung) (see Fig. 1 for locations). They found that the number of strong rainfall events (hourly rainfall rate exceeding 20 mm h^{-1}) in northern Taiwan is higher during the period of 1996–2004 than the period of 1951–95. The number of strong rainfall events in eastern Taiwan is higher during the period of 1988–2004 than the period of 1951–87. The number of strong rainfall events in western Taiwan is about the same before and after 1978. Heavy rainfall events during the period of 1997–2002 in our study are near the average value in western Taiwan, whereas heavy rainfall events in the period of 1997–2002 in northern and eastern Taiwan are slightly above the average.

From May to early November, typhoons frequently bring in heavy rainfall over Taiwan. Therefore, we separate heavy rainfall days and the average occurrences of groups A, B, and C per heavy rainfall day for each half-month period into typhoon and nontyphoon cases. In this study, if the center of the typhoon (from the report from the CWB) is within 3° latitude or longitude of Taiwan, the rainfall is designated as typhoon rainfall. The spatial distributions of heavy rainfall occurrences for different seasons (mei-yu, summer, autumn, winter, and spring) for each rainfall group for both typhoon and nontyphoon rainfalls are also analyzed. The diurnal variations of frequencies of hourly rainfall rate exceeding 15 mm at each station for each season for both typhoon and nontyphoon rainfalls are computed.

3. The seasonal variations of heavy rainfall days and heavy rainfall occurrences

a. Nontyphoon heavy rainfall days

During the seasonal transition between the northeasterly and southwesterly monsoon flows in early May, the precipitable water and the potential instability

[1] The number of rainfall stations is 348, 362, 365, 369, 352, and 375 from 1997 to 2002, respectively.

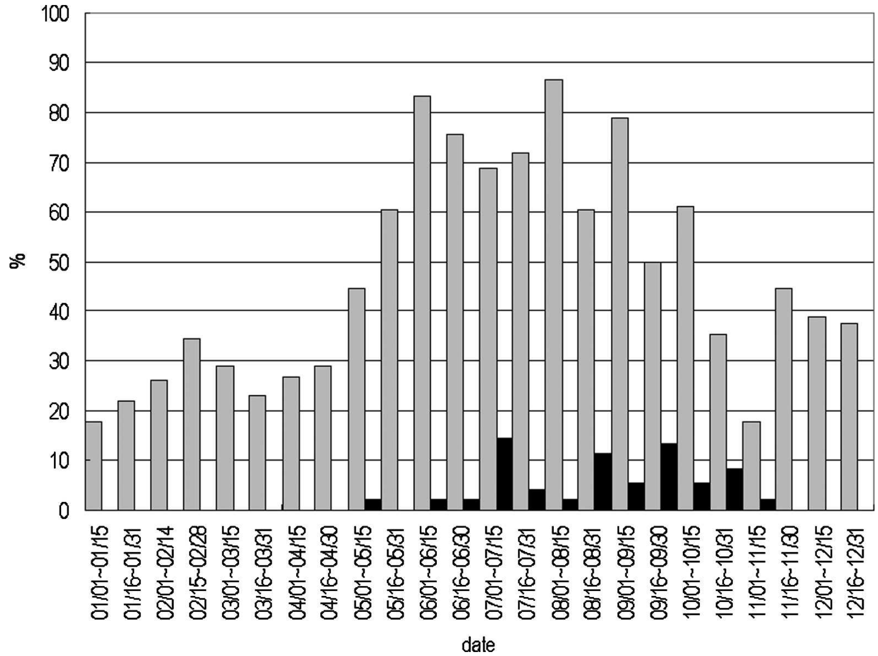

FIG. 2. The frequency (%) of nontyphoon and typhoon heavy rainfall days for each of the half-month periods over the entire island. These heavy rainfall days have one or more rain gauges with hourly rainfall rates exceeding 15 h^{-1} mm at least once and daily rainfall amounts greater than 50 mm (i.e., for all groups A, B, and C combined). The dark bars represent the heavy rainfall days caused by typhoons.

increase (Chen and Chen 2003, their Fig. 2). During this period, the frequency of nontyphoon heavy rainfall days increases significantly (Fig. 2). From late May to early October, the nontyphoon heavy rainfall days are frequent (>60%) with peaks in early June (~82%), early August (~88%), early September (~79%), and early October (~60%), corresponding to the climax of the mei-yu, summer, summer–autumn transition, and autumn rainfall regimes, respectively (Chen and Chen 2003). It is apparent that because of the presence of steep terrain, heavy rainfall events are common during May–October when the atmosphere is conditionally unstable with abundant moisture (Chen and Chen 2003).

Over western Taiwan, similar to Fig. 2, the maximum frequencies of the nontyphoon heavy rainfall days occur in early June (69%), early August (80%), and early September (63%) (Fig. 3). After the onset of northeasterly monsoon flow, the frequencies of nontyphoon heavy rainfall days in late September and early October are still above 30%, mainly because of afternoon rainshowers over the mountainous regions (Kerns 2003). From November to early April, western Taiwan is on the lee side of the northeasterly monsoon flow. With stable atmospheric stratification and low moisture content (Chen and Chen 2003), heavy rainfall days are infrequent on the lee side.

Over northern Taiwan (Fig. 3), in contrast to western Taiwan, the frequency of nontyphoon heavy rainfall days in June (~50%) is slightly higher than during the summer peak (~45%). During the summer, most of the rainfall stations over northern Taiwan are not on the windward side of the CMR (Fig. 1) when low-level winds are south-southwesterly (Chen and Chen 2003). In addition, northern Taiwan is closer to the ridge axis of the western Pacific subtropical high than western Taiwan during summer (Chen and Chen 2003) with fewer orographic rainshowers than in western Taiwan (C.-S. Chen et al. 2004).

Over northeastern Taiwan (Fig. 3), there is no apparent summer peak of nontyphoon heavy rainfall days because it is on the lee side of the CMR. Similar to northern Taiwan, the mei-yu season has the highest frequency (42%) of heavy rainfall days there during the annual cycle. Secondary peaks occur during the summer–autumn transition (37%) and the autumn rainfall regime (33%). During November–December, heavy rainfall days are more frequent over northeastern Taiwan than any other subregions because it is on the windward side of the CMR under the northeasterly monsoon flow. However, rainfall rates during November–December over northeastern Taiwan are frequently relatively light because of low moisture content

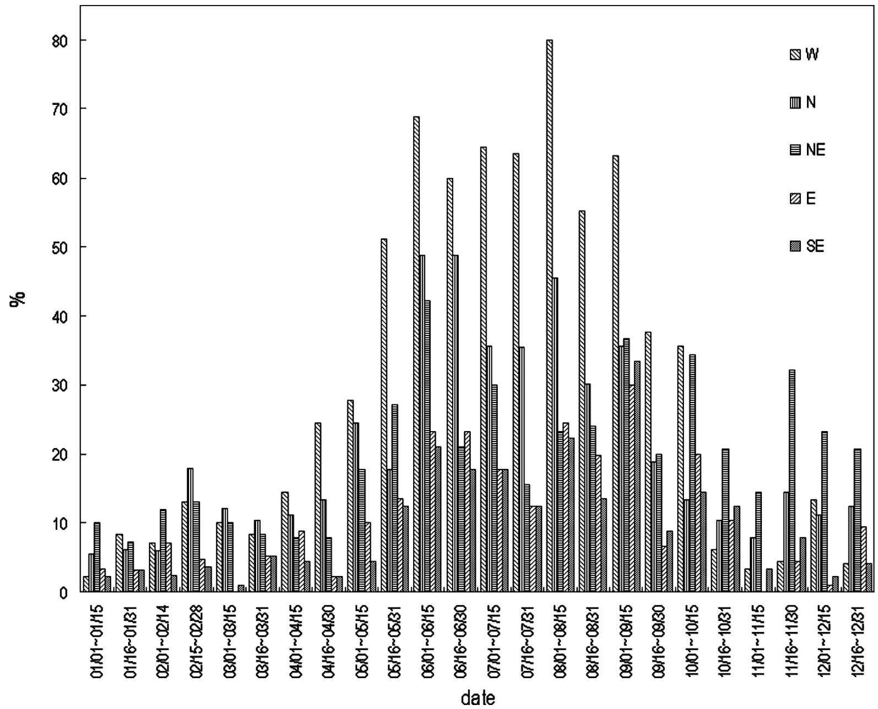

FIG. 3. The frequency (%) of nontyphoon heavy rainfall days for each of the half-month periods in western (W), northern (N), northeastern (NE), eastern (E), and southeastern (SE) Taiwan. These heavy rainfall days have one or more rain gauges with hourly rainfall rates exceeding 15 h^{-1} mm at least once and daily rainfall amounts greater than 50 mm (i.e., for all groups A, B, and C combined).

and stable atmospheric stratification (Chen and Chen 2003). As a result, nontyphoon heavy rainfall days on the windward side of the northeasterly winter monsoon are far less frequent as compared with the windward slopes of the southwesterly monsoon flow during the summer months.

For eastern and southeastern Taiwan (Fig. 3), the maximum frequency of heavy rainfall days occurs in early September. During this period, these subregions are on the windward side of the CMR under an easterly flow during the summer–autumn transition (Chen and Chen 2003, their Fig. 3a). The subregions on the eastern side of the CMR exhibit a secondary early October peak because of the strengthening of low-level northeasterly monsoon flow from late September (Chen and Chen 2003, their Figs. 3b,c).

b. Nontyphoon heavy rainfall occurrences

During the mei-yu season (15 May–15 June), mei-yu fronts and mesoscale convective systems embedded in the southwesterly monsoon flow are the main disturbances that bring in widespread heavy rainfall (Li et al. 1997; Yeh and Chen 2002; Chen et al. 2005). The highest average total number of rainfall stations with rainfall rates >15 mm h^{-1} and daily accumulations >50 millimeters per nontyphoon heavy rainfall day occur during the second half of the mei-yu season in early June (approximately 29 stations or about 8% of the total rainfall stations; Fig. 4). Most of the rainfall stations with rainfall rates >15 mm h^{-1} and daily accumulations >50 mm (approximately 20 stations or about 6% of the total rainfall stations) during the mei-yu season are over western Taiwan on the windward side of the CMR (Fig. 5). The second highest number of rainfall stations with rainfall rates >15 mm h^{-1} and daily accumulations >50 mm are in northern Taiwan (approximately five stations or about 1% of the total rainfall stations). Over northeastern (Fig. 5), eastern (not shown), and southeastern Taiwan (not shown) on the lee side of the CMR under the southwesterly monsoon flow, the heavy rainfall occurrences are relatively infrequent (about one station) as compared with other subregions. It is apparent during the mei-yu season that orographic effects play an important role in determining the locations for development of heavy rainfall.

Although the nontyphoon heavy rainfall days during the climatological monsoon break in late June and early July are comparable to that during the mei-yu season

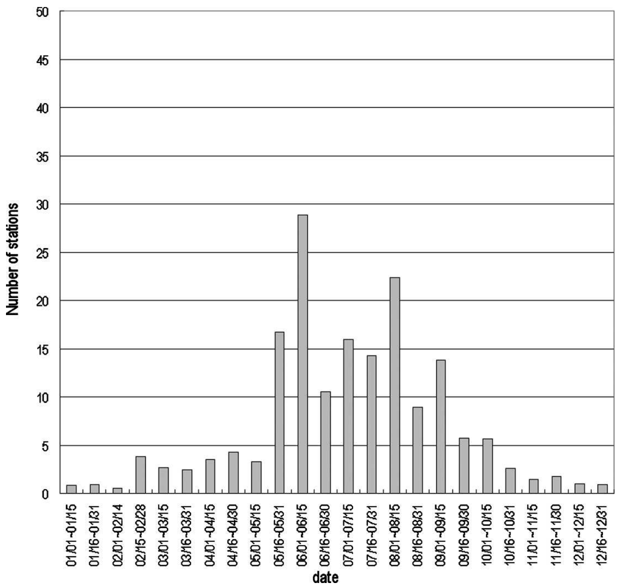

FIG. 4. Average total number of rainfall stations per nontyphoon heavy rainfall day for each half-month period for all groups A, B, and C combined over the entire island.

(Fig. 2), the average total number of rainfall stations with rainfall rates >15 mm h^{-1} and daily accumulations >50 millimeters per nontyphoon heavy rainfall day during the monsoon break is only about 34% of that in early June (or about 3% of the total rainfall stations; Fig. 4), which is in agreement with Wang et al. (1984). It is evident that the nontyphoon heavy rainfall days during the monsoon break are dominated by local orographic showers.

Another peak in the average total number of rainfall stations with rainfall rates >15 mm h^{-1} and daily accumulations >50 millimeters per nontyphoon heavy rainfall day occurs in early August (22 stations or about 6% of the total rainfall stations; Fig. 4) when the monsoon trough over the South China Sea/western Pacific reaches its northernmost position near southern Taiwan (Chen and Chen 2003). During this period, in addition to frequent heavy orographic showers in the afternoon hours, mesoscale convective systems (MCSs) frequently drift inland (C.-S. Chen et al. 2004). Similar to the mei-yu season, most of the heavy rainfall events in early August occur over western Taiwan on the windward side of the CMR (Fig. 5).

During the summer–autumn transition and the autumn rainfall regime, the baroclinic disturbances and MCSs embedded in the northeasterly monsoon flow are the main transient disturbances that bring in heavy rainfall (Chen and Chen 2003). The average total number of rainfall stations with rainfall rates >15 mm h^{-1} and daily accumulations >50 millimeters per nontyphoon heavy rainfall day during the summer–autumn transition in early September (approximately 13 stations or about 4% of the total rainfall stations) and October (approximately 6 stations or about 2% of the total rainfall stations) are lower than those of the mei-yu (approximately 29 stations or about 8% of the total rainfall stations) and the summer rainfall regimes (ap-

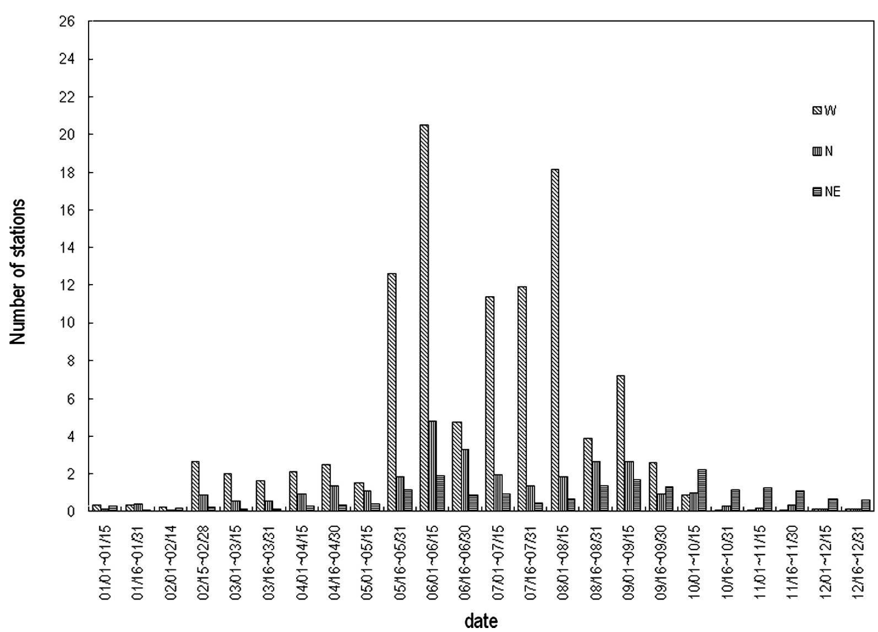

FIG. 5. Same as in Fig. 4 but for W, N, and NE Taiwan.

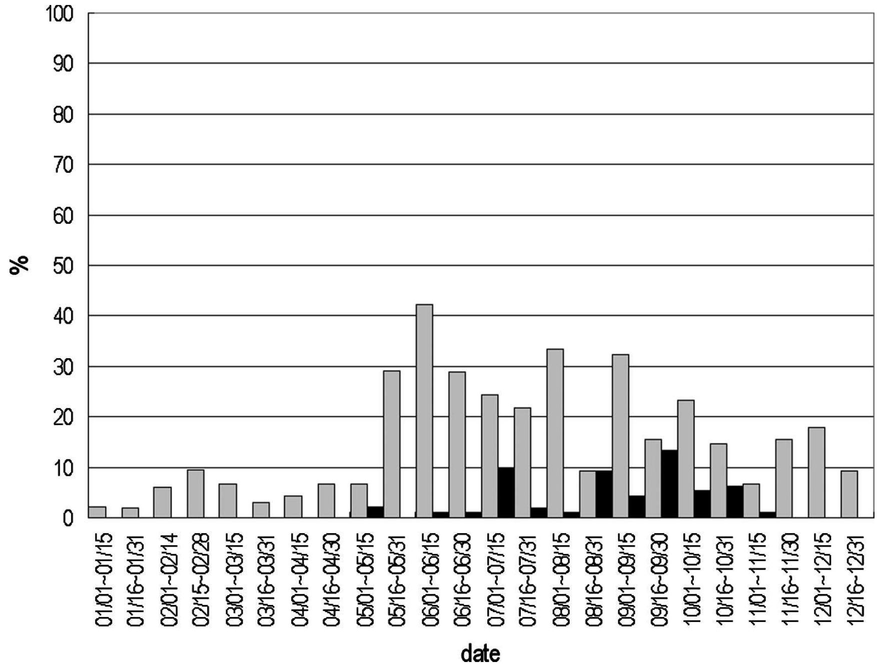

FIG. 6. Same as in Fig. 2 but for daily rainfall amount greater than 130 mm (group C).

proximately 22 stations or about 6% of the total rainfall stations; Fig. 4) because of the rapid decrease in convective instability after summer (Chen and Chen 2003). In early September (summer–autumn transition), the number of rainfall stations with rainfall rates >15 mm h^{-1} and daily accumulations >50 mm are the highest over western Taiwan than any other subregions (Fig. 5). However, in early October under relatively strong northeasterly monsoon flow, northeastern Taiwan has the highest number of rainfall stations with rainfall rates >15 mm h^{-1} and daily accumulations >50 mm among all of the subregions.

From early September to December, the average total number of rainfall stations with rainfall rates >15 mm h^{-1} and daily accumulations >50 millimeters per nontyphoon heavy rainfall day decrease significantly (from 13 stations to about 1; Fig. 4). However, the frequency of nontyphoon heavy rainfall days in late November and December remains around 40% (Fig. 2). The number of averaged rainfall stations with rainfall rates >15 mm h^{-1} and daily accumulations >50 millimeters per nontyphoon heavy rainfall day is the least during the winter months (Fig. 4) because of low moisture and stable atmospheric conditions. As will be shown later, heavy rainfall days under the northeasterly winter monsoon flow are caused by a few localized orographic showers along the northeastern windward slopes. During the transition from winter to spring season, a notable increase in the number of rainfall stations with rainfall rates >15 mm h^{-1} and daily accumulations >50 mm occurs (Fig. 4), especially over western Taiwan (Fig. 5), as the atmosphere gradually transforms from stable to conditionally unstable stratification (Chen and Chen 2003).

The maximum frequencies for heavy rainfall days that have one or more stations with an hourly rainfall rate exceeding 15 mm h^{-1} at least once and a daily rainfall accumulation exceeding 130 mm (group C) for the mei-yu (early June), summer (early August), summer–autumn transition (early September), and autumn rainfall regimes (early October) are ~41%, ~32%, ~31%, and ~24%, respectively (Fig. 6). From May to September, with a conditionally unstable stratification (Chen and Chen 2003), landslides are more likely to occur.

Even though heavy rainfall days are frequent during the warm season, we will show that these events are frequently localized in nature because of the presence of the CMR. The average number of rainfall stations with rainfall rates >15 mm h^{-1} and daily accumulations >50 millimeters per nontyphoon heavy rainfall day is fewer for a higher threshold of daily rainfall accumulation. The averaged heavy rainfall occurrences for group A per nontyphoon heavy rainfall day are most frequent during the mei-yu season (approximately 17 occurrences or about 5% of the total rainfall stations) (Fig. 7) with secondary peaks in early August (approximately 14 occurrences or about 4% of the total rainfall sta-

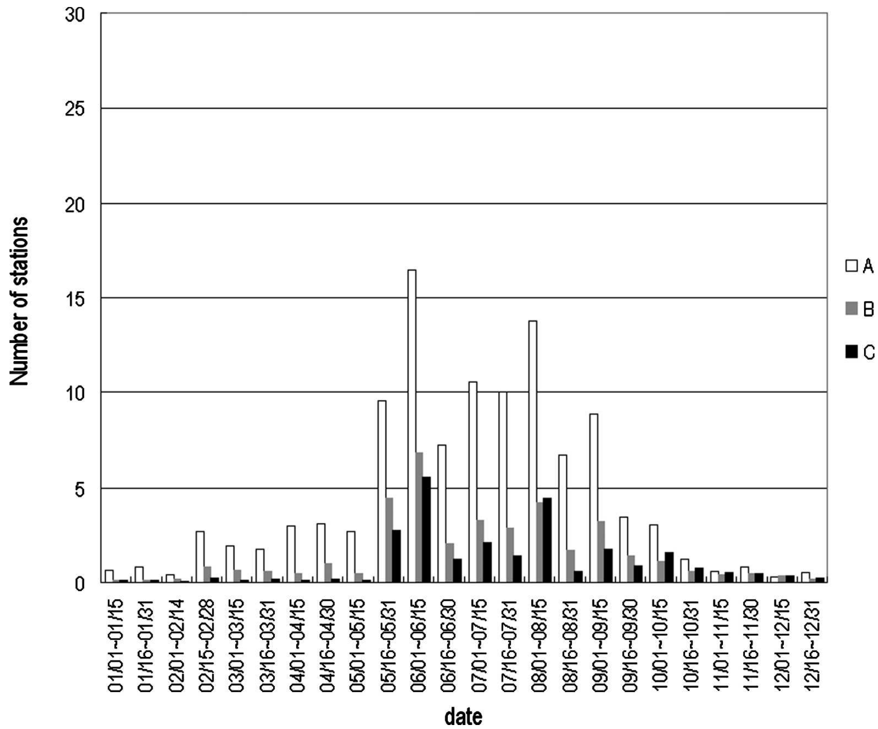

FIG. 7. Average number of rainfall stations for group A (50 mm $\leqq$ daily rainfall accumulation < 90 mm), group B (90 mm $\leqq$ daily rainfall accumulation < 130 mm), and group C (130 mm $\leqq$ daily rainfall accumulation) per nontyphoon heavy rainfall day over the entire island.

tions) and early September (approximately 9 occurrences or about 3% of the total rainfall stations) corresponding to the summer and the summer–autumn transition rainfall regimes, respectively. The averaged heavy rainfall occurrences for group A per nontyphoon heavy rainfall day in early October number less than five. Only during the mei-yu season do the averaged occurrences for group C per heavy rainfall day reach five or more (or about 2% of the total rainfall stations; Fig. 7). The averaged occurrences for group C per heavy rainfall day in every subregion during the mei-yu season are fewer than 5 (not shown). In other words, from late May to October, even though heavy rainfall days are frequent (>60%), for most cases, only a few stations would likely record extremely heavy rainfall (>130 mm day^{-1}) for each heavy rainfall day. Most of the group C events occur under favorable large-scale conditions (e.g., Li et al. 1997 and others). During the mei-yu season, these events are more widespread than in other seasons with a higher likelihood to produce flooding and landslides.

c. Typhoon heavy rainfall days and occurrences

The typhoon heavy rainfall days start in early May and become more frequent (5%–15%) during July–October (Fig. 2). Typhoon heavy rainfall days are less frequent (5%–15%) than those of the nontyphoon heavy rainfall days (50%–85%). However, typhoons frequently produce more widespread heavy rainfall events than nontyphoon heavy rainfall days. The average number of rainfall stations with rainfall rates >15 mm h^{-1} and daily accumulations >50 millimeters per typhoon heavy rainfall day during the typhoon season (Fig. 8) is significantly larger (>100 stations or about 28% of the total rainfall stations) than the average number of rainfall stations with rainfall rates >15 mm h^{-1} and daily accumulations >50 millimeters per nontyphoon heavy rainfall day (Fig. 4) with much higher rainfall. The average number of rainfall stations with rainfall rates >15 mm h^{-1} and daily accumulations >50 millimeters per typhoon heavy rainfall day exceeds 72 stations (about 20% of the total rainfall stations) in late summer and autumn. During the summer–autumn transition (early September), there is a local minimum of rainfall stations with rainfall rates >15 mm h^{-1} and daily accumulations >50 mm (Fig. 8). This is probably mainly a result of sampling problems. Another factor that affects the decrease in early September may be related to the flow circulations. During this period, the upper-level Tibetan high is still over the East China Sea and the Taiwan area (Chen and Chen 2003, their Fig. 23a). In the meantime, the monsoon trough shifts

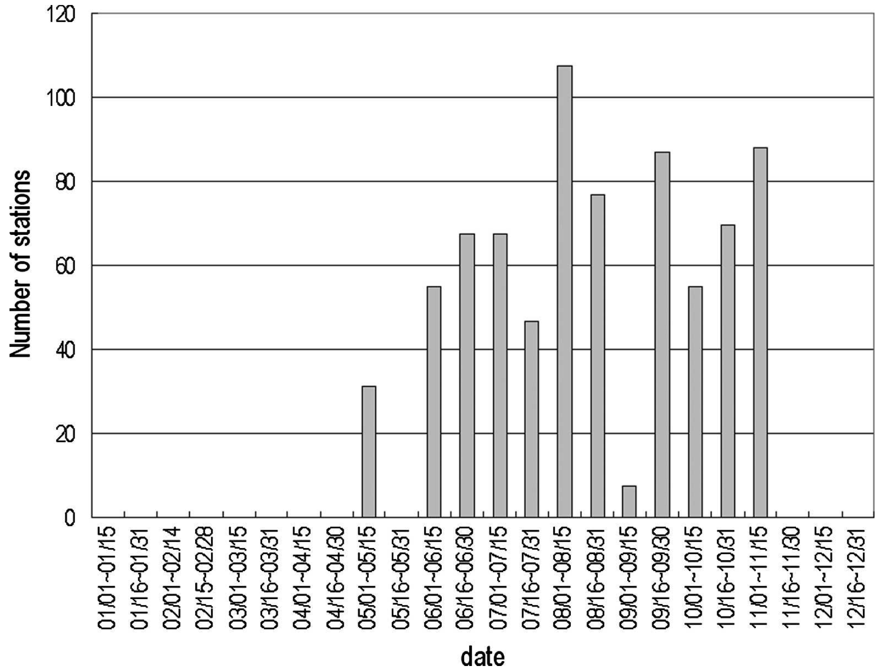

FIG. 8. Same as in Fig. 4 but for typhoon heavy rainfall days.

southward from its northernmost position in August to over the central South China Sea and eastward to the western Pacific (Chen and Chen 2003, their Fig. 3a). Consequently, the tropical disturbances that originated from the monsoon trough may be less likely to affect the Taiwan area than those from the rest of the storm season.

It is well known that rainfall amount is enhanced on the windward side of the typhoon circulation, whereas rainfall amount is much less on the lee side (Y.-L. Lin et al. 2002; Wu et al. 2002; Yang and Ching 2005, and others). In addition, a typhoon's circulation may also be enhanced by the monsoon flow resulting in localized heavy rainfall on the windward side (Lin et al. 2001;

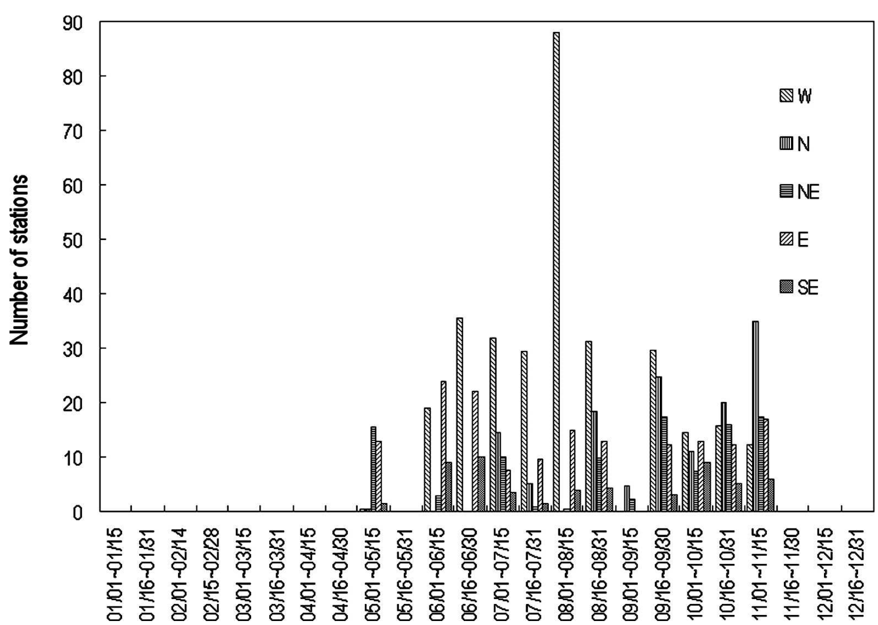

FIG. 9. Same as in Fig. 8 but for W, N, NE, E, and SE Taiwan.

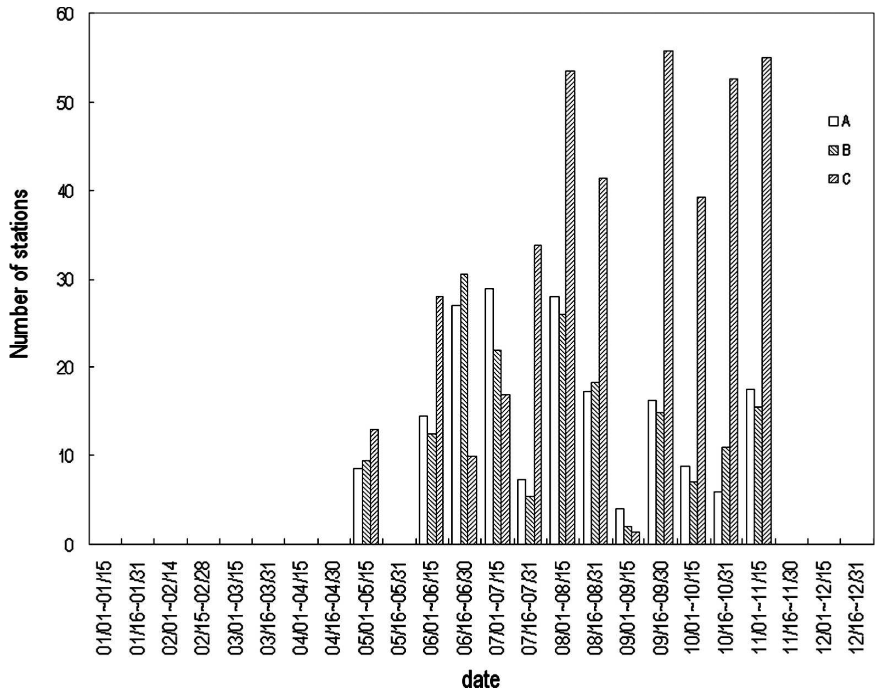

FIG. 10. Same as in Fig. 7 but for typhoon heavy rainfall day.

Chiao and Lin 2003; Sui et al. 2002). In May, the subregions east of the CMR have a higher average number of rainfall stations with rainfall rates >15 mm h^{-1} and daily accumulations >50 millimeters per typhoon heavy rainfall day than do the subregions in the western CMR (Fig. 9). Our results are consistent with the observed higher frequencies of tropical cyclones in the areas east of the CMR rather than to the west of CMR before late

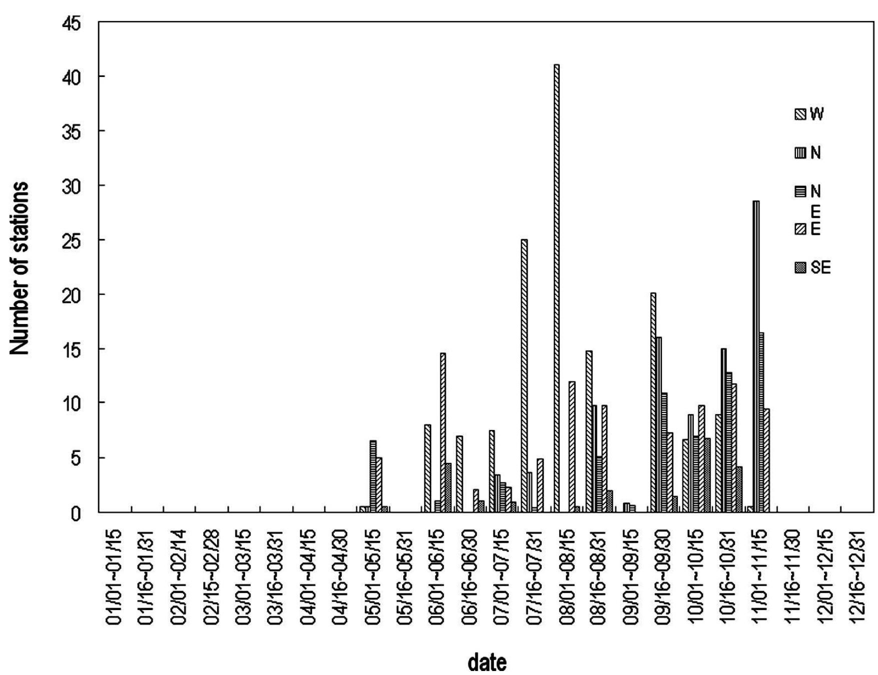

FIG. 11. Same as in Fig. 9 but for group C (130 mm ≦ daily rainfall accumulation) per typhoon heavy rainfall day.

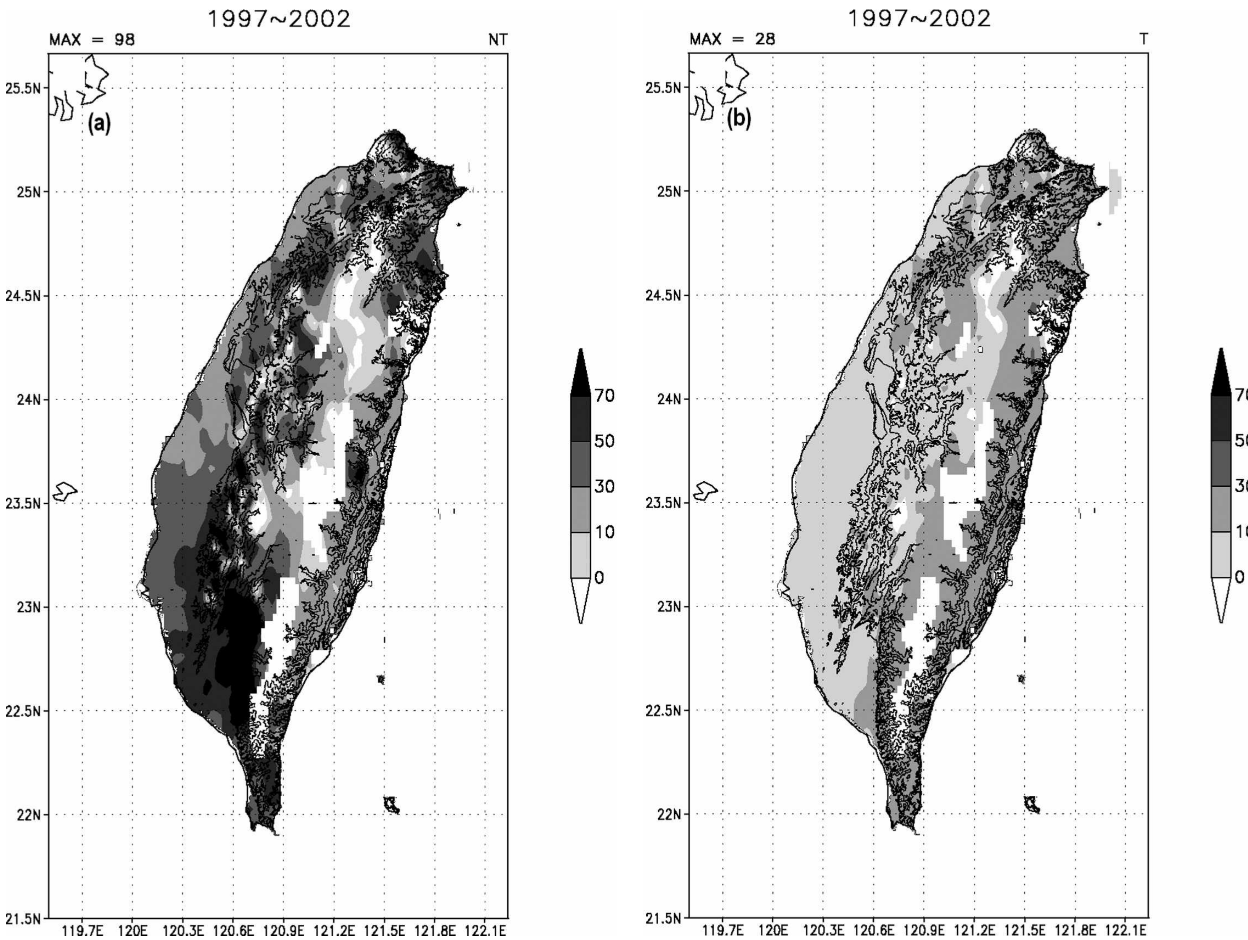

FIG. 12. (a) The spatial distributions of averaged annual nontyphoon heavy rainfall occurrences with daily rainfall totals exceeding 50 mm during 1997–2002. (b) Same as in (a) but for the annual typhoon heavy rainfall occurrences. The number of occurrences is shown by the grayscale. Terrain conftours are 100, 200, 500, and 1000 m.

May, as analyzed by T.-C. Chen et al. (2004, their Fig. 7a) from 50 yr of tropical cyclone data (1952–2001). In early August, the average number of rainfall stations with rainfall rates >15 mm h^{-1} and daily accumulations >50 millimeters per typhoon heavy rainfall day in western Taiwan have the highest peak of the year (Fig. 9). T.-C. Chen et al. (2004) showed that the frequencies of tropical cyclones over western Taiwan and within the Taiwan Strait increase substantially in early August. At this time, the monsoon trough over the northern South China Sea reaches its northernmost position during the year (Chen and Chen 2003). The western and southwestern slopes of the CMR are located on the windward side of the typhoon's circulation with frequent heavy rainfall when typhoons move to the west of the CMR. In addition, the storm circulations over southwestern Taiwan are frequently enhanced by the southwesterly monsoon flow (Lin et al. 2001; Chiao and Lin 2003). In autumn, the average number of rainfall stations with rainfall rates >15 mm h^{-1} and daily accumulations >50 millimeters per typhoon heavy rainfall day in northern and northeastern Taiwan increases from summer (Fig. 9). During the same period, the frequencies of tropical cyclones to the east and northeast of the CMR increase (T.-C. Chen et al. 2004) with northeastern and northern Taiwan on the windward side of storm circulations. Furthermore, in autumn, the storm circulations in these areas are frequently enhanced by the northeasterly monsoon flow (Sui et al. 2002).

The peak values of the averaged heavy rainfall occurrences for groups A and B per typhoon heavy rainfall day are in early July (approximately 29 occurrences or about 8% of the total rainfall stations) and late June (approximately 30 occurrences or about 8% of the total rainfall stations; Fig. 10), respectively. However, in contrast to the mei-yu and summer rainfall regimes, the occurrences of group C per typhoon heavy rainfall days

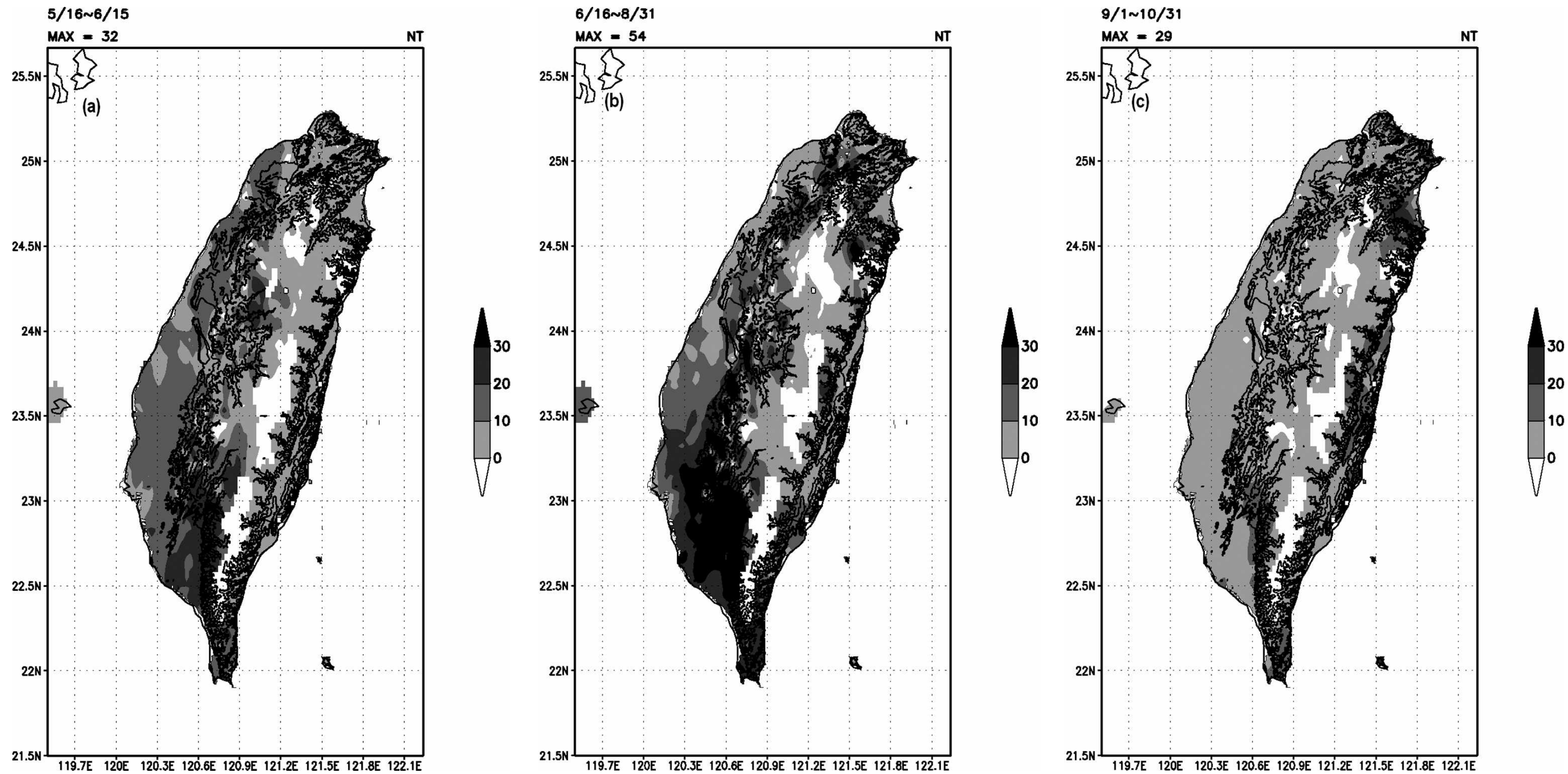

FIG. 13. (a) The nontyphoon heavy rainfall occurrences with daily rainfall totals exceeding 50 mm for the period from mid-May to mid-June during 1997–2002. Same as in (a), but for (b) mid-June–August, (c) September–October, (d) November–January, and (e) February–April. The number of occurrences is shown by the grayscale. Terrain contours are 100, 200, 500, and 1000 m.

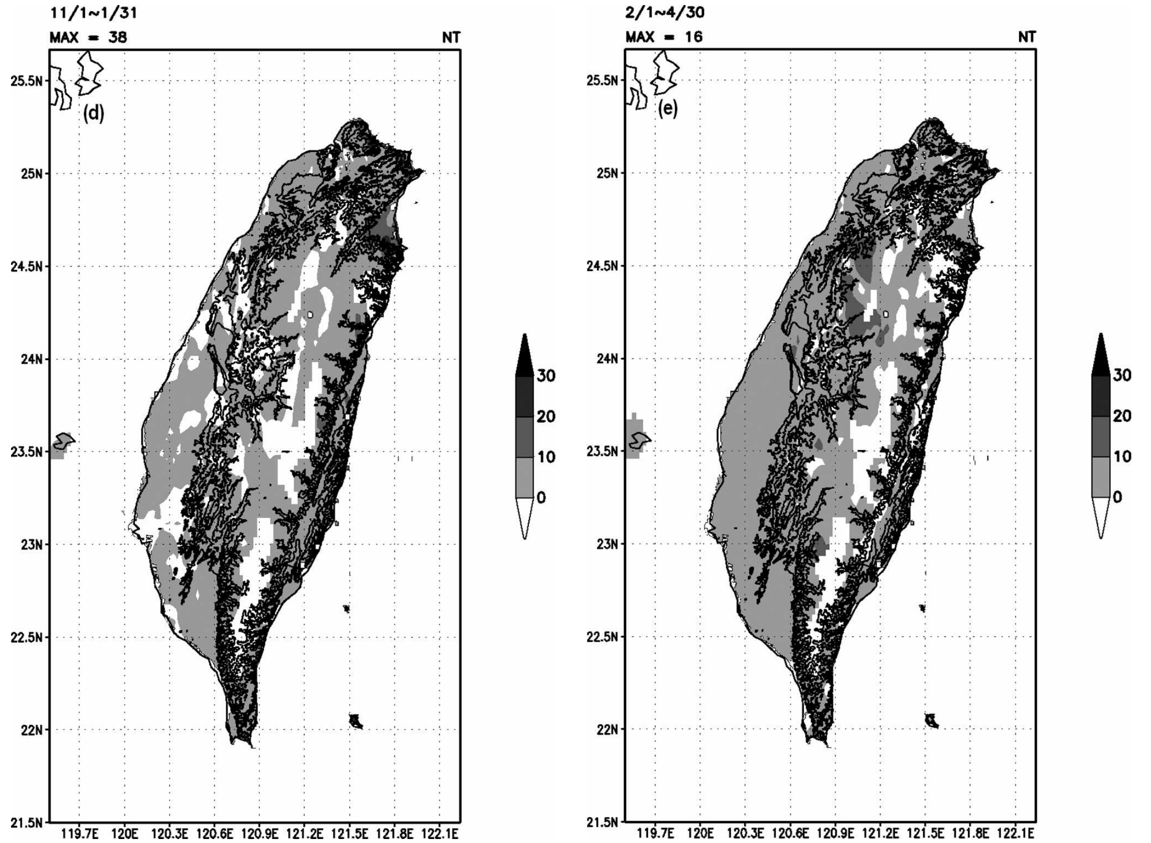

FIG. 13. (*Continued*)

in summer and early autmun (Fig. 10) are more frequent than groups A and B (Fig. 10). During the analysis period, the occurrences of group C increase from early May to summer with a peak of about 54 occurrences per typhoon heavy rainfall day (or about 15% of the total rainfall stations) in early August and about 55 occurrences per typhoon heavy rainfall day (or about 16% of the total rainfall stations) in early November. Over western Taiwan, the maximum occurrences for group C have peaks in late summer and early autumn (Fig. 11). Over northern and northeastern Taiwan, the maximum occurrences for group C have peaks in autumn (Fig. 11). Hence, during the analysis period, the period from late summer to early autumn is the most hazardous season for heavy flooding and landslide caused by typhoons.

4. The spatial distributions of heavy rainfall occurrences

a. Annual distributions of heavy rainfall occurrences

Because typhoons contribute significantly to the number of rainfall stations with rainfall rates >15 mm h^{-1} and daily accumulations >50 mm during summer and autumn (Fig. 8), it is desirable to analyze the spatial distribution of the annual number of rainfall stations with rainfall rates >15 mm h^{-1} and daily accumulations >50 mm for nontyphoon and typhoon heavy rainfall separately. The major areas with high numbers of rainfall stations with rainfall rates >15 mm h^{-1} and daily accumulations >50 mm for nontyphoon heavy rainfall (Fig. 12a) are over the western slopes of the CMR, the lowlands of southwestern Taiwan, the northern coast, and the northeastern slopes. Those areas are on the windward side of either the southwesterly or the northeasterly monsoon flow. It is apparent that orographic effects are important for the development of heavy rainfall events.

The maximum numbers of rainfall stations with rainfall rates >15 mm h^{-1} and daily accumulations >50 mm for typhoon heavy rainfall (Fig. 12b) are located over the eastern and northeastern slopes of the CMR and the northern coast. These regions are on the windward side of the frequently observed westward/northwestward-moving typhoon from the western Pacific (Shieh et al. 1998). The presence of the CMR reduces the number of rainfall stations with rainfall rates

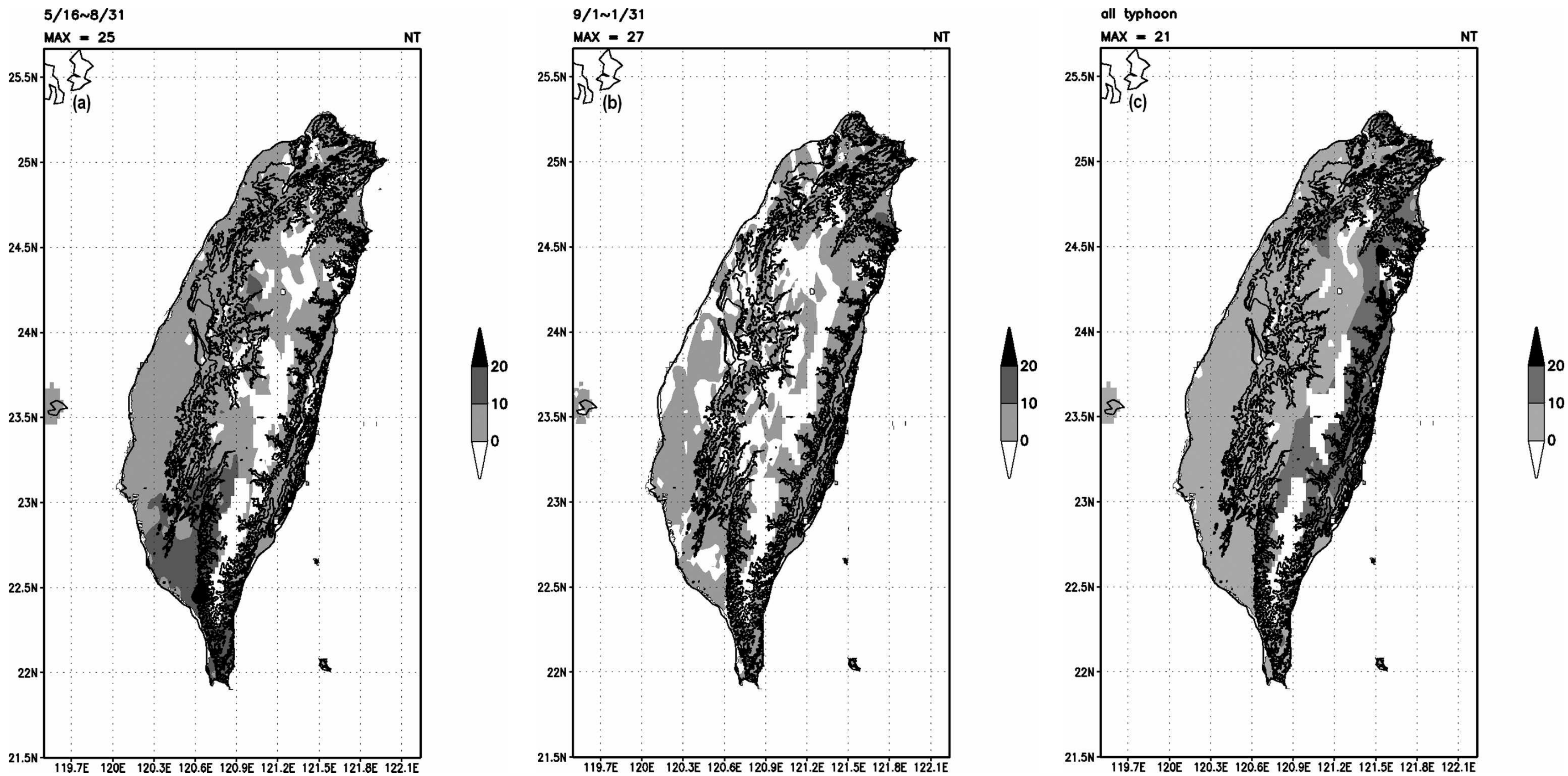

FIG. 14. (a) The nontyphoon heavy rainfall occurrences with daily rainfall totals exceeding 130 mm at one or more rain gauge stations from mid-May to August during 1997–2002. (b) Same as in (a) but for September–January. (c) The annual typhoon heavy rainfall occurrences with daily rainfall total exceeding 130 mm during 1997–2002. The number of occurrences is shown by the grayscale in (c). Terrain contours are 100, 200, 500, and 1000 m.

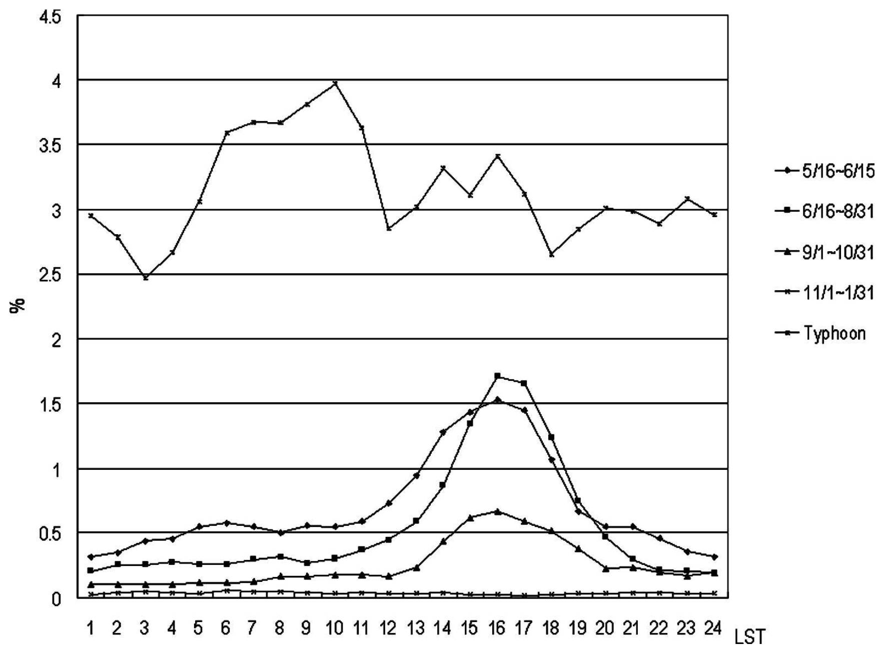

FIG. 15. Diurnal variations (LST) of the nontyphoon hourly rainfall frequency >15 mm h^{-1} (%) for the mei-yu season (diamonds), summer (squares), early autumn (September and October, triangles), late autumn to winter (November–January, crosses), and typhoons (asterisks) during 1997–2002.

>15 mm h^{-1} and daily accumulations >50 mm for typhoon heavy rainfall over western Taiwan, especially over the western coastal plains. Relatively high occurrences are found over the southwestern slopes of the CMR. Western and southwestern Taiwan could be on the windward side of the typhoon circulation if a typhoon moves across northern Taiwan or is north of Taiwan.

b. *Seasonal distributions of nontyphoon heavy rainfall occurrences*

Because the prevailing wind direction affects the spatial distribution of rainfall in different rainfall regimes (Chen and Chen 2003), it is desirable to examine the spatial distributions of the number of rainfall stations with rainfall rates >15 mm h^{-1} and daily accumulations >50 mm for different seasons.

During the mei-yu season, the number of rainfall stations with rainfall rates >15 mm h^{-1} and daily accumulations >50 mm for nontyphoon heavy rainfall is more frequent over the western windward side than the eastern lee side (Fig. 13a). The maximum occurrences are over the southwestern lowlands and slopes of the CMR. Heavy rainfall events are also relatively frequent over the northwestern slopes. Yeh and Chen (1998) found that during the 1987 mei-yu season, more than 80% of rainfall along the northwestern coast occurred during frontal periods. The convergence due to the interactions among the barrier jet along the coast (Li and Chen 1998), the prefrontal southwesterly monsoon flow, and the mei-yu front affects the rainfall production there (Li et al. 1997; Yeh and Chen 2002; Kerns 2003). Over northern coastal areas and the northeastern slopes, heavy rainfall is also frequent (Fig. 13a) within the postfrontal northeasterly flow (Chen and Chen 2003; Yeh and Chen 2004).

In summer (16 June–31 August), the number of rainfall stations with rainfall rates >15 mm h^{-1} and daily accumulations >50 mm for nontyphoon heavy rainfall has a pronounced maximum over the western slopes of the CMR and southwestern Taiwan (Fig. 13b). In addition to orographic showers in the afternoon hours on the slopes (Kerns 2003), the drifting of MCSs embedded in the southwesterly monsoon flow from nearby ocean inland (C. S. Chen et al. 2004) also contributes to the heavy rainfall occurrences over southwestern Taiwan (Fig. 13b).

In early September, the southwesterly monsoon flow is replaced by the northeasterly monsoon flow. Concurrently, the monsoon trough just south of Taiwan retreats southward (Chen and Chen 2003). The horizontal distribution of the rainfall stations with rainfall rates >15 mm h^{-1} and daily accumulations >50 mm during September–October has a local maximum over the

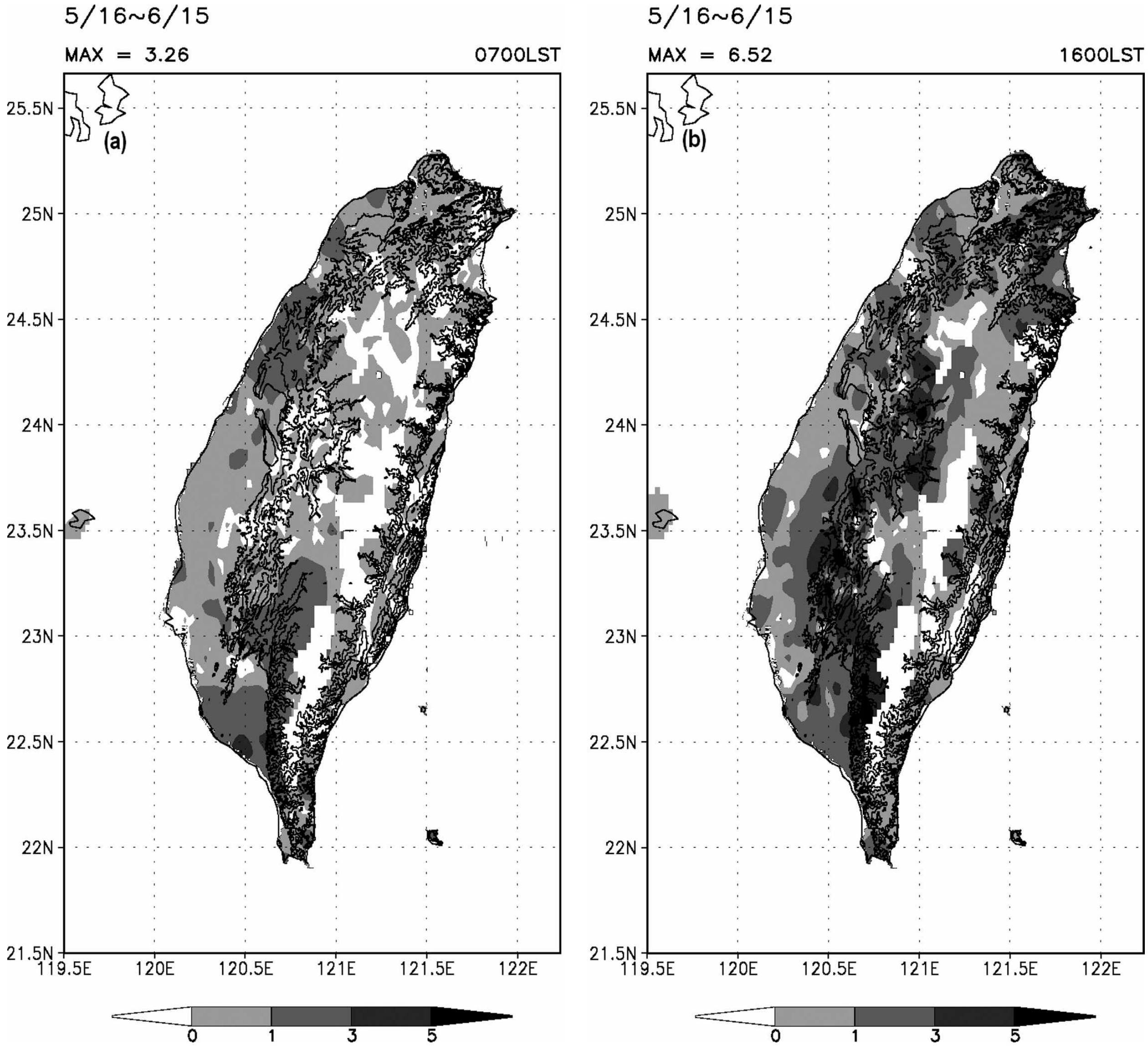

FIG. 16. (a) The spatial distribution of hourly rainfall frequency >15 mm h^{-1} for nontyphoon heavy rainfall at 0700 LST during the mei-yu season. (b) Same as in (a) but at 1600 LST. The frequency (%) is shown by the grayscale. Terrain contours are 100, 200, 500, and 1000 m.

northeastern slopes and northern coast under the northeasterly monsoon flow (Fig. 13c). With the decrease in potential instability and moisture in conjunction with the change in wind direction (Chen and Chen 2003), the number of rainfall stations with rainfall rates >15 mm h^{-1} and daily accumulations >50 mm over southwestern Taiwan and the western slopes of the CMR decreases significantly during the summer–autumn transition season.

In winter, with a stable atmospheric stratification and dry conditions (Chen and Chen 2003, their Fig. 2), the number of rainfall stations with rainfall rates >15 mm h^{-1} and daily accumulations >50 mm over most of Taiwan decreases further (Fig. 13d) from that in autumn (Fig. 13c) except over the northern and northeastern coastal areas where the northeasterly monsoon flow prevails. The main rainfall stations with rainfall rates >15 mm h^{-1} and daily accumulations >50 mm are over windward coastal areas (Fig. 13d) with a maximum on the northeastern coast.

In spring, as the northeasterly monsoon flow weakens (Chen and Chen 2003), the heavy rainfall events along the northern and northeastern coastal areas diminish. The heavy rainfall occurrences are infrequent with a local maximum over the northwestern and western-central slopes (Fig. 13e). The local maximum over

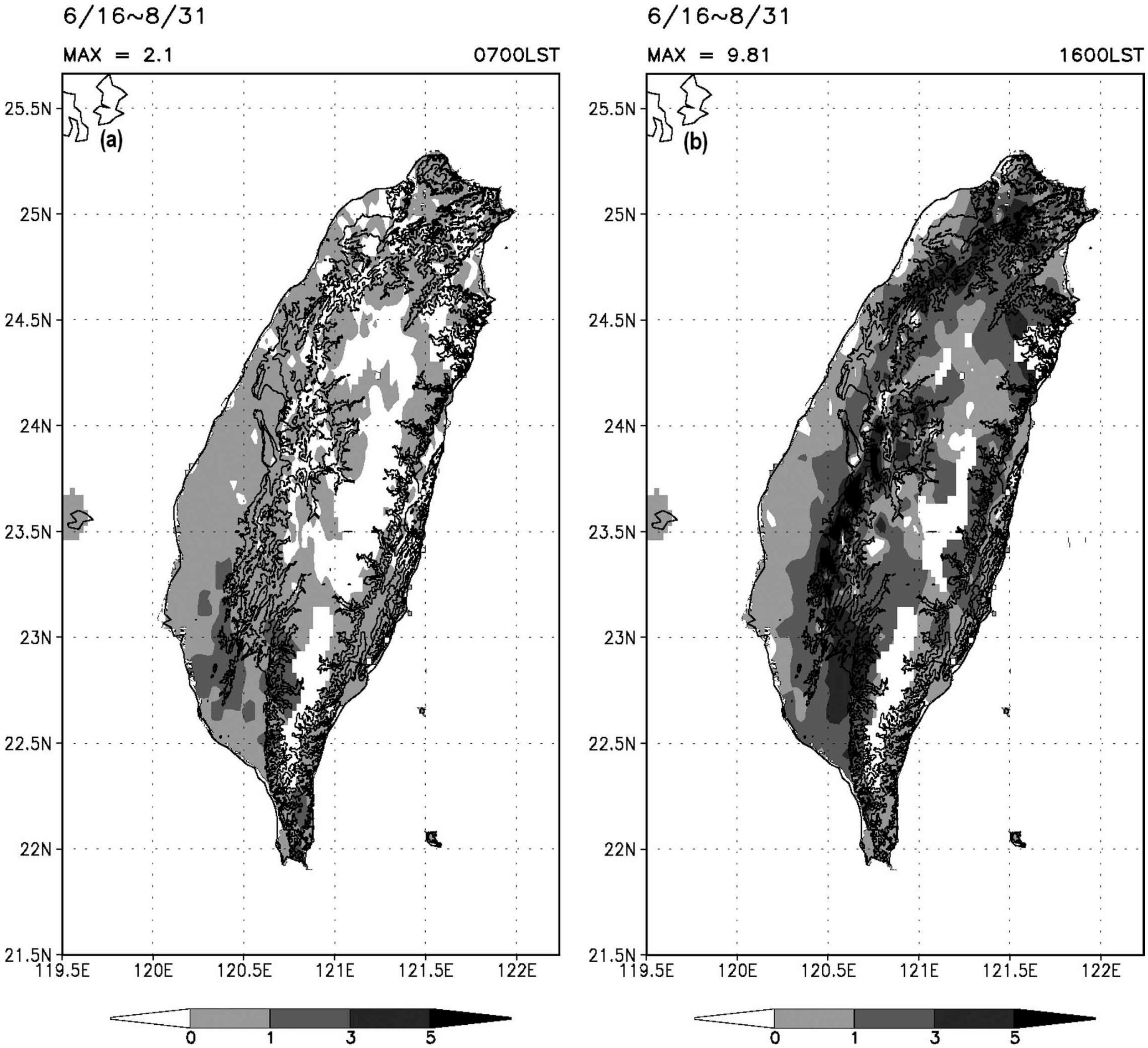

FIG. 17. (a) Same as in Fig. 16a but for the summer season. (b) Same as in (a) but at 1600 LST.

northwestern Taiwan occurs on the windward side of the southwesterly winds at the 850-hPa level as a result of the development of the western Pacific subtropical high (Chen and Chen 2003).

Because extremely heavy rainfall with daily rainfall amounts exceeding 130 mm (group C) frequently results in landslides in the mountainous regions (M.-L. Lin et al. 2002), it is desirable to construct the spatial distribution of the heavy rainfall occurrences for group C. The number of nontyphoon heavy rainfall occurrences for group C from mid-May to August under the southwesterly monsoon flow has a maximum over southwestern Taiwan (Fig. 14a). On the other hand, the number of nontyphoon heavy rainfall occurrences for group C from September to January under the northeasterly monsoon flow is more frequent over the northeastern slopes of the CMR than other areas of Taiwan (Fig. 14b). It is apparent that for group C heavy rainfall events, orographic effects are important.

The typhoon heavy rainfall occurrences for group C (Fig. 14c) are higher over eastern Taiwan and the northern coastal areas than any other areas of Taiwan. The maximum occurrences for group C are about 2/3 of the total typhoon heavy rainfall occurrences (Fig. 12b). It is apparent that group C dominates the typhoon heavy rainfall occurrences. Over the northwestern and southwestern slopes of the CMR, there are secondary maxima.

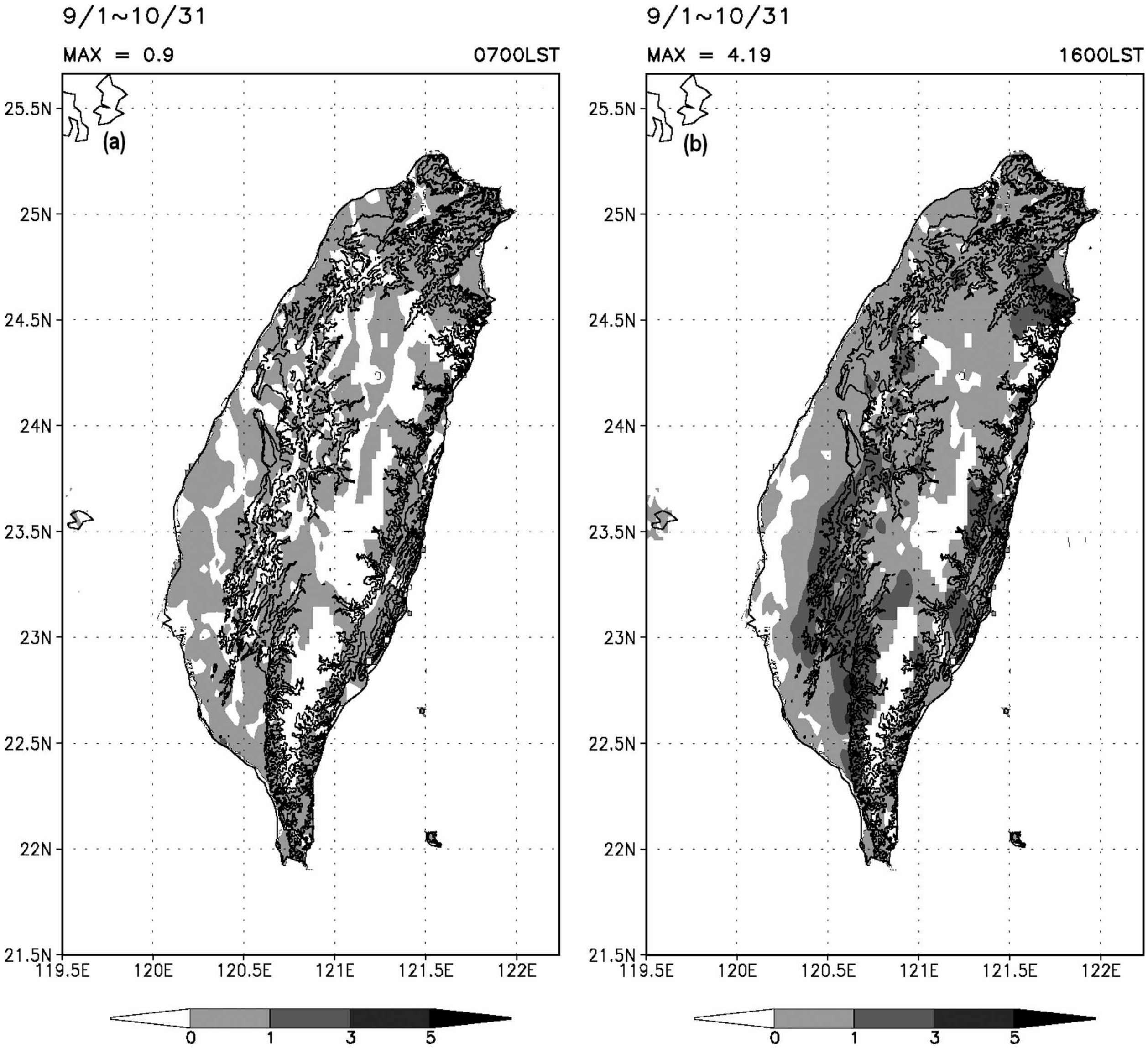

FIG. 18. (a) Same as in Fig. 16a but for the autumn season. (b) Same as in (a) but at 1600 LST.

5. Diurnal variations of heavy rainfall events

Because diurnal variations of rainfall are important during May–early October (Yeh and Chen 1998; Chen et al. 1999; Kerns 2003), it is desirable to study to what extent the diurnal cycle affects the heavy rainfall occurrences with rain rates >15 mm h^{-1} for different rainfall regimes.

The average nontyphoon high hourly rainfall (hourly rainfall rate exceeding 15 h^{-1} mm) frequency from all stations has a pronounced afternoon maximum for the mei-yu, summer, and early autumn rainfall regimes (Fig. 15). The occurrence of high rainfall rate is infrequent (<0.1%) during November–January without significant diurnal variations.

The spatial distribution of the frequency of a high nontyphoon rainfall rate during the mei-yu, summer, and early autumn seasons in the morning (in the afternoon) is shown in Figs. 16a, 17a, and 18a (Figs. 16b, 17b, and 18b) at 0700 LST (1600 LST), respectively. Relatively higher afternoon frequencies are evident over the CMR slopes and coastal mountains (Figs. 16b, 17b, and 18b). Apparently, the enhanced orographic lifting by the development of the upslope/onshore flow in the afternoon hours is one of the important factors for the development of heavy rainfall. In the early morning (0700 LST), the frequency has a local maximum over southwest Taiwan during both the mei-yu and summer seasons (Figs. 16a and 17a), but not in early autumn (Fig. 18a). This is mainly due to the drifting of MCSs

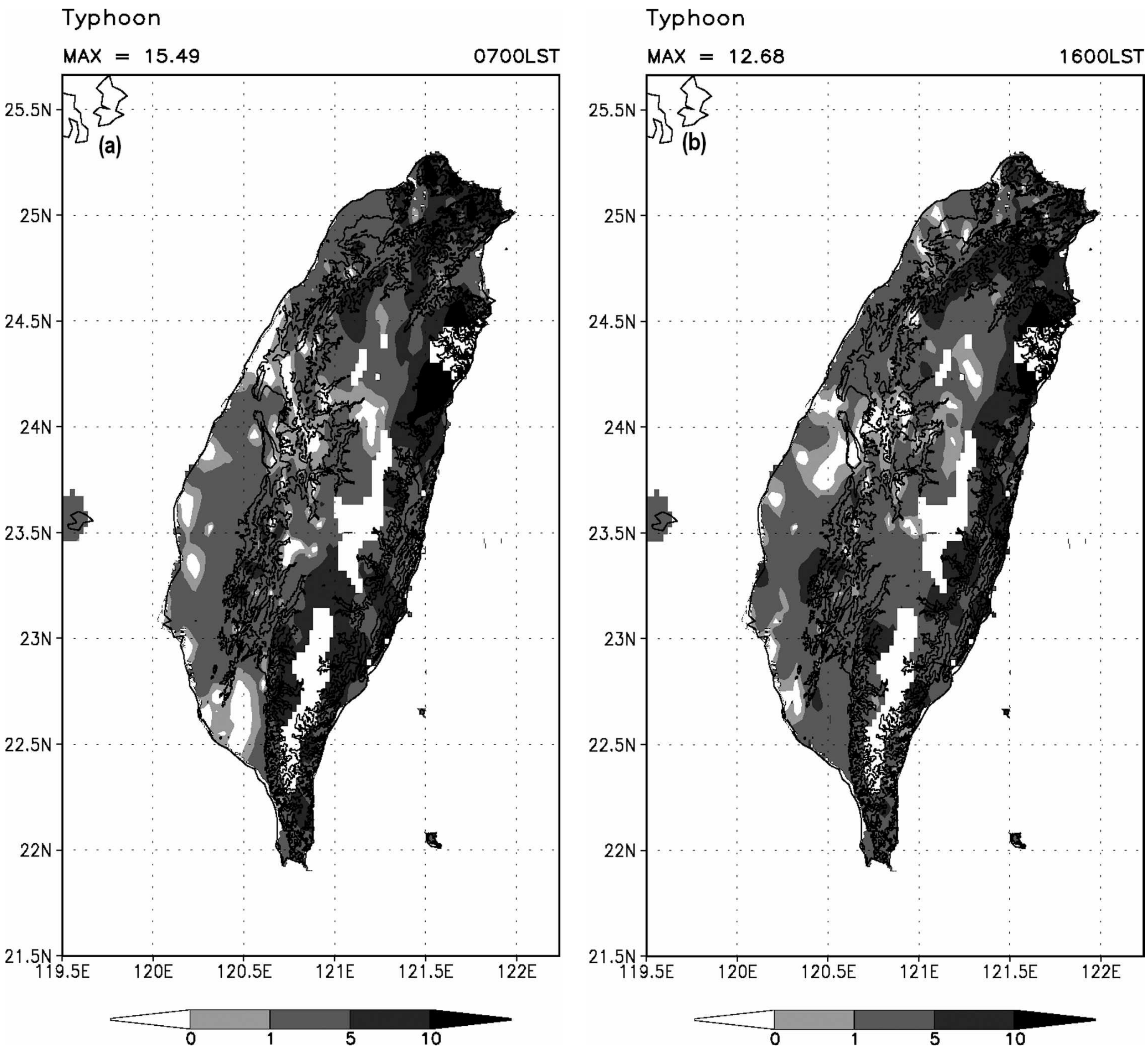

FIG. 19. (a) The spatial distribution of heavy rainfall frequency >15 mm h^{-1} for typhoon heavy rainfall at 0700 LST during mid-May–October. (b) Same as in (a) but at 1600 LST. The frequency (%) is shown by the grayscale. Terrain contours are 100, 200, 500, and 1000 m.

embedded within the southwesterly monsoon flow inland and is enhanced by the island-induced circulations (C.-S. Chen et al. 2004, 2005). The convergence between the decelerating prevailing wind and the offshore flow in the early morning would enhance the rainfall production over the southwestern coast. The relatively high frequency over the northwestern and western coast in the early morning during the mei-yu season (Fig. 16a) may be due to the offshore convergence resulting from the interactions among the barrier jet, the offshore flow, and the mei-yu front (Li et al. 1997; Yeh and Chen 2002). The prefrontal barrier jet is expected to be stronger before sunrise than at other time periods during the day because of more significant island blocking in the early morning related to cool land surface temperatures.

The diurnal variation of the frequency of high rainfall rate associated with typhoons depends on the arrival time of typhoons without significant diurnal variations (Fig. 15). Over western Taiwan, the frequency of the typhoon high rainfall rate is about the same or only slightly higher in the afternoon as compared to that in the early morning (Figs. 19a,b), but is slightly lower on the southeastern slopes of the CMR in the afternoon. The differences are not significant and may be simply related to sampling problems.

6. Conclusions

The seasonal variations of heavy rainfall days (days with at least one heavy rainfall occurrence) over Taiwan are analyzed using 6 yr (1997–2002) of hourly rainfall data from about 360 rainfall stations, including high-spatial-resolution ARMTS stations and 25 conventional stations. The heavy rainfall occurrences for each heavy rainfall day are defined as the number of stations with an hourly rainfall rate exceeding 15 mm at least once and a daily rainfall amount greater than 50 mm (Wang et al. 1985). The seasonal variations and spatial variations of heavy rainfall occurrences are analyzed over the entire island and in five subregions. Nontyphoon and typhoon cases are analyzed separately.

From late May to early autumn, nontyphoon heavy rainfall days are frequent (>60%) with peaks in early June (82%), early August (88%), early September (79%), and early October (60%) corresponding to the mei-yu, summer, summer–autumn transition, and early autumn rainfall regimes. For most cases, only a few stations would record extremely heavy rainfall (>130 mm day^{-1}) for each heavy rainfall day except during the passage of synoptic disturbances or drifting of MCSs inland. The averaged heavy rainfall occurrences (>50 mm day^{-1}) per nontyphoon heavy rainfall day are most frequent during the mei-yu season, especially in early June with secondary peaks in late summer in early August. During the mei-yu season and the summer rainfall regime, most of the rainfall stations with rainfall rates >15 mm h^{-1} and daily accumulations >50 mm are over western Taiwan on the windward side of the CMR. Heavy rainfall is also frequent over the northern coastal areas and the northeastern slopes of the CMR during the mei-yu season. These areas are on the windward side of the postfrontal northeasterly flow.

In addition to peaks in early June and early August, the average number of rainfall stations with rainfall rates >15 mm h^{-1} and daily accumulations >50 millimeters per nontyphoon heavy rainfall day over the entire island has secondary peaks during the summer–autumn transition in early September and in early October. During the summer–autumn transition, the number of rainfall stations with rainfall rates >15 mm h^{-1} and daily accumulations >50 mm is the highest over western Taiwan among all subregions. However, in early October under relatively strong northeasterly monsoon flow, northeastern Taiwan has the highest occurrences among all subregions. In early winter, although the frequency of heavy rainfall days (about 40%) is comparable to that in autumn, the average number of rainfall stations with rainfall rates >15 mm h^{-1} and daily rainfall accumulations >50 millimeters per heavy rainfall day is only about 1. Heavy rainfall occurrences during the winter months are infrequent and are dominated by localized orographic showers along the northeastern windward slopes. During the transition from the winter to the spring rainfall regime in late February, the average number of rainfall stations with rainfall rates >15 mm h^{-1} and daily accumulations >50 millimeters per nontyphoon heavy rainfall day increases, especially over western Taiwan.

The spatial distribution of annual nontyphoon heavy rainfall occurrences exhibits local maxima over the western slopes of the CMR, the lowlands of southwestern Taiwan, the northern coast, and the northeastern slopes. The spatial distributions of nontyphoon heavy rainfall occurrences depend on the direction of the low-level winds with local maxima on the windward slopes. From mid-May to August, under the southwesterly monsoon flow, the horizontal distribution of extremely nontyphoon heavy rainfall occurrences (>130 mm day^{-1}) exhibits a maximum on the southwestern of the CMR, whereas from September to January, extremely heavy rainfall events mainly occur along the northeastern slopes of the CMR under the northeasterly monsoon flow.

Typhoon heavy rainfall events begin in early May. Typhoon heavy rainfall days become more frequent (5%–15%) in summer and autumn but are lower (50%–85%) than are nontyphoon heavy rainfall days, which is consistent with the climatologically frequent appearances of tropical cyclones in the vicinity of Taiwan in August and September. Typhoons frequently bring in more widespread heavy rainfall than do nontyphoon heavy rainfall days. From May to early autumn, the average number of rainfall stations with rainfall rates >15 mm h^{-1} and daily accumulations >50 millimeters per typhoon heavy rainfall day is greater than for nontyphoon heavy rainfall days. However, heavy rainfall occurrences for group C per typhoon heavy rainfall day (daily rainfall exceeding 130 mm) increase from May to early autumn with peaks in early August, late September, and in early November. Hence, during the analysis period, the period from late summer to early autumn is the most hazardous season for heavy flooding and landslides caused by typhoons. Heavy rainfall occurrences associated with typhoons are more frequent over the eastern and northeastern slopes of the CMR and the northern coast. These regions are frequently on the windward side of the westward/northwestward-moving typhoon from the west Pacific.

The occurrences of nontyphoon heavy rainfall rates (>15 mm h^{-1}) during the mei-yu season and summer are affected by the diurnal heating cycle. Over the slopes and coastal mountains, the occurrences of heavy rainfall rates >15 mm h^{-1} have an afternoon maximum as a result of the development of onshore/anabatic flow. The frequencies of nontyphoon high rainfall rates from midnight to early morning during the mei-yu and summer rainfall regimes are much less than those in the afternoon hours. Secondary local maxima of heavy rainfall rates are observed over southwestern Taiwan in the mei-yu and summer rainy seasons and over northwestern coasts in the mei-yu season. In early autumn, the afternoon maximum of nontyphoon high rainfall rates is less pronounced as compared with the summer rainy season. The diurnal variations of the typhoon high rainfall rates are insignificant because the occurrences of high rainfall rates depend on the timing of the arrival of typhoons.

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REFERENCES

Akaeda, K., J. Reisner, and D. Parsons, 1995: The role of mesoscale and topographically induced circulations initiating a flash flood observed during the TAMEX project. *Mon. Wea. Rev.,* **123,** 1720–1739.

Brooks, H., and D. J. Stensrud, 2000: Climatology of heavy rain events in the United States from hourly precipitation observations. *Mon. Wea. Rev.,* **128,** 1194–1201.

Chen, C.-S., and Y.-L. Chen, 2003: The rainfall characteristics of Taiwan. *Mon. Wea. Rev.,* **131,** 1323–1341.

——, W.-C. Chen, and W.-K. Tao, 2004: Characteristics of heavy summer rainfall in southwestern Taiwan in relation to orographic effects. *J. Meteor. Soc. Japan,* **82,** 1521–1543.

——, ——, Y.-L. Chen, P.-L. Lin, and H.-C. Lai, 2005: Investigation of orographic effects on two heavy rainfall events over southwestern Taiwan during the mei-yu season. *Atmos. Res.,* **73,** 101–130.

Chen, G. T.-J., and T.-S. Lin, 1997: On the climatological characteristics of heavy rain events over central and southern Taiwan in mei-yu season (in Chinese with English abstract). *Atmos. Sci.,* **25,** 289–306.

——, and T.-C. Chang, 2002: On the climatological characteristics of heavy rain events over central and northern Taiwan in mei-yu season (in Chinese with English abstract). *Atmos. Sci.,* **30,** 171–185.

Chen, T.-C., M.-C. Yen, J.-C. Hsieh, and R. W. Arritt, 1999: Diurnal and seasonal variations of the rainfall measured by the automatic rainfall and meteorological telemetry system in Taiwan. *Bull. Amer. Meteor. Soc.,* **80,** 2299–2312.

——, S.-Y. Wang, W.-R. Huang, and M.-C. Yen, 2004: Variation of the east Asian summer monsoon rainfall. *J. Climate,* **17,** 744–762.

Chen, Y.-L., 2000: Effects of island-induced airflow on rainfall distributions during the Mei-yu season over Taiwan. *Proc. Workshop on Numerical Simulations of Precipitation in Taiwan Area,* Chung-Li, Taiwan, National Central University, 5–11.

——, and J. Li, 1995: Characteristics of surface airflow and pressure patterns over the island of Taiwan during TAMEX. *Mon. Wea. Rev.,* **123,** 695–716.

Chiao, S., and Y.-L. Lin, 2003: Numerical modeling of an orographically enhanced precipitation event associated with Tropical Storm Rachel over Taiwan. *Wea. Forecasting,* **18,** 325–344.

Johnson, R. H., and J. F. Bresch, 1991: Diagnosed characteristics of precipitation systems over Taiwan during the May–June 1987 TAMEX. *Mon. Wea. Rev.,* **119,** 2540–2557.

Kerns, B., 2003: Diurnal cycle of wind, clouds, and rain over Taiwan and the surrounding areas during the southwesterly monsoon rainy seasons. M.S. thesis, Dept. of Meteorology, University of Hawaii at Manoa, 139 pp.

Li, J., and Y.-L. Chen, 1998: Barrier jets during TAMEX. *Mon. Wea. Rev.,* **126,** 959–971.

——, ——, and W.-C. Lee, 1997: Analysis of a heavy rainfall event during TAMEX. *Mon. Wea. Rev.,* **125,** 1060–1081.

Lin, M.-L., T.-J. Chen, H.-J. Lin, J.-L. Lee, S.-M. Wey, S.-Y. Yeh, and W.-H. You, 2002: A preliminary study of landslides alert model in Taipei. (in Chinese with English abstract). *Proc. Conf. on Weather Analysis and Forecasting,* Taipei, Taiwan, Central Weather Bureau, 1–6.

Lin, Y.-L., S. Chiao, T.-A. Wang, M.-L. Kaplan, and R. P. Weglarz, 2001: Some common ingredients for heavy orographic rainfall. *Wea. Forecasting,* **16,** 633–660.

——, D. B. Ensley, S. Chiao, and C.-Y. Huang, 2002: Orographic influences on rainfall and track deflection associated with the passage of a tropical cyclone. *Mon. Wea. Rev.,* **130,** 2929–2950.

Lu, M.-M., and C.-J. Chen, 2005: A study of a sudden change of the frequency of strong rain in Taiwan. *Proc. Conf. on Weather Analysis and Forecasting,* Taipei, Taiwan, Central Weather Bureau, 415–422.

Ogura, Y., and M. Yoshizaki, 1988: Numerical study of orographic-convective precipitation over the eastern Arabian Sea and the Ghat Mountains during the summer monsoon. *J. Atmos. Sci.,* **45,** 2097–2122.

Ramage, C. S., 1971: *Monsoon Meteorology*. Academic Press, 296 pp.

Schumacher, R. S., and R. H. Johnson, 2006: Characteristics of U.S. extreme rain events during 1999–2003. *Wea. Forecasting,* **21,** 69–85.

Shieh, S.-L., 1986: A survey of meteorological disasters over Taiwan area (in Chinese with English abstract). *Atmos. Sci.,* **13,** 89–108.

——, S.-T. Wang, M.-D. Cheng, and T.-C. Yeh, 1998: Tropical cyclone tracks over Taiwan from 1897 to 1996 and their applications. Central Weather Bureau Technique Rep. CWB86-1M-01, 497 pp. [Available from Central Weather Bureau, 64 Gongyuan Rd., Taipei, Taiwan 10048.]

Sui, C.-H., and Coauthors, 2002: Meteorology–hydrology study targets typhoon Nari and Taipei flood. *Eos, Trans. Amer. Geophys. Union,* **83,** 265–270.

Teng, J.-H., C.-S. Chen, T.-C. Chen Wang, and Y.-L. Chen, 2000: Orographic effects on a squall-line system over Taiwan. *Mon. Wea. Rev.,* **128,** 1123–1138.

Wang, S.-T., H. Cheng, and Y.-K. Chao, 1984: Natural seasons of the weather in the Taiwan area (in Chinese with English abstract). *Atmos. Sci.,* **9,** 125–146.

——, ——, C.-H. Shu, and Y.-K. Chao, 1985: The environmental condition for heavy rainfall in Taiwan during May and June. *Proc. Conf. on Weather Analysis and Forecasting,* Taipei, Taiwan, Central Weather Bureau, 55–88.

Wang, T.-C. C., Y.-J. Lin, R. W. Pasken, and H. Shen, 1990: Characteristics of a subtropical squall line determined from TAMEX dual-Doppler data. Part I: Kinematic structure. *J. Atmos. Sci.,* **47,** 2357–2381.

Watanabe, H., and Y. Ogura, 1987: Effects of orographically forced upstream lifting on mesoscale heavy precipitation: A case study. *J. Atmos. Sci.,* **44,** 661–675.

Wu, C.-C., T.-H. Yen, Y.-Y. Kuo, and W. Wang, 2002: Rainfall simulation associated with Typhoon Herb (1996) near Taiwan. Part I: The topographic effect. *Wea. Forecasting,* **17,** 1001–1015.

Yang, M.-J., and L. Ching, 2005: A modeling study of typhoon Toraji (2001): Physical parameterization sensitivity and topographic effect. *Terr. Atmos. Oceanic Sci.,* **16,** 177–214.

Yeh, H.-C., and Y.-L. Chen, 1998: Characteristics of rainfall distributions over Taiwan during the Taiwan Area Mesoscale Experiment (TAMEX). *J. Appl. Meteor.,* **37,** 1457–1469.

——, and ——, 2002: The role of offshore convergence on coastal rainfall during TAMEX IOP 3. *Mon. Wea. Rev.,* **130,** 2709–2730.

——, and G. T.-J. Chen, 2004: Case study of an unusually heavy rainfall event over eastern Taiwan during the mei-yu season. *Mon. Wea. Rev.,* **132,** 320–337.