Characteristics of Heavy Summer Rainfall in Southwestern Taiwan in Relation to Orographic Effects

Ching-Sen Chen [1], Wan-Chin Chen [1], and Wei-Kuo Tao [2]

1 Institute of Atmospheric Physics, National Central University,
Chung-Li, Taiwan

2 Mesoscale Modeling and Dynamics Group,
Mesoscale Atmospheric Processes Branch, Code 912,
Laboratory for Atmospheres,
NASA/Goddard Space Flight Center,
Greenbelt, MD 20771, U. S. A.

Submitted to J. Meteor. Soc. Japan

(27 September 2002)
Revised (13 June 2003)
Second revision (5 November 2003, Minor revision)
Third revision (3 May 2004, Minor revision)

Corresponding author address: Dr. Ching-Sen Chen, Institute of Atmospheric Physics, National Central University, Chung-Li, 320 , Taiwan
Email: tchencs@atm.ncu.edu.tw

ABSTRACT

On the windward side of southwestern Taiwan, about a quarter to a half of all rainfall during mid-July through August from 1994 to 2000 came from convective systems embedded in the southwesterly monsoon flow. In this study, the causes of two heavy rainfall events (daily rainfall exceeding 100 mm day $^{-1}$ over at least three rainfall stations) observed over the slopes and/or lowlands of southwestern Taiwan were examined. Data from European Center for Medium-Range Weather Forecasts/Tropical Ocean-Global Atmosphere (EC/TOGA) analyses, the rainfall stations of the Automatic Rainfall and Meteorological Telemetry System (ARMTS) and the conventional surface stations over Taiwan, and the simulation results from a regional-scale numerical model were used to accomplish the objectives. In one event (393 mm day $^{-1}$ on 9 August 1999), heavy rainfall was observed over the windward slopes of southern Taiwan in a potentially unstable environment with very humid air around 850 hPa. The extreme accumulation was simulated and attributed to orographic lifting effects. No preexisting convection drifted in from the Taiwan Strait into western Taiwan.

However, in the other event (450 mm day $^{-1}$ on 13 August 1994), a westerly, potentially unstable flow with very moist air in the boundary layer converged with northwesterly flow from the central Taiwan Strait over the southwestern coast. The westerly flow decelerated while approaching Taiwan and provided additional upward motion over the

coastal convergence area, causing high rainfall amounts there. In addition, a mesoscale convergence area was produced over the southern Taiwan Strait near the southwestern coast of Taiwan due to synoptic circulations. Some convection formed in the ocean near the southwest coast and drifted inland, enhancing precipitation and promoting heavy rainfall there. The northwesterly flow transported rainwater from the coastal and lowland areas southeastward away from the southwestern slopes. Subsequently, less rainfall occurred over the southwestern slopes than over the coastal areas.

1. Introduction

Mid-July through August is one of the predominant rainy periods over Taiwan during the southwesterly monsoon (Chen and Chen 2003). According to Chen and Chen (2003), the two major forms of disturbances passing over Taiwan that produce summer rainfall are typhoons (Shieh *et al*. 1998) and convective systems embedded in the southwesterly monsoon flow (Lin *et al.* 2001; Sheih and Sheih 1989). Besides these disturbances, afternoon rain showers over the slopes of the central mountain range (CMR), that extends through Taiwan in a nearly north-northeast to south-southwest direction (Fig. 1) with an average height of about 2 km, can also generate rainfall in Taiwan (Chen and Lin 1986; Lin and Kuo 1996). Since 1994, the high density Automatic Rainfall and Meteorological Telemetry System (ARMTS) with more than 300 stations over Taiwan has been established (Chen *et al.* 1999). The mean rainfall rate over Taiwan (Fig. 2a) from mid-July to August during 1994-2000 derived from the ARMTS and 25 conventional stations shows heavy rainfall over the windward slopes from central to southern Taiwan, the lowland and coastal area of southwestern Taiwan, and the northeastern slopes of the island. Rainfall over the lowland and coastal area of western and southwestern Taiwan was partially due to convective systems embedded in the southwesterly monsoon flow (Fig. 2b). These convective systems did not contribute significantly to the rainfall over northern Taiwan as the mean position of the ridge associated with the Tibetan high at 200-hPa and the west Pacific subtropical high at 850-hPa is around 30°N in summer (Chen and Chen 2003). Their contribution (Fig. 2b) was comparable to that from typhoons

(Fig. 2c) over southwestern Taiwan.

During summer, heavy rainfall has been observed over western and southwestern Taiwan in the southwesterly monsoon flow. In this study, a heavy rainfall event is defined as having a daily rainfall accumulation that exceeds 100 mm day $^{-1}$ over at least three rainfall stations. The period of study is from mid-July through August from 1994 to 2000. Figure 2d shows the locations of the maximum daily rainfall accumulations for 12 heavy rainfall events. The maximum daily rainfall was observed either over the slopes (represented by MA through MG) or over coastal or lowland areas (denoted by CA through CE). Among these 12 events, MD and CB were the strongest producing 393 mm and 450 mm on 9 August 1999 and on 13 August 1994, respectively. Although the occurrence of heavy rainfall over southwestern Taiwan is not uncommon, the investigation of heavy rainfall over either the slopes or the lowlands of western and southwestern Taiwan in summer has been rather minimal.

Besides the effect of large-scale circulations on the formation of heavy rainfall over southwestern Taiwan, orographic effects can also be important as the CMR occupy about two-thirds of the Taiwan landmass (Chen and Chen 2003). The orographic effects on rainfall over the western windward slopes of the CMR during the 1987 mei-yu season have been studied extensively (Yeh and Chen 1998). Chen (2000) summarized the orographic effects on the 1987 mei-yu into lifting (Yeh and Chen 1998; Trier *et al.* 1990), blocking (Li *et al.* 1997; Akaeda *et al.* 1995), and thermal effects (Chen *et al.* 1991; Johnson and Bresch 1991; Akaeda *et al.* 1995; Yeh and

Chen 1998; Lin and Chen 2002). Recently, Bresch (2001) investigated a morning cloud band with light rain showers parallel to the Taiwan east coast. This feature was attributed to the effect of a land breeze.

The above studies demonstrated the important role of island-induced circulations on producing rainfall in Taiwan. Island-induced circulations also greatly influence precipitation characteristics around the island of Hawaii. Chen and Nash (1994), Carbone *et al.* (1998), Feng and Chen (2001), Wang and Chen (1998), Li and Chen (1999), Wang *et al.* (2000), Smolarkiewicz *et al.* (1988) and Chen and Feng (2001) all conferred that the convergence as a result of the deceleration of the oncoming prevailing wind and/or the interaction with offshore flow on the windward side of Hawaii was vital for forming or maintaining precipitation during night time. During the day, showers formed over the windward slopes from orographic lifting provided by anabatic-trade-wind flow (Chen and Nash 1994).

Few studies have investigated the characteristics of summer rainfall over southwestern Taiwan in the past. The present investigation examines the origins of two localized heavy rainfall events over the slopes and/or coastal lowlands of southwest Taiwan. The first case occurred on 9 August 1999 with a maximum rainfall of 393 mm day $^{-1}$ over the slopes of southwestern Taiwan (MD in Fig. 2d). The second case was on 13 August 1994 with a maximum rainfall of 450 mm day $^{-1}$ over the lowlands of southwestern Taiwan (CB in Fig. 2d). The similarities and differences in the synoptic circulation that produced these heavy rainfall events over the slopes and lowlands, respectively, will be discussed too.

2. Observational data analysis

2.1 *Data characteristics*

The synoptic analyses around Taiwan are based on the European Center for Medium-Range Weather Forecasts/Tropical Ocean-Global Atmosphere (EC/TOGA) data in 2.5 degree by 2.5 degree intervals. Rainfall comes from the 242 ARMTS stations[1] and 25 conventional surface stations over the island (Fig. 1).

2.2 *Synoptic environment on 9 August 1999*

At 0800 LST (UTC + 8 hours) on 9 August 1999, a low-pressure belt extended from the east coast of China into the west Pacific south of Japan, and a monsoon trough extended from southern China to the South China Sea at 850 hPa (Fig. 3a). The western Pacific subtropical high (WPSH) was observed east of the Philippines. Consequently, a moist southwesterly flow prevailed over the central and southern South China Sea and the Philippines. With a weak ridge over southeastern China, the southwesterly flow changed to a west-southwesterly flow with a decrease in speed from the northern South China Sea to the northern Taiwan Strait. At upper levels (200 hPa), the Tibetan ridge was near 32° N (not shown). Satellite images at 0400 LST on 9 August 1999 showed that major clouds developed over

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1 There were 242 stations in 1999 and 266 in 1994.

southern Taiwan and the Bashi Channel (Fig. 3b) but not over northern Taiwan, the Taiwan Strait and northern South China Sea. This suggests that the intense rainfall over western Taiwan was not from cloud systems drifting from the Taiwan Strait into western Taiwan.

When fast west-southwesterly moist flow (~ 10 m s^{-1}) impinged upon the CMR, heavy rainfall commenced over the western slopes in the early morning and continued until noon over the slopes in southern Taiwan (Figs. 4a and 4b). In the afternoon, high pressure over southeast China weakened (not shown). Subsequently, the pressure gradient over the northern South China Sea and Taiwan area decreased, reducing the west-southwesterly wind speed and rainfall accumulation (Fig. 4c). Total rainfall amounts were much higher over the slopes (Fig. 4d) compared to over the lowlands. Apparently, orographic lifting was important for promoting rainfall over the slopes in this particular case. There were not any convective systems that moved from the Taiwan Strait into western Taiwan to promote rainfall over the coast and lowlands. Over the slopes of southwestern Taiwan, down slope wind became evident after 0600 LST (Figs. 3c and 3d), and rainfall continued until the afternoon (Fig. 4). Over the coastal area in southwestern Taiwan, onshore flow prevailed until noon (Figs. 3c and 3d); offshore flow then began over the coast and lowland areas in southwestern Taiwan at 1200 LST (Fig. 3d) when the rain was heavy (Figs. 4b) and the prevailing wind speed decreased.

The synoptic pattern for most of the other cases with the maximum rainfall over the slopes (Fig. 2d) was similar to that on 9 August 1999 (except on 17 July 2000). The WPSH was observed over or east of the Philippines with low pressure over the east coast of China or southwest of Japan and a fast southwesterly or west-southwesterly moist flow over southern Taiwan. However, on 17 July 2000, a tropical depression over southern China induced a fast south-southwesterly moist flow over Taiwan. Convective clouds embedded in this moist flow drifted into Taiwan and generated heavy rainfall over the slopes on that particular day.

2.3 *Synoptic environment on 13 August 1994*

At 0800 LST on 13 August 1994, typhoon Ellie reached the southwest corner of Japan, and a low pressure center transformed from a weakening typhoon Doug on the previous day was located over the eastern coast of China at 850 hPa (Fig. 5a). A monsoon trough extended from southern China southeastward toward the South China Sea. High pressure was over the eastern South China Sea and the Philippines. Consequently, a moist, westerly wind prevailed over the northern South China Sea, the southern Taiwan Strait and southern Taiwan. This westerly flow was similar to the previous case. However, unlike the previous case, a northwesterly wind associated with typhoon Ellie and the low pressure over the eastern coast of China dominated the southeastern coast of China and northern Taiwan Strait. Over the eastern slopes of the Tibetan Plateau, more northwesterly flow pushed down from midlatitudes into southeastern China and the southern Taiwan Strait. Flow was confluent due to the northwesterly wind and the westerly wind over the northern part of the South China Sea and the southern portion of the Taiwan Strait (Fig. 5a). Over the Bashi Channel, southwesterly winds converged with westerly flow (Fig. 5a).

Satellite images at 0800 LST on 13 August 1994 (Fig. 5b) show that cloud systems developed over the southern Taiwan Strait and Bashi Channel and coastal area of southwestern Taiwan. Although no radar reflectivity data was available, the appearance of clouds over the southern Taiwan Strait near the southwestern coast of Taiwan suggests that clouds drifting into southern Taiwan may have enhanced rainfall there. Most of the rainfall was observed over southwestern coastal areas from early morning till the afternoon (Figs. 6a, 6b, and 6c). There was less rainfall over the slopes than the coastal area. In the evening at 2000 LST, typhoon Ellie moved westward and weakened slightly (not shown). Northwesterly wind was still observed over the coast of southeastern China (not shown). West-southwesterly wind and southeasterly flow were observed over the southern and northern Taiwan Strait, respectively (not shown). Cloud disappeared over the southern Taiwan Strait and coastal area of southwestern Taiwan. Rainfall decreased over the island with total amounts of about 450 mm over the southwestern coastal and lowland areas (Fig. 6d). It appears that the convective systems that were generated near the southwest coast and/or over the southern Taiwan Strait that drifted into southwestern Taiwan were responsible for most of the rainfall there. The impact of the convergence, due to the deceleration of the prevailing flow on the upstream side of the CMR in southwestern Taiwan, on the heavy rainfall will be examined in the simulation results. Over the coast at Tainan and Kaohsiung in southwestern Taiwan (Fig. 1), heavy rainfall was observed (Fig. 6d). However, offshore flow and onshore flow was noticed at

Tainan and Kaohsiung, respectively (Figs. 5c and 5d), implying that the enhanced convergence from the interaction between the prevailing westerly flow and offshore flow over southwestern Taiwan might not be the primary mechanism generating the heavy rainfall in this case.

The synoptic pattern for the cases that produced heavy rainfall over the lowlands on 12 August 1994 and 11 August 2000 (CA and CD in Fig. 2d) was similar to that on 13 August 1994. On these two days, an area of low pressure or a typhoon over the east coast of China produced a dry northwesterly flow over most of Taiwan. This northwesterly flow converged with moist westerly flow over the Bashi Channel and southern Taiwan Strait promoting rainfall over the southwestern coast of Taiwan. On 12 August 1999 and 3 August 2000, two more cases with heavy rainfall over the lowlands (CE and CC in Fig. 2d), Taiwan was situated on the outskirts of a circulation associated with a low pressure center over southern China. Convective clouds embedded in a moist west-southwesterly flow drifted over the lowlands of southwestern Taiwan. The synoptic pattern for these last two cases was different from the previous three cases.

The present investigation will use a mesoscale model to verify the hypotheses regarding the occurrence of heavy rainfall over either the slopes (the 9 August 1999 case) or the lowland areas (the 13 August 1994 case) of southwestern Taiwan.

3. Simulation results

The nonhydrostatic fifth-generation Mesoscale Model from the National Center for Atmospheric Research and Pennsylvania State University (MM5; Grell et al. 1994) is employed in the present investigation. Nested grids were used with horizontal resolutions of 45 km (domain 1, 98.3°E to 136.5°E, 11.4°N to 44.2°N), 15 km (domain 2, 115.3°E to 130.2°E, 16.4°N to 28.2°N) and 5 km (domain 3, 117.3°E to 123.2°E, 20.1°N to 26.0°N). All the grids have 30 levels[2] from the surface to 100 hPa in the vertical dimension. The hydrological cycle includes the subgrid-scale convective parameterization of Anthes and Kuo (Anthes 1977) and Grell (1993) in domain 1 and domain 2, respectively, and the grid-resolvable mixed-phase microphysics scheme of Reisner et al. (1998), containing prognostic equations for water vapor, cloud water, rainwater, cloud ice and snow for the first case, 9 August 1999. In the other case, 13 August 1994, the grid-resolvable microphysics scheme was adopted from Dudhia's simple ice scheme (Dudhia 1993). In the 5 km grid domain, the convective parameterization scheme is turned off. Hong-Pan PBL parameterization (Hong and Pan 1996) is used to represent planetary boundary layer processes. The radiative flux including the effects of clouds on short and long wave radiation and the surface latent and sensible heat fluxes are also calculated in the model. The model was initialized from EC/TOGA

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[2] The vertical coordinate _ is defined as $(p-p_t)(p_s-p_t)^{-1}$, where p is pressure, p_s is surface pressure, and p_t is a constant pressure (100hpa) at the top of the model. The values 0.99, 0.98, 0.97, 0.96, 0.95, 0.94, 0.92, 0.90, 0.88, 0.86, 0.84, 0.82, 0.79, 0.76, 0.73, 0.70, 0.65, 0.60, 0.55, 0.50,0.45,0.40,0.35,0.30,0.25,0.20, 0.15, 0.10, 0.05 and 0.00 were used.

analyses at 0800 LST on 8 August 1999 (0800 LST on 12 August 1994) for the 9 August 1999 (13 August 1994) case and run for 48 hours. In addition, the simulation utilized an upper radiative boundary condition, relaxation lateral boundary conditions, and two-way interactive nested grids.

3.2 9 August 1999 Case

After 24 hours of simulation, the simulated moist southwesterly flow over the South China Sea and Bashi Channel at 0800 LST (0000 UTC) on August 9 at 850 hPa (Fig. 7a) was similar to that observed (Fig. 3a). A weak ridge was also simulated over southeastern China (Fig. 7a). In general, westerly flow was simulated over the Taiwan Strait with speed decreasing from southern Taiwan to northern Taiwan. Figure 7b indicated that the main convergence area and upward motion at the 850 hPa-level were over the Bashi Channel and southern Taiwan. Downward motion was simulated over most of the Taiwan Strait, suppressing the development of clouds there. The hourly variation of relative humidity and equivalent potential temperature (_$_e$) over the southern Taiwan Strait revealed that potentially unstable west-southwesterly flow with very humid air (relative humidity_ 95 %) at the 850hPa-level approached Taiwan in the early morning on 9 August (Fig.7c). Rainfall over Taiwan was not a result of systems drifting in from the Strait into Taiwan but rather due to very humid air interacting with the CMR. In northern Taiwan, divergence and downward motion were found (Fig. 7b) limiting the rainfall potential.

In the simulation, rainfall appeared over the slopes in southern Taiwan in the early morning (Fig. 8a) as westerly wind encountered the CMR, intensified over the slopes between 0600-1200 LST (Fig. 8b), and decreased over the western slopes in the afternoon when the wind switched to weak westerly (_ 5 m s^{-1}) over southern Taiwan (Fig. 8c). Rainfall diminished in the evening (not shown) when there were weak southwesterlies with less low-level moisture than in the early morning (Fig. 7c). The simulated rainfall pattern (Fig. 8d) was similar to that observed (Fig. 4). Over the lowland and coastal areas of southwestern Taiwan, there were only light rainfall accumulations as there was less orographic lifting of the very moist air near 850 hPa than over the slopes. In addition, no intense cloud systems moved from the Strait into Taiwan to promote rainfall over the coast and lowlands. Over eastern Taiwan, the observed and simulated rainfall (Figs. 4 and 8c) both occurred over the eastern slopes mainly in the afternoon due to the prevailing onshore flow and upslope wind (Chen 2002). The simulated maximum daily rainfall accumulation was 375 mm over the slopes (point A in Fig. 8d). This was 20 mm less and about 30 km to the south of the observed maximum daily rainfall accumulation (Fig. 2d). Over the Bashi Channel, heavy, simulated rainfall amounts corresponded with the thick cloudiness observed in the satellite images (Fig. 3b).

To illustrate the orographic lifting effect on the formation of heavy rainfall over the slopes, a time-longitude cross section of the average vertically integrated rainwater content (the product of rainwater mixing ratio and air density) along an east-west cross section in southern Taiwan (Fig. 8d) is shown in Fig. 9. Rainwater content was produced over the slopes in the morning when fast westerly wind at 850-hPa impinged upon the CMR (Fig. 9a). Rainwater content intensified over the windward slopes from 0800 to 1200 LST (Fig. 9a) but decreased in the afternoon as the upstream wind changed to weak westerly or northwesterly (Fig. 9a) resulting in less lifting over the CMR. Meanwhile, moisture was less in the afternoon than in the morning at the 850 hPa-level (Fig. 7c). Most of the high rainwater contents were simulated over the western slopes or mountain tops. Owing to the mid-level rainwater, a local maximum rainwater content was over the eastern slopes. Near the surface (Fig. 9b), down-slope wind was simulated over the western slopes after 0700 LST when cool air was simulated over the slopes. The appearance of down-slope wind in the simulation was similar to the observations (~ 22.5°N, 120.6°E in Fig. 3d). Onshore flow (~ 120.5°E in Fig. 9b) dominated over the coast in the morning as was observed (~ 22.5°N, 120.5°E in Fig. 3c). When cool air arrived at the west coast at 1000 LST in the simulation, offshore flow (~ 120.5°E in Fig. 9b) began as observed (~ 22.5°N, 120.6°E in Fig. 3d). No rain areas drifted in from the nearby ocean to produce rainfall over the coast.

To further demonstrate the effect of the CMR on the production of heavy rainfall, a sensitivity test was conducted removing the CMR (no terrain run). The simulation indicated convergence and upward motion over the Bashi Channel (not shown) as in the case with terrain (Fig. 7b). However, only weak convergence and upward motion appeared over southeastern Taiwan (not shown), much less than in the case with terrain (Fig. 7b). There was no significant rainfall over Taiwan before 1200 LST (Chen 2002). Most of the rainfall over the island in the no terrain run commenced in the afternoon when the onshore flow interacted with the predominant southwesterly wind (Chen 2002) from central to eastern Taiwan (Fig. 8e). This was in contrast to the control run (Fig. 8d), confirming the key role of orographic effects in the production of heavy rainfall. Rainfall over the Bashi Channel was similar to the control run (Fig. 8d), implying it was the result of convergence from the large-scale (synoptic scale) circulation. The sensitivity test suggested that orographic lifting on a fast moist flow was the principal factor responsible for the heavy rainfall over the windward slopes of the CMR.

3.3 *13 August 1994 Case*

Since heavy rainfall over the southwest coast began in the early morning, the simulated large-scale circulation (Fig. 10a) at 0200 LST on 13 August 1994 will be discussed here. A monsoon trough was simulated in southern China with a fast, moist westerly flow over southern China, the northern South China Sea, and the southern Taiwan Strait. Low pressure was over the coast of eastern China. A northwesterly flow on the southern side of this low pressure converged with the westerly flow over the coast of southeastern China (Fig. 10b). The westerly flow decreased in speed while approaching the hilly coast of southeastern China and the island of Taiwan. Over the central Taiwan Strait, the weak, westerly flow (~ 5 m s^{-1}) passed around Taiwan island due to having the characteristics of a low Froude number flow (Fr ~ 0.25, assuming a 2 km mountain height and 0.01 s^{-1} Brunt Väisällä frequency, Smolarkiewicz and Rotunno 1990). Subsequently, the upstream westerly flow changed to northwesterly flow over the southwestern Taiwan while approaching Taiwan (Fig. 10a) and produced coastal convergence (Fig. 10b) with the westerly flow over the ocean near the southwestern Taiwan coast. The decrease in the eastward-component of the prevailing flow further enhanced convergence and upward motion over the coast of southwestern Taiwan (Fig. 10b).

Over southern Taiwan, northwesterly flow approached a fast, westerly flow and produced divergence and downward motion (Fig. 10b), unfavorable for heavy rainfall. At 0800 LST, northwesterly wind associated with a typhoon circulation flowed around the hilly terrain in southeastern China (not shown) and joined with another northwesterly wind (not shown), originating from the eastern slopes of the Tibetan Plateau at 0200 LST (Fig. 10a), to enhance convergence over the southern Taiwan Strait (Fig. 10c). Over the southern Taiwan Strait, highly moist air (relative humidity _ 95 %) extended from 850 hPa down to near the surface (Fig. 10d). The location of the highly moist air was lower on 13 August 1994 (Fig. 10d) than on 9 August 1999 (Fig. 7c). At the mid-levels, a northerly dry wind produced low _$_e$ air in the early morning (Fig. 10d) resulting in a very high potential instability. Once the potentially unstable and moist air continued entering into the convergence area over the southwestern coast, heavy rainfall commenced.

Over the central and northern Taiwan Strait, westerly flow changed to southwesterly near Taiwan producing divergence and downward motion (Figs. 10b and 10c) creating an unfavorable environment for cloud development. Since the strength of the typhoon was weaker in the simulation than observed at 0800 and 2000 LST on 13 August (not shown), the dry northwesterly flow and low _$_e$ air in the midlevels associated with typhoon Ellie 's circulation over the Taiwan Strait decreased from the very early morning (Fig. 10d). As a result, potential instability decreased in the late morning and afternoon from the very early morning.

As low-level convergence and upward motion continued over the west coast of central Taiwan in the early morning (Figs. 10b and 10c), rainfall amounts exceeding observations were produced along the coast of central Taiwan (Figs. 11a and 6a). However, the simulated rainfall over the convergence area near the southwest coast in the early morning (Fig. 11a) was similar to that observed (Fig. 6a). The wind direction changed to westerly or southwesterly over the ocean near the southwestern Taiwan coast after 1200 LST (Figs. 11b and 11c). Although convergence near the coast due to flow deceleration (not shown) and rainfall continued in the simulation over the southwestern coast and nearby ocean (Figs. 11b and 11c), rainfall amounts were less in the afternoon than in the early morning (Fig. 11a). The decrease in potential instability in the afternoon (Fig. 10d) caused the weaker upward motion and less rainfall. The northwesterly wind near the southwestern slopes in Fig. 11a and Fig. 11b transported rainfall from the southwest coast southeastward away from the slopes, resulting in less rainfall over the southwestern slopes than over coastal areas (Fig. 11). This feature is further illustrated by the average vertically integrated rainwater content (the product of rainwater mixing ratio and air density) along a northwest-southeast cross section (Fig. 12a) passing through the lowlands of southwestern Taiwan (line N in Fig. 11d). From early morning till 1600 LST, a northerly wind component transported rainwater content over the lowlands (120.1°E to 120.6° E) southward to the southern tip of the island. The maximum rainfall accumulation over the coast line was about 308 mm day $^{-1}$ (point A in Fig. 11d), about 140 mm lower than the observed maximum value (Figs. 6d and 2d) and 30 km north of the observed maximum (Fig. 2d). Another rainfall maximum of about 425 mm day $^{-1}$ over the nearby ocean, close to the coast line (point B in Fig. 11d), was about 20 km west of the observed maximum. Heavy rainfall accumulations over the southern Taiwan Strait and Bashi Channel corresponded with the observed cloud cover there.

To show the formation of rainfall over the nearby ocean close to the southwestern lowlands, a time-longitude cross section of the average vertically integrated rainwater content along an east-west cross section (line S, Fig. 11d) passing through the rainfall maximum (point B) near the southwestern coast line (Fig. 11d) is constructed in Figs. 12b and 12c. In the early morning, westerly wind converged with northwesterly wind at 850 hPa (Figs. 11a and 12b) near the coast producing convergence as shown in Figs. 10a and 10b. In addition, surface flow also converged near the coastal area (Fig. 12c). Consequently, high rainwater amounts were simulated over the ocean near the coast in the morning. When large-scale convergence was strong over the southern Taiwan Strait (Fig. 10c) around 0800 LST, high rainwater values formed over the ocean near the coast and moved inland from 0400 to 0800 LST (Figs. 12b and 12c). Although rainwater continued forming over the ocean near the coast of southwestern Taiwan from noon to evening, the intensity was not as strong as in the morning due to the decrease in potential instability (Fig. 10d). Offshore flow associated with cool air near the coast (~ 120.3°E in Fig. 12c) interacted with southwesterly flow in the afternoon and evening (Fig. 12c). But, rainwater contents were less than in the early morning over the coast. This suggests that the interaction between the onshore and offshore flows were not the primary reason for the heavy rainfall over the coast. Although there was southwesterly flow at 850 hPa in the afternoon (Fig. 12b), rainfall was not heavy over the slopes due to the decrease in potentially unstable air. Subsequently, rainwater values decreased beyond the coastal area toward the slopes (Fig. 12b).

A sensitivity test with no terrain shows convergence over the southern side of the hilly terrain in southeastern China and divergence and downward motion over the coast of southwestern Taiwan in the early morning (Fig. 13a). This feature suggests that the Taiwan terrain enhanced convergence by generating convergence between the northwesterly flow that resulted from weak westerlies over the central Taiwan Strait passing around the CMR and the prevailing westerly flow and by reducing the westerly wind speed. Over southern Taiwan and the Bashi Channel, the simulated rainfall (Fig. 13b) was over the large-scale convergence area. But, rainfall amounts over the southwestern coast were weaker than in the case with Taiwan terrain (Fig. 11d). Also, high rainfall amounts appeared in the interior and on the east coast of Taiwan in the no terrain case (Fig. 13b) in contrast to the run with terrain (Fig. 11d).

The simulation results confirmed the hypothesis regarding the formation of heavy rainfall over the slopes and/or coastal lowland areas proposed in the previous section. In the case on 9 August1999, orographic lifting enhanced heavy rainfall over windward slopes in an environment with very moist air near 850hPa embedded in a fast, southwesterly monsoon flow. No preexisting cloud systems from the Taiwan Strait drifted into Taiwan to enhance rainfall over the coastal area. In another case on 13 August 1994, a convergence area created by the large-scale circulation was over the southern Taiwan Strait. Low-level convergence and upward motion were enhanced near the coast of southwestern Taiwan due to the prevailing westerly flow converging with northwesterly flow that resulted from weak westerlies over the central Taiwan Strait passing around the CMR. Additional lifting over southwestern Taiwan was provided by the deceleration of westerly flow as it approached Taiwan. As a result, heavy rainfall was produced over the coast and lowland areas from potentially unstable air with very high moisture in the boundary layer. Some rain formed in the convergence area over the ocean near the coast of southwestern Taiwan and drifted into Taiwan to enhance rainfall there and generated heavy rainfall over the southwestern coast and lowland areas. Over the southwestern slopes, the decelerated westerly flow moved around the terrain to transport rainwater from the southwest coast and lowland area towards the southeast away from the slopes. Consequently, rainfall was minimal over the slopes in southern Taiwan.

4. Conclusions

Mei-yu season (mid-May to mid-June) and late summer (mid-June to August) are two major rainy seasons over Taiwan (Chen and Chen 2003). Convective systems embedded in the southwesterly monsoon flow accounted for about a quarter to a half of the summer rainfall over the lowland and coastal areas of southwestern Taiwan from 1994 to 2000. This contribution was comparable to that of typhoons. Heavy rainfall associated with those convective systems occurred over coastal and lowland areas and/or the slopes over southwestern Taiwan. This study investigates the orographic effects on the production of two localized heavy rainfall events over southwestern Taiwan. For the first event (9 August 1999), up to 393 mm day $^{-1}$ fell over the slopes in southwestern Taiwan while in the second event (13 August 1994), up to 450 mm day $^{-1}$ fell over the coastal and lowland areas of southwestern Taiwan. European Center for Medium-Range Weather Forecasts/Tropical Ocean-Global Atmosphere (EC/TOGA) data, rainfall data from the Automatic Rainfall and Meteorological Telemetry System (ARMTS, Chen *et al.* 1999), conventional surface stations over Taiwan, and MM5 were employed to investigate the causes of heavy rainfall observed over the slopes and/or lowlands.

The synoptic situation in both events showed that a low pressure belt extended from the east coast of China into the west Pacific south of Japan and a monsoon trough stretched from southern China into the South China Sea. In the first case on 9 August 1999, a weak ridge was observed over southeastern coastal China and a potentially unstable west-southwesterly flow with very moist air at 850 hPa prevailed over Taiwan. High rainfall accumulations were observed and simulated over the windward slopes of southern Taiwan. The simulation results indicated that orographic lifting due to west-southwesterly monsoon flow with very moist air near 850 hPa resulted in heavy rainfall over the windward slopes. No significant convergence to promote convection was simulated in the

Strait, and no cloud systems drifted in from the Taiwan Strait to produce rainfall over the coastal area.

On 13 August 1994, a weak westerly flow over the central Taiwan Strait passed around the CMR to form a northwesterly flow over southwestern Taiwan. This northwesterly flow converged with another westerly flow having a very high moisture content in the boundary layer to form convergence and upward motion over southwestern Taiwan. In addition, the westerly flow decelerated while approaching Taiwan and provided additional lifting near the coast and lowland area. High rainfall amounts were generated over the coastal convergence area. In addition, as the intensity of typhoon Ellie located over southwestern Japan in this event was stronger than the low pressure on 9 August 1999, the northwesterly wind associated with typhoon's circulation passed around the hilly terrain in southeastern China and joined with another northwesterly wind, originating from the eastern slopes of the Tibetan Plateau, to generate convergence over the southern Taiwan Strait. Furthermore, the northwesterly wind over the southern Taiwan Strait converged with westerly flow to strengthen the convergence over the southern part of the Strait. This feature was quite different from the former case. Rain formed frequently in the convergence area over the ocean near the coast of southwestern Taiwan and drifted toward southwestern Taiwan. As a result, heavy rainfall (425 mm day^{-1}) was produced over the ocean near the southwest coast in the simulation. Over the slopes of southwestern Taiwan, the northwesterly flow over the southwestern slopes moved rainwater from coast and lowland areas southeastward away from the southwestern slopes. Subsequently, rainfall was less over the slopes than over the coast.

However the simulation did not capture the observed heavy rainfall over the southwest coast very well. This was because typhoon Ellie and its associated circulation were not well simulated. The mid-level air over the southern Taiwan Strait in the simulation was moister than observed. Consequently, the instability and rainfall amounts over southwestern Taiwan were less than observed. A better numerical method for simulating typhoon Ellie could improve the rainfall simulation.

5. Acknowledgments

The constructive comments from two anonymous reviewers were highly appreciated. The first author is supported by the National Science Council, Taiwan, Republic of China under grant NSC 90-2111-M-008-038. The computer resources are supported by the Institute of Atmospheric Physics and the computer center of the National Central University. The authors thank two anonymous reviewers for their constructive comments that improved this paper considerably and Mr. S. Lang for reading the manuscript.

The third author is supported by the NASA Headquarters Atmospheric Dynamics and Thermodynamics Program and the NASA Tropical Rainfall Measuring Mission (TRMM). The author is grateful to Dr. R. Kakar at NASA headquarters for his support.

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Figure Captions

Fig. 1 Topography of Taiwan. Contours are at 500 and 1500 m. Distribution of the rainfall stations in the Automatic Rainfall and Meteorological Telemetry System (ARMTS, triangles) and 25 conventional stations (crosses).

Fig. 2 **(a)** Mean daily rainfall distribution from mid-July to August during 1994-2000. The rainfall amount is shown by the gray scale in mm day $^{-1}$. **(b)** The contribution by convective systems embedded in the southwesterly monsoon flow to the mean daily rainfall distribution in Fig. 2a. The magnitude of the contribution is shown by the gray scale in %. **(c)** The contribution by typhoons to the mean daily rainfall distribution in Fig. 2a. The magnitude of the contribution is shown by the gray scale in %. **(d)** The location and the magnitude of the maximum daily rainfall accumulation on August 12, 1994 (CA, 368 mm), August 13, 1994 (CB, 450 mm), August 3, 2000 (CC, 159 mm), August 11, 2000 (CD, 163 mm), August 12, 1999 (CE, 214 mm), August 10, 1994 (MA, 258 mm), August 11, 1994 (MB, 228 mm), August 7, 1999 (MC, 348 mm), August 9, 1999 (MD, 393 mm), July 25, 1999 (ME, 197 mm), July 28, 1999 (MF, 180 mm), and July17, 2000 (MG, 169 mm). The terrain heights are 500 and 1500 m.

Fig.3 **(a)** Synoptic analysis at 850 hPa from EC/TOGA, including heights (solid lines, 10 gpm contour interval), wind (a pennant, a full barb, and a half barb represent 25, 5, and 2.5 m s^{-1}, respectively), and relative humidity (dark areas > 80 %, 80% > gray areas > 50%, and light gray areas <50%) at 0800 LST (0000 UTC) on 9 August 1999.

(b) IR satellite image at 0400 LST on 9 August 1999.

(c) The observed surface wind at 0600 LST on 9 August 1999. A full barb and a half barb represent 5 and 2.5 m s^{-1}, respectively.

(d) The observed surface wind at 1200 LST on 9 August 1999. A full barb and a half barb represent 5 and 2.5 m s^{-1}, respectively.

Fig. 4 Rainfall distribution on 9 August 1999 for **(a)** 0100-0600 LST, **(b)** 0700-1200 LST, **(c)** 1300-1800 LST and **(d)** the 24-hour rainfall accumulation. The rainfall amount is shown by the gray scale (mm). The scale in Fig. 4d is different from the other three panels.

Fig. 5 **(a)** Synoptic analysis at 850 hPa from EC/TOGA, including heights (solid lines, 10 gpm contour interval), wind (a pennant, a full barb, and a half barb represent 25, 5, and 2.5 m s^{-1}, respectively), and relative humidity (dark areas > 80 %, 80% > gray areas > 50%, and light gray areas <50%) at 0800 LST (0000 UTC) on 13 August 1994.

(b) IR satellite image at 0800 LST on 13 August 1994 .

(c) The observed surface wind at 0200 LST on 13 August 1994. A full barb and a half barb represent 5 and 2.5 m s^{-1}, respectively.

(d) The observed surface wind at 0800 LST on 13 August 1994. A full barb and a half barb represent 5 and 2.5 m s^{-1}, respectively.

Fig. 6 Rainfall distribution on 13 August 1994 for **(a)** 0100-0600 LST, **(b)** 0700-1200 LST, **(c)** 1300-1800 LST and **(d)** the 24-hour rainfall accumulation. The rainfall amount is shown by the gray scale (mm). The scale in Fig. 6d is different from the other three panels.

Fig. 7 **(a)** The simulated synoptic pattern at 850-hPa, including heights (solid lines, 10 gpm contour interval), wind (a pennant, a full barb, and a half barb represent 25, 5, and 2.5 m s^{-1}, respectively), and relative humidity (dark areas > 80 %, 80% > gray areas > 50%, and light gray areas <50%) valid at 0800 LST (0000 UTC) on 9 August 1999 at 45 km resolution. The triangle in the southern Taiwan Strait represents the position for the profiles in Fig. 7c.

(b) The simulated divergence (solid lines) and convergence (dashed lines) at 850 hPa at 0800 LST on 9 August 1999 at 45 km resolution. The contour interval is 3 _ 10^{-5} s^{-1}. Dark (light gray) areas represent upward (downward) motion at 850 hPa.

(c) The hourly variation of profiles of relative humidity (dark areas > 95 %, 95% > gray areas > 80%, and light gray areas <80%), wind (a pennant, a full barb, and a half barb represent 25, 5, and 2.5 m s^{-1}, respectively), and equivalent potential temperature (_$_e$) over the southern Taiwan Strait (~ 22.02°N, 117°E) near the triangle in Fig. 7a from 2300 LST on 8 August to 2000 LST on 9 August 1999. The contour interval for _$_e$ is 5 K.

Fig. 8 The simulated rainfall distribution on 9 August 1999 for **(a)** 0100-

0600 LST, **(b)** 0700-1200 LST, **(c)** 1300-1800 LST and **(d)** the 24-hour rainfall accumulation at 5 km resolution. The rainfall amount is shown by the gray scale (mm). The scale in Fig. 8d is different from the other three panels. The maximum simulated rainfall was 375 mm shown by point A in Fig. 8d. The simulated wind at 850 hPa is superimposed on Figs. 8a-c at the end of the accumulated rainfall period. A full barb and a half barb represent 5 and 2.5 m s^{-1}, respectively. Line S in Fig. 8d shows the location of the east-west cross section that appears in Fig. 9.

(e) Same as in Fig. 8d but without topography over Taiwan.

Fig. 9 **(a)** Time-longitude cross section of the average vertically integrated rainwater content (the product of rainwater mixing ratio and air density) along an east-west cross section in southern Taiwan (Line S in Fig. 8d) from 0000 LST to 2400 LST on 9 August 1999 at 5 km resolution. The contours for rainwater content are 0.1, 1, and 2 g m^{-3}. The horizontal wind at 850 hPa along Line S is also shown in Fig. 9a. A full barb and a half barb represent 5 and 2.5 m s^{-1}, respectively. The terrain height along line S is shown at the bottom of Fig. 9a.

(b) Time-longitude cross section of the average vertically integrated rainwater content, near surface temperature and near surface horizontal wind along an east-west cross section in southern Taiwan (Line S in Fig. 8d) from 0000 LST to 2400 LST on 9 August 1999 at 5 km resolution. A full barb and a half barb represent 5 and 2.5 m s^{-1}, respectively. The contours for rainwater content (solid lines) are 0.1, 1, and 2 g m^{-3}. The contours for near surface temperature (dashed lines) are 2 C. The terrain height along line S is shown at the bottom of Fig. 9b.

Fig. 10 **(a)** The simulated synoptic pattern at 850-hPa, including heights (solid lines, 10 gpm contour interval), wind (a pennant, a full barb, and a half barb represent 25, 5, and 2.5 m s^{-1}, respectively), and relative humidity (dark areas > 80 %, 80% > gray areas > 50%, and light gray areas <50%) valid at 0200 LST on 13 August 1994 at 45 km resolution. The triangle in the southern Taiwan Strait represents the position for the profiles in Fig. 10d.

(b) The simulated divergence (solid lines) and convergence (dashed lines) at 850 hPa at 0200 LST on 13 August 1994 at 45 km resolution. The contour interval is 3 _ 10^{-5} s^{-1}. Dark (light) gray areas represent upward (downward) motion at 850 hPa.

(c) The simulated divergence (solid lines) and convergence (dashed lines) at 850 hPa at 0800 LST on 13 August 1994 at 45 km resolution. The contour interval is 3 _ 10^{-5} s^{-1}. Dark (light) gray areas represent upward (downward) motion at 850 hPa.

(d) The hourly variation of profiles of relative humidity (dark areas > 95 %, 95% > gray areas > 80%, and light gray areas <80%), wind (a pennant, a full barb, and a half barb represent 25, 5, and 2.5 m s^{-1}, respectively), and equivalent potential temperature (_$_e$) over the southern Taiwan Strait (~ 22.9°N, 118°E) near the triangle in Fig. 10a from 2300 LST on 12 August to 2000 LST on 13 August 1994. The contour interval for _$_e$ is 5 K.

Fig. 11 The simulated rainfall distribution on 13 August 1994 for **(a)** 0100-0600 LST, **(b)** 0700-1200 LST, **(c)** 1300-1800 LST and **(d)** the 24-hour rainfall accumulation at 5 km resolution. The rainfall amount is shown by the gray scale (mm). The scale in Fig. 11d is different from the other three panels. The simulated wind at 850 hPa is superimposed on Figs. 11a-c at the end of the accumulated rainfall period. A full barb and a half barb represent 5 and 2.5 m s^{-1}, respectively. Line S and line N in Fig. 11d show the location of the east-west cross section and northwest-southeast cross section that appears in Fig. 12. The rain accumulation at point A and B is 308 and 425 mm, respectively.

Fig. 12 **(a)** Time-longitude cross section of the average vertically integrated rainwater content (the product of rainwater mixing ratio and air density) along a northwest-southeast cross section in southwestern Taiwan (Line N in Fig. 11d) from 0000 LST to 2400 LST on 13 August 1994 at 5 km resolution. The contours for rainwater content are 0.1, 1, 2, and 3 g m^{-3}. The wind at 850 hPa along line N is also shown in Fig. 12a. A full barb and a half barb represent 5 and 2.5 m s^{-1}, respectively. The terrain height along line N is shown at the bottom of Fig. 12a.

(b) Time-longitude cross section of the average vertically integrated rainwater content (the product of rainwater mixing ratio and air density) along an east-west cross section in southern Taiwan (Line S in Fig. 11d) from 0000 LST to 2400 LST on 13

August 1994 at 5 km resolution. The contours for rainwater content are 0.1, 1, 2,3, 4 and 5 g m^{-3}. The horizontal wind at 850 hPa along line S is also shown in Fig. 12b. A full barb and a half barb represent 5 and 2.5 m s^{-1}, respectively. The terrain height along line S is shown at the bottom of Fig. 12b.

(c) Time-longitude cross section of the average vertically integrated rainwater content, near surface temperature and near surface horizontal wind along an east-west cross section in southern Taiwan (Line S in Fig. 11d) from 0000 LST to 2400 LST on 13 August 1994 at 5 km resolution. A full barb and a half barb represent 5 and 2.5 m s^{-1}, respectively. The contours for rainwater content (solid lines) are 0.1, 1, 3, and 5 g m^{-3}. The contours for near surface temperature (dashed lines) are 3 C. The terrain height along line S is shown at the bottom of Fig. 12c.

Fig. 13 **(a)** Same as in Fig. 10b but without topography over Taiwan. **(b)** Same as in Fig. 11d but without topography over Taiwan.

Characteristics of Heavy Summer Rainfall in Southwestern Taiwan in Relation to Orographic Effects

Chen, C. S., W.-C. Chen, and W.-K. Tao, 2004

J. Meteor. Soc. Japan

Popular Summary

On the windward side of southwestern Taiwan, about a quarter to a half of all rainfall during mid-July through August from 1994 to 2000 came from convective systems embedded in the southwesterly monsoon flow. In this study, the causes of two heavy rainfall events (daily rainfall exceeding 100 mm day $^{-1}$ over at least three rainfall stations) observed over the slopes and/or lowlands of southwestern Taiwan were examined. Data from European Center for Medium-Range Weather Forecasts/Tropical Ocean-Global Atmosphere (EC/TOGA) analyses, the rainfall stations of the Automatic Rainfall and Meteorological Telemetry System (ARMTS) and the conventional surface stations over Taiwan, and the simulation results from a regional-scale numerical model were used to accomplish the objectives. In one event (393 mm day $^{-1}$ on 9 August 1999), heavy rainfall was observed over the windward slopes of southern Taiwan in a potentially unstable environment with very humid air around 850 hPa. The extreme accumulation was simulated and attributed to orographic lifting effects. No preexisting convection drifted in from the Taiwan Strait into western Taiwan.

However, in the other event (450 mm day $^{-1}$ on 13 August 1994), a westerly, potentially unstable flow with very moist air in the boundary layer converged with northwesterly flow from the central Taiwan Strait over the southwestern coast. The westerly flow decelerated while approaching Taiwan and provided additional upward motion over the coastal convergence area, causing high rainfall amounts there. In addition, a mesoscale convergence area was produced over the southern Taiwan Strait near the southwestern coast of Taiwan due to synoptic circulations. Some convection formed in the ocean near the southwest coast and drifted inland, enhancing precipitation and promoting heavy rainfall there. The northwesterly flow transported rainwater from the coastal and lowland areas southeastward away from the southwestern slopes. Subsequently, less rainfall occurred over the southwestern slopes than over the coastal areas.