

Orographic Effects on Airflow and Mesoscale Weather Systems Over Taiwan

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ABSTRACT

The mountains of Taiwan affect both the airflow and mesoscale weather systems impinging on the island significantly since two-thirds of the land-mass of the country is covered by rugged terrain. The orographic feature which has the most significant impact on atmospheric systems is the Central Mountain Range (CMR) which runs through Taiwan in a NNE-SSW direction with a width of about 120 km, a length of about 300 km and an average height of 2 km. The dominant peak of the CMR has a height of 3997m above the mean sea level. Since Taiwan is surrounded by oceans, it provides a unique environment for studying the orographic effects on prevailing airflow and impinging mesoscale weather systems. In this paper, we review several prominent weather problems related to the orographic effects of the topography of Taiwan, which includes: (a) local rainfall enhancement by the CMR on prevailing winds and mesoscale convective systems, (b) the formation of mesolows and mesocyclones, (c) the effects on Mei-Yu fronts, (d) the effects on mesoscale convective systems, and (e) the influence on typhoon circulations and tracks. Understanding the first four problems is essential in improving the weather forecasting of flash floods in Taiwan during the Mei-Yu season, and is one of the major objectives of the Taiwan Area Mesoscale Experiment (TAMEX) which was a joint field experiment conducted by Taiwanese and American scientists during the period of 1 May to 29 June 1987. When a typhoon impinges on Taiwan, its circulation and track is significantly affected by the CMR. The typhoon track may be continuous or discontinuous depending upon the impinging angle, intensity, and preexisting synoptic scale pressure system. This proposes a serious forecasting problem in Taiwan. Similar problems have also been found in other parts of the world, such as Caribbean islands and Phillipines.

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1. INTRODUCTION

The mountains of Taiwan affect both the airflow and mesoscale weather systems impinging on the island significantly since two-thirds of the landmass of the country is covered by rugged terrain. The orographic feature which has the most significant impact on atmospheric systems is the Central Mountain Range (CMR) which runs through Taiwan in a NNE-SSW direction with a width of about 120 km, a length of about 300 km and an average height of 2 km (Figure 1). The dominant peak of the CMR has a height of 3997m above the mean sea level. Since Taiwan is surrounded by oceans, it provides a unique environment for studying the orographic effects on particular mesoscale weather systems. Understanding the orographic effects on local rainfall enhancement, the Mei-Yu front, and mesoscale convective systems over Taiwan is essential in improving the weather forecasting of flash floods during the Mei-Yu season, and is one of the major objectives of the Taiwan Area Mesoscale Experiment (TAMEX) which was a joint field experiment conducted by Taiwanese and American scientists during the period of 1 May to 29 June 1987. An overview of specific TAMEX objectives can be found in Kuo and Chen (1990). The mesoscale weather features observed in the Mei-Yu season has also been documented in Chen (1992). Another important influence of the Taiwan topography on mesoscale weather systems is its influence on typhoon tracks and circulations, which also proposes a serious forecasting problem.

In this paper, we will review several prominent weather problems related to the orographic effects of the topography of Taiwan, which includes but not limited to: (a) local rainfall enhancement by the CMR on prevailing winds and mesoscale convective systems,

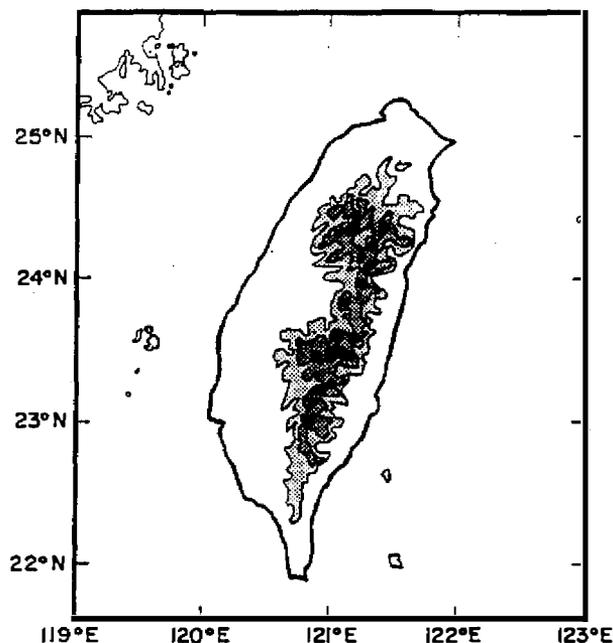


Fig. 1. Taiwan topography. Contoured shaded regions indicate elevations of every 1000 m.

(b) the formation of mesolows and mesocyclones, (c) the effects on Mei-Yu fronts, (d) the effects on mesoscale convective systems, and (e) the influence on typhoon circulations and tracks. The local rainfall enhancement is mainly produced by both orographic and thermal forcings associated with the mountain range. The low-level sensible heating often produces a nocturnal downslope flow which may intercept the prevailing southwesterly flow and trigger convection. The mechanical forcing associated with the mountain range tends to block and deflect the incoming prevailing flow. This, in turn, may alter the flow circulations around the island significantly. Mountain waves may be produced under a large or moderate Froude-number flow, while mesovortices may form to the southeast or northwest of the island under a low Froude-number flow. The southeast mesovortex may further develop into a mesocyclone. When the east-west or southwest-northeast oriented Mei-Yu front impinges on the CMR, it tends to split into two branches with the eastern branch moving southward much faster than the western branch. Under a southwesterly (northeasterly) flow, a mesolow tends to form to the southeast (west or northwest) of Taiwan.

When a mesoscale convective system impinges on the CMR during the Mei-Yu season, the local circulation associated with the mesoscale convective system may interact with the mountain wind, which may trigger or enhance convections. Thus, understanding the orographic effects on the landfalling mesoscale convective systems will help to forecast the location and strength of flash floods more accurately. The orographic effects on local rainfall enhancement, Mei-Yu fronts, and mesoscale convective systems are not isolated incidents. For example, mesoscale convective systems embedded in the Mei-Yu front may interact with local circulations, such as land-sea breezes and mountain-valley winds, mesoscale circulations often induced in or near a region of irregular terrain. Therefore, the local rainfall enhancement associated with Mei-Yu fronts or mesoscale convective systems in Taiwan needs to be investigated.

Another major concern of weather forecasting in Taiwan is the prediction of typhoon tracks and circulations. When a typhoon impinges on Taiwan, its circulation and track is significantly affected by the CMR. The orographic influence on typhoon tracks is extremely complicated. For example, the typhoon track may be continuous or discontinuous depending upon the impinging angle, intensity, and preexisting synoptic scale pressure system. For typhoons whose tracks are discontinuous, secondary mesolows or vortices may form on the downstream side of the CMR, which may further develop and augment to replace the parent typhoon.

The orographic effects of rainfall enhancement on prevailing winds and mesoscale convective systems by the topography of Taiwan will be reviewed in section 2. In section 3, we will review the formation mechanisms of lee mesolows, mesovortices, and mesocyclones. Effects of the CMR on the frontal passage will be discussed in section 4. The influence of the CMR on altering the track and modifying the circulations associated with an approaching typhoons will be reviewed in section 5. A summary is given in section 6.

2. RAINFALL ENHANCEMENT BY CMR ON PREVAILING WINDS AND MESO-SCALE CONVECTIVE SYSTEMS

2.1 Rainfall Distributions in Taiwan

An observational analysis of the rainfall distribution over Taiwan during Mei-Yu season (May 15 – June 15) averaged over the period from 1972-77 (Chen, 1978) indicated that the maximum rainfall is located on the windward slopes of the CMR (Figure 2a). The frequency

distribution of heavy rain showers, with hourly accumulated rainfall greater than 15 cm, during May and June averaged over the period from 1960-84 (Wang *et al.*, 1985) also indicates that the maximum frequency is located over the windward (southwestern) slope of the CMR (Figure 2b). Notice that the exact locations of the rainfall maximum in Figure 2 may be affected by the lack of observation stations over the mountain area. However, they tend to be located on the upslope of the CMR. In addition, the prevailing wind during the Mei-Yu season is the southwesterly monsoon current. Thus, the rainfall maximum is located on the windward slope and the dry, rain-shadow region is located on the lee slope. This type of rainfall distribution has also been observed over other major mesoscale mountain ranges in the world. For example, the rainfall rate over the Andes in South America increases with height to a certain location on the windward slope and then decreases with height (Smith, 1979). These observational analyses also indicate that the overall rainfall distribution is controlled by the CMR. In addition, during the Mei-Yu season, the rainfall is often associated with showers or convective systems embedded in Mei-Yu fronts (Wu and Wang, 1985).

During winter, the northeasterly monsoon current prevails, which brings in moisture from the East China Sea. As a result, the rainfall in Taiwan is focused on the rugged terrain in the northeast (Chi, 1969). In this region, the rainfall maxima are often located at about 500 to 600 m on the upslope, instead of directly over the mountain peaks, since the moist layer associated with the northeasterly monsoon is very shallow. The precipitation appears to be produced by the forced lifting in a stable atmosphere. This mechanism is different from the rainfall produced during the Mei-Yu season, which is often associated with impinging mesoscale convective systems or closely packed convection triggered in an conditionally unstable atmosphere. During summer and early fall, the majority of rainfall in Taiwan is linked to the passage of typhoons which release a tremendous amount of rainfall on the eastern and western sides of the CMR (Chi, 1969). However, these mechanisms proposed by Chi still need to be examined by mesoscale analysis since they are mainly based on climatological data and should be confirmed by mesoscale analysis.

In an observational analysis of precipitation systems over Taiwan during the May-June 1987 TAMEX field experiment, Johnson and Bresch (1991) found that: (a) the major rainfall events are linked to the passage of midlatitude disturbances which typically consist of both deep convective and stratiform components, and (b) there is a pronounced diurnal variability in the rainfall. Deep convection is primarily prefrontal or frontal, while the stratiform precipitation is postfrontal, presumably in association with overrunning and orographic lifting. It also has been observed that convective systems may form over the mountain peaks and the sloped terrain area in the early afternoon, which then continues to move to the lee slope (Chen *et al.*, 1991). Figure 3 shows the radar reflectivity associated with a mountain-induced precipitation system developing on the western slope of the mountains in northwestern Taiwan during the afternoon of 7 June 1987 during TAMEX IOP#8. The orographic clouds become organized into a NNE-SSW band along the western slope of the mountain range at about 1300 LST. The cloud system then propagates eastward toward the Pacific Ocean and lasts for several hours before dissipating. The eastward movement is related to the southwesterly prevailing wind (see Figure 5 of Chen *et al.*, 1991). The total amount of precipitation at Tah-Shi reached 109 mm in 5 h during the afternoon of June 7. It is also important to note that the convective system is composed primarily of closely packed, individual convective cells (Figure 4). Similar phenomenon has also been found by Jou and Chin (1993).

Heavy rainfall may be triggered or enhanced by the effects of orographic forcing on preexisting mesoscale convective systems embedded within Mei-Yu fronts. Chiou and Liu

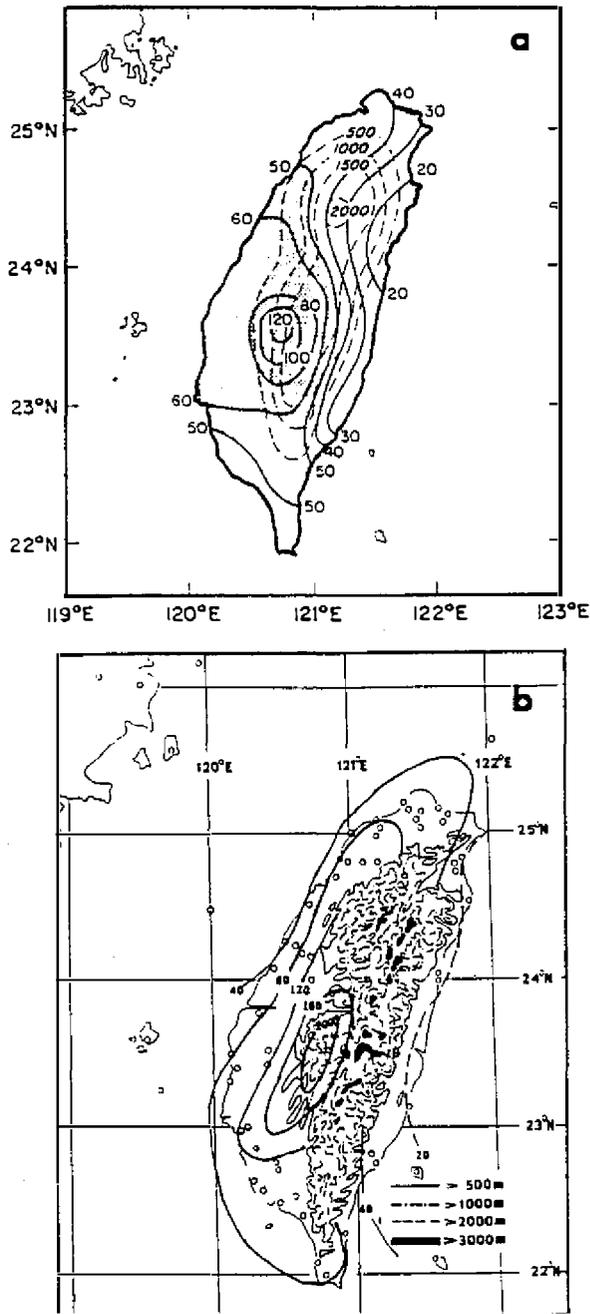


Fig. 2. (a) The rainfall distribution (in cm) over Taiwan during 15 May-15 June averaged over the period of 1972-77. The dashed contours denote the smoothed terrain in meters (after Chen, 1978). (b) Frequency distribution of heavy rain showers (hourly accumulated rainfall greater than 15 cm) for 142 "widespread precipitation" days during May and June over a period of 1960-84 (after Wang *et al.*, 1985)

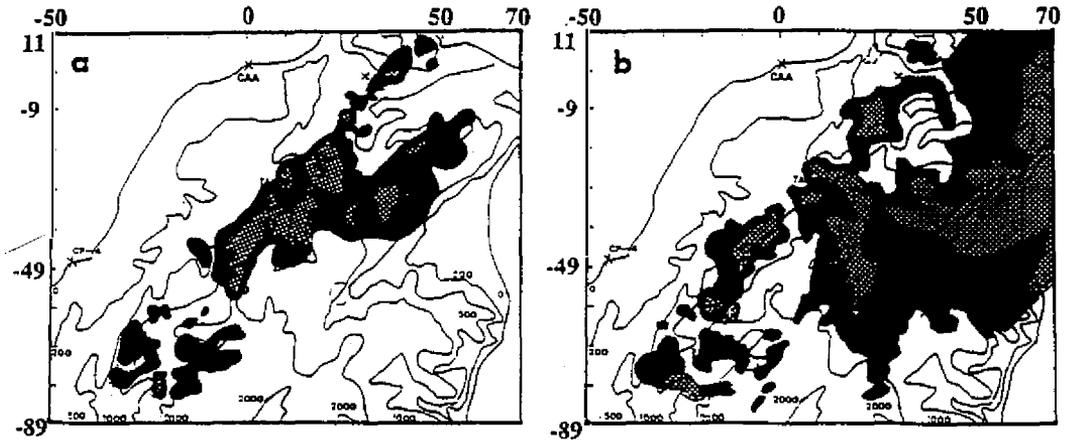


Fig. 3. Radar reflectivity at 3-km height observed by CAA radar at (a) 1300, and (b) 1550 LST of June 7, 1987 in northwestern Taiwan. Stippled and darkened area denote the 10- and 30-dBZ echo contours, respectively. Solid lines denote terrain heights in meters: The labels of x and y-axes are in km. The precipitation system developed on the northwestern slope in the afternoon and then propagated eastward (after Chen *et al.*, 1991)

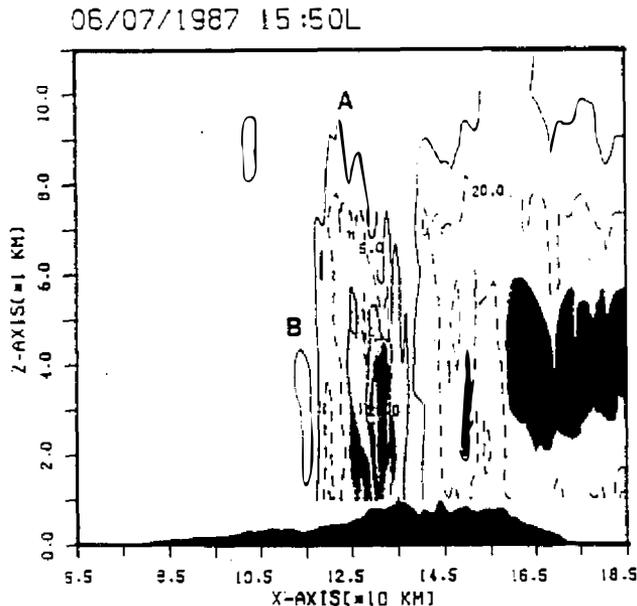


Fig. 4. Radar reflectivity in an east-west vertical cross section passing through Tah-Shi at 1550 LST 7 June 1987, corresponding to Fig. 3b. Stippled and darkened regions denote reflectivity greater than 35 and 50 dBZ, respectively. Notice that the convective system is composed by closely packed, individual convective cells. (after Chen *et al.*, 1991)

(1985) observed that new convective cells were triggered and formed an arc cloud line when one of the mesoscale convective systems, embedded in a Mei-Yu front moving toward Taiwan at 1400 LST on 2 June 1984, moved to the mountainous area. These convective cells produced a devastatingly heavy rainfall in northern Taiwan during the early morning of June 3. Figure 5 also shows an example (Y.-J. Lin, 1993). On 25 June 1987, a line of convection oriented in a direction from east-northeast to west-southwest parallel to the front developed

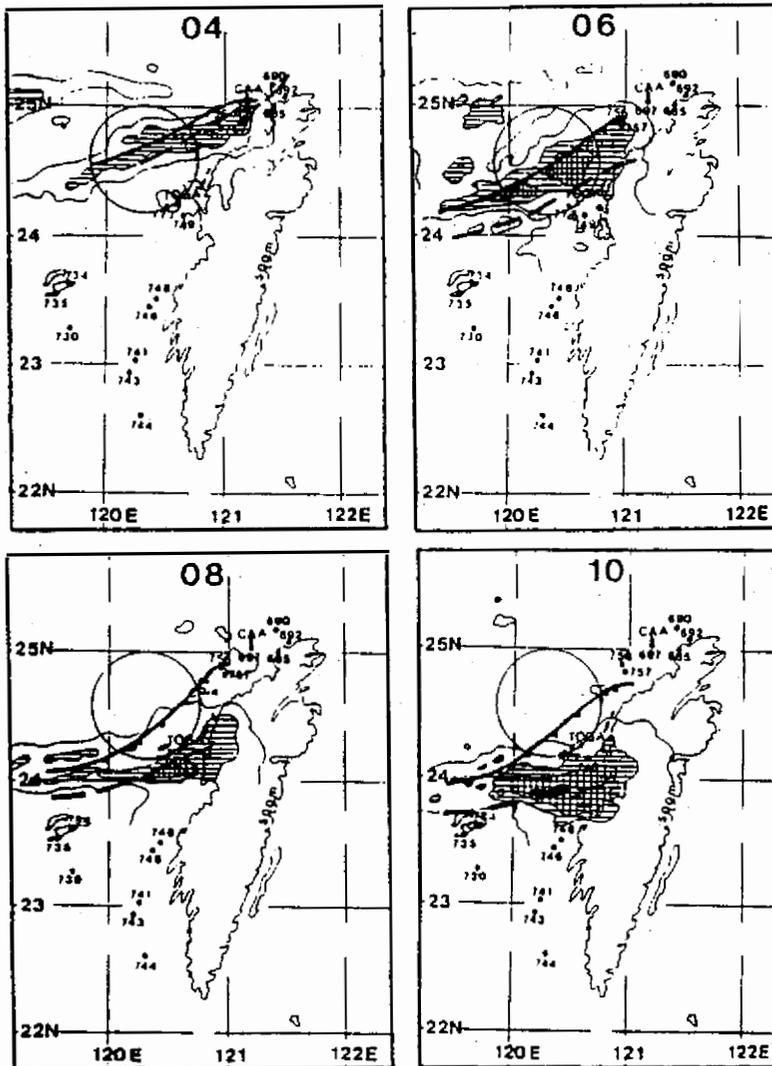


Fig. 5. An example of heavy rainfall enhanced by orographic lifting on a pre-existing mesoscale convective system. PPI displays as seen from the Kaohsiung radar from 03 to 10 LST 25 June 1987. Contour interval is 10 dBZ beginning with 15 dBZ. The darkened area signifies regions greater than 45 dBZ. The heavy and dashed lines denote the Mei-Yu front and the squall-line gust front. (after Y.-J. Lin, 1993)

in a broad area ahead of the Mei-Yu front. This prefrontal rainband traveled at a very slow speed toward south-southeast. As the system entered the dual-Doppler coverage area of CP-4 and TOGA (see the circle of Figure 5), it produced extremely heavy rainfall. Y.-J. Lin pointed out that the squall line quickly moved away from the cold front as gust fronts were formed by convective cells at the leading edge of the system. On the other hand, a preexisting squall line may be weakened by the CMR due to the blockage of the low-level moist inflow (Wang *et al.*, 1990). Orographic lifting plays an important role in enhancing the rainfall. Wu and Wang (1985) made an analysis of four such cases of flash flood events associated with the passage of fronts during periods of seasonal change. They proposed four mechanisms in order to explain the formation of the heavy rainfall: (a) convergence produced by a meso- β scale wave disturbance formed from the interaction between the southwesterly monsoon and the Mei-Yu front, (b) orographic distortion of the front with the addition of convection forced by low-level sensible heating, (c) convergence formed by the interaction of a cold front and the southeasterly trade wind, and (d) upslope orographic rain produced by the northeasterly winter monsoon. Although these mechanisms proposed by Wu and Wang may provide explanations for different types of flash floods, more rigorous investigations remain to be done to determine the exact or most dominative mechanisms.

Therefore, the rainfall distribution in Taiwan is highly dependent upon the prevailing wind direction, impinging weather systems, and orography. Based on the above observations, the rainfall in Taiwan may be classified into the following three types: (a) orographic lifting of the southwesterly monsoon currents during the Mei-Yu season or the northeasterly monsoon current during winter, (b) enhancement on mesoscale convective systems and Mei-Yu frontal rain during the Mei-Yu season, and (c) enhancement of rainfall on the passage of typhoons during summer and fall.

2.2 Formation Mechanisms of Orographic Rain

The strong influence of mesoscale mountains on local rainfall is striking for both large mountains and small hills. On large mountain ranges, the places with highest rainfall are located on the windward slopes, while for small hills they are located on the hill tops. The mechanisms of orographic rain for small hills and for large mountains are quite different. Based on the formation mechanisms of orographic rain proposed by Smith (1979) and Lin (1986, 1992) and observations in Taiwan (*italicized*), the orographic rain may be classified as follows:

- (a) Upslope orographic rain in a stable atmosphere (summarized in Smith, 1979; Johnson and Bresch, 1991).
- (b) Orographic rain in a conditionally unstable atmosphere.
 1. upslope rain, instability released by forced orographic ascent.
 - i. convective systems embedded within frontal clouds (Browning *et al.*, 1974; Chen, 1978; Wang *et al.*, 1985; Johnson and Bresch, 1991).
 - ii. closely packed convections (Smith and Lin, 1983; Chen *et al.*, 1991).
 2. lee convective rain, instability triggered by slope heating (Henz, 1972; Chen *et al.*, 1991; Johnson and Bresch, 1991; Jou and Chin, 1993).
- (c) Orographic rain over small hills by seeder cloud-feeder cloud mechanism (Bergeron, 1968).

- (d) Orographic rain triggered by convergence of a southwesterly monsoon current or a mesoscale convective system and thermally-induced downslope wind (Chiou and Liu, 1985; Hong and Hu, 1989; Y.-J. Lin, 1993).
- (e) Orographic rain induced by the low-level jet, as a conveyor belt of warm and moist air to the upslope of the mountain, associated with the passage of a front (Harrold, 1973; Chen, 1977; Chen and Yu, 1988; Jou and Deng, 1992).

The above mechanisms are sketched in Figure 6. The orographic rain on small hills in Taiwan may be dominated by the third mechanism (Figure 6c). For the first and second mechanisms (Figure 6a and b) to be important, the effect of condensation must play an active role in

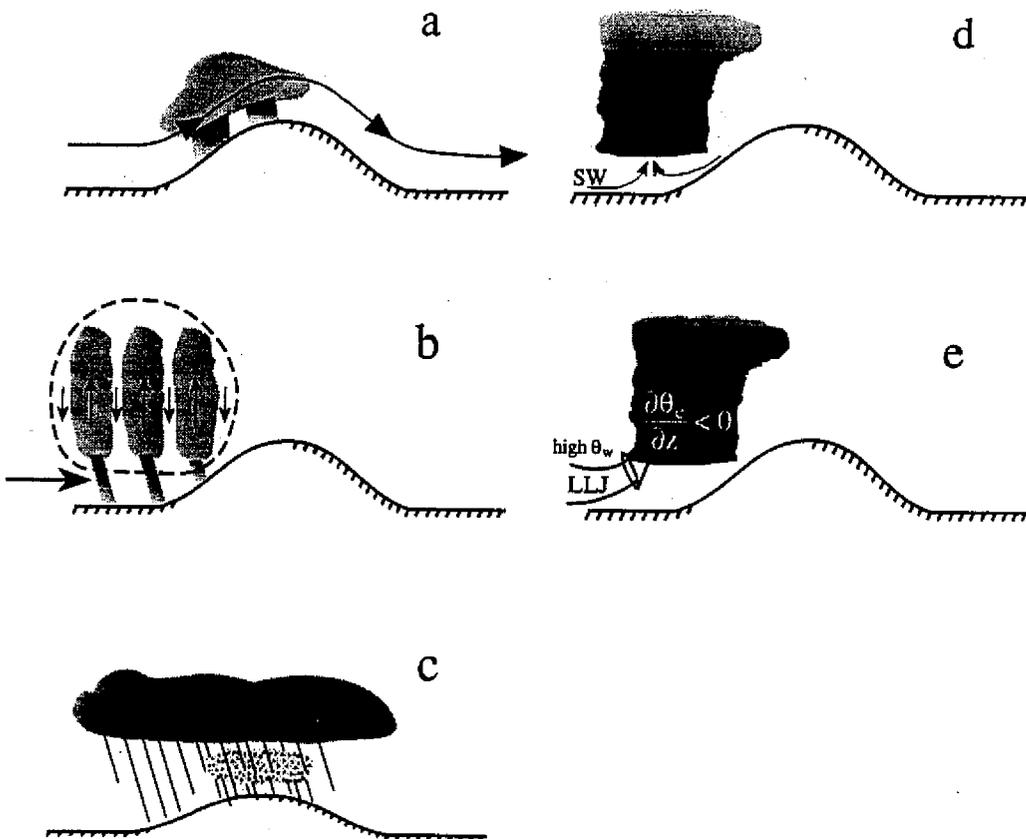


Fig. 6. A sketch of the formation mechanisms of orographic rain: (a) stable upglide, (b) closely packed convection, (c) orographic rain over small hills by seeder cloud-feeder cloud mechanism, (d) orographic rain triggered by convergence of the southwesterly monsoon current (SW) or a mesoscale convective system and the thermally-forced downslope wind, and (e) orographic rain induced by low-level jet (LLJ) ahead of Mei-Yu fronts. The first three figures are reproduced from Smith (1979).

triggering the convective clouds, since a large amount of latent heat is released once the moist air is lifted to its condensation level. This may cause the wave to amplify, or damp and induce convection currents. The last mechanism (Figure 6e) will be discussed in Section 4b. Theoretical and numerical studies on effects of moisture on orographic clouds and rain have been studied by several authors (Durran and Klemp, 1982; summarized in Lin, 1986).

2.3 Discussion

- The rainfall distribution in Taiwan is extremely complicated and may not be explained by any one of single mechanisms listed above. It appears that the formation mechanisms responsible for the orographic rain in Taiwan are dependent upon the prevailing wind directions, weather systems, and the orography.
- Observational analysis of cross sections of rainfall distribution in the direction of the prevailing wind during different seasons will be helpful in isolating the formation mechanism. For example, a northeast-to-southwest cross section of rainfall distribution should be made during the winter monsoon season which has a prevailing wind from northeast. On the other hand, the same cross section of rainfall distribution should be made during the Mei-Yu season which has a prevailing wind from southwest.
- It has been suggested that the rainfall rate is dependent upon the amount and size distributions of cloud condensation nuclei, the applicability of the Bergeron process and the orographic lifting in many studies (e.g., Kuo and Chen, 1990). However, there is a deficiency of these types of studies in TAMEX research. The relative importance of the microphysical processes to the orographic forcing needs to be investigated further.
- The basic dynamics associated with formation mechanism (d) still needs to be examined. For example, it is still not clear whether the effect of the CMR on an impinging mesoscale convective system is positive (e.g., Hong and Hu, 1989; Y.-J. Lin, 1993) or negative (e.g., Wang *et al.*, 1990). If both positive and negative relationship are able to occur, then it is essential to find out the control parameter. To thoroughly understand the orographic enhancement on rainfall associated with impinging mesoscale convective systems, theoretical studies or idealized numerical simulations of an isolated convective system passing an idealized topography with prescribed low-level surface heating will be helpful. The numerical study of Hong and Hu (1989) may be extended to include a more realistic moist budget or rain parameterization.
- Formation mechanisms c, d and e need to be examined by analyzing observational data, such as the TAMEX data.

3. FORMATION OF MESOLOWS AND MESOCYCLONES

3.1 Observations and Overview

Shallow mesolows and mesocyclones often form to the southeast or to the northwest of Taiwan when the Mei-Yu front passes over the island (Chen, 1978; Chen and Tsay, 1978). Figure 7 shows one example of the mesolows formed to the southeast of Taiwan at 1800 UTC 16 May 1987 during TAMEX (Kuo and Chen, 1990). On the upstream side of the CMR, the southwesterly or westerly wind prevails before the frontal passage. The location of the southeast mesolow shifts farther to the south for a westerly flow compared with that for a southwesterly flow. The wind speed may vary from 5 to 15 ms^{-1} in the lower layer.

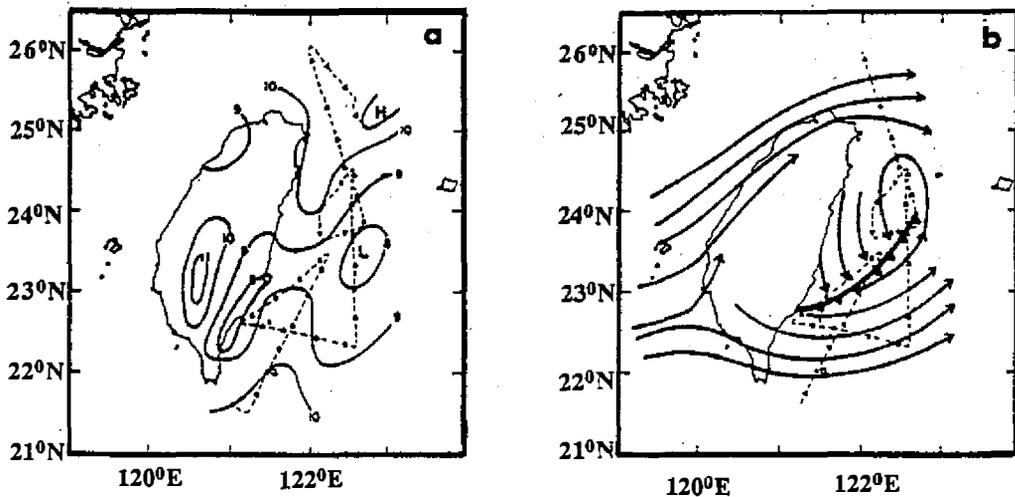


Fig. 7. An example of mesolows observed during the Mei-Yu season: (a) Sea-level pressure at 1800 UTC, May 16, 1987 and (b) 900 mb streamlines for (a). (after Kuo and Chen, 1990)

The wind turns to a more northeasterly direction behind the Mei-Yu front. The northwest mesolow is responsible for enhancing local rainfall which often leads to flash floods in northern Taiwan during the Mei-Yu season (Chen, 1978; Chen and Chi, 1980). For example, Chen and Chi found that the existence of mesolows off the northwest coast of Taiwan tends to strengthen the southwesterly monsoon current, which then produces heavy (rainfall rate > 10.1 mm/6h) and torrential rainfall (rainfall rate > 60 mm/6h). The southeast low occurs more frequently and more prominently than the northwest low. However, this northeast mesolow may be produced by the southwesterly or southerly flow over the CMR. It is essential to understand the formation mechanism of the mesolow since it is highly related to the flow structure over and around the CMR. The dynamics governing the formation mechanism will also help in understanding the orographic effects on Mei-Yu fronts and Mesoscale Convective Systems, which is one of the major scientific objectives of the TAMEX field project (Kuo and Chen, 1990).

The frequency distribution of mesolows in a six year period (1972-1977) during the Mei-Yu season indicates that about 72.5% of the mesolows form to the southeast of Taiwan, while the rest form to the northwest (Chen, 1978; Chen and Tsay, 1978; also see Figure 8). However, the existence of mesolows over the ocean is questionable due to the lack of observational data. In addition, readers should keep in mind that there is a tendency for traditional synopticians to draw a closed circulation around a low pressure center, which is not necessarily true in a mesoscale flow and is misleading. Occasionally, two mesolows may form simultaneously to the east and to the southeast of the island, such as those observed during TAMEX IOP#2 (Figure 7). The southeast mesolow often forms near the mountain and elongates in the northeast-southwest direction. A typical southeast mesolow has a short axis of about 50 - 100 km and a pressure perturbation of 3 to 5 mb. The northwest mesolow forms less frequently and is smaller in size. Observations indicate that mesolows do not form at any particular time of the day. The Taiwan mesolow is shallow and has a height of about

1.5 to 2 km. Observations also show that the southeast mesolow is warmer and less humid than its surroundings. Accompanying the southeast mesolow is a mesoscale high pressure center formed to the west or northwest of Taiwan on the windward slope. The upslope mesohigh is relatively weaker, but pronounced. When the southwesterly flow impinges upon the mountain, a major portion of the flow splits on the upwind slope and most of the low-level flow is blocked and forced to go around the CMR (Figure 7b). The frequency distributions of mesolows and mesocyclones are shown in Figure 8, which has maxima located in the southeast and northwest of Taiwan.

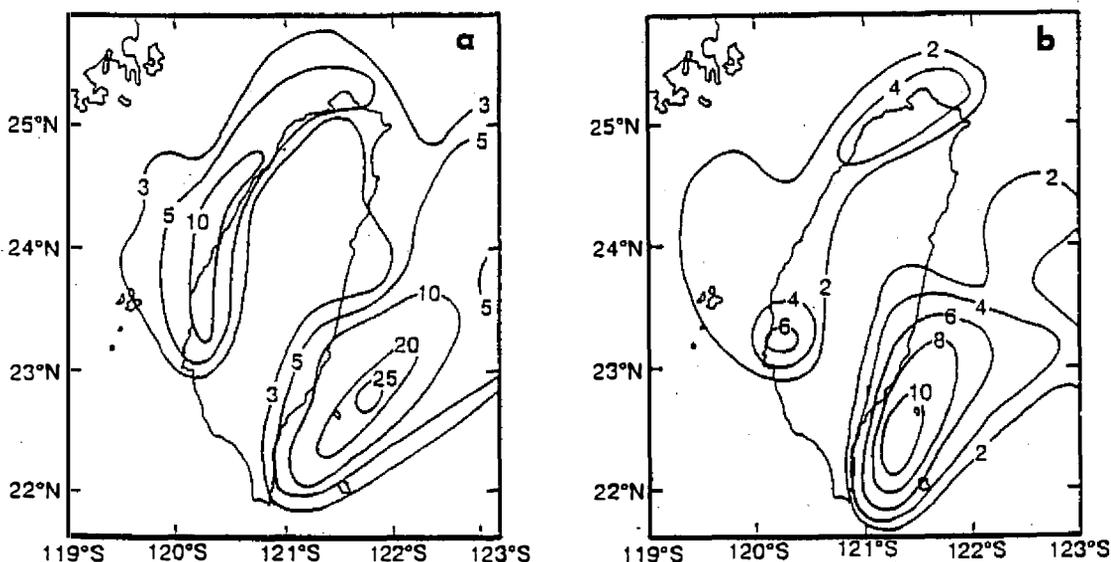


Fig. 8. The frequency distributions of mesolows and lee cyclones during the Mei-Yu period from 1972 to 1977 (after Chen, 1978 and Chen and Tsay, 1978)

A careful inspection of the analysis of TAMEX data (e.g., Kuo and Chen, 1990; also see Figure 7) indicates that the southeast Taiwan mesolow is not necessarily coupled with a mesovortex. Figure 7 also indicates that the mesolow located to the east of Taiwan is collocated with the cyclonic vortex. This combined mesolow and closed cyclonic circulation may be regarded as a mesocyclone (Lin *et al.*, 1992). In a recent numerical study of an inviscid low-Froude number flow over eastern Colorado, Crook *et al.* (1990) found that a mesocyclone forms over the Denver region which is located to the east of the Continental Divide (Denver Cyclone, see Szoke *et al.*, 1984) and moves downstream. This phenomenon is similar to the mesocyclones observed to the southeast of Taiwan.

Several mechanisms have been suggested in the literature as plausible formation mechanisms of lee mesolows and mesovortices: (a) boundary layer separation (Hunt and Snyder, 1980), (b) baroclinic vorticity tilting (Smolarkiewicz and Rotunno, 1989), (c) potential vorticity generation (Smith, 1989), (d) mountain waves (Smith, 1980), and (e) planetary vorticity stretching (Newton, 1956). A more detailed review of these mechanisms can be found in Lin *et al.* (1992).

In numerical simulations of the Denver Cyclone, Crook *et al.* (1990) found that the boundary layer does not play an important role in the formation of the lee vortex. In a numerical modeling simulation of flow past the CMR, Huang and Raman (1990) showed that the results obtained from the addition of the planetary boundary layer does not differ significantly from the inviscid flow results. However, the most challenging problem in testing the effects of boundary layer separation on the formation of the lee vortex in a mesoscale numerical model is that the grid resolution should be fine enough to resolve the turbulent eddies or to properly parameterize the physical processes associated with them. Thus, this mechanism still needs to be tested more rigorously before any conclusions can be made to its dynamical influence.

Based on the conservation of potential vorticity ($((\zeta+f)/\delta z = \text{constant})$), Kuo and Chen (1990) proposed that a cyclonic vorticity center may form on the lee side through stretching of the air column. With upstream blocking and wave breaking in a stratified flow, Ertel's (1942) theorem, which expresses the conservation of potential vorticity for adiabatic flow is violated (Smith, 1989). In addition, the rotational effect may not be significant enough to produce a lee vortex for a flow over a mesoscale mountain compared with that over a large scale mountain. Air parcels which pass around the mountain and inertia-gravity waves generated above the mountain may also modify the formation and development of the vorticity generated by the air column stretching. Since there exists air column stretching on both slopes to the northeast and southeast, one would expect two cyclonic vortices instead of a pair of cyclonic and anticyclonic vortices to form on the lee side. As will be demonstrated later, the numerical simulations do not seem to support this mechanism (Kuo and Chen, 1990) for the generation of a lee mesovortex.

In addition to the above-mentioned mesolows, mesovortices and mesocyclones formed to the southeast and northwest of Taiwan, mesoscale midlevel vortices have also been observed during TAMEX (e.g., Chen and Liang, 1992; Bluestein and Hrebensch, 1990). Analysis of the midlevel vortex which occurred during the period of 16-17 June 1987 indicates that it formed to the southeast of Taiwan and then moved northward and made a landfall near Taitung (Chen and Liang, 1992). After its northward journey along the CMR, the vortex finally moved eastward offshore to the south of Suaou into the Pacific. The life span of this vortex was more than 24 h. This midlevel vortex was primarily steered by the mean large-scale southerly flow. Chen and Liang suggested that during its northward journey the vortex possibly helped to organize the MCS. In addition, Chen and Liang proposed that the vertical vortex stretching process coupled with the local topographical effect and the pre-existing vorticity associated with the westward propagating trough is responsible for the formation of this vortex. As discussed earlier, the vortex stretching may not play major roles in generating a mesoscale vortex. This remains to be examined.

3.2 Numerical Modeling Studies

The formation of the Taiwan mesolow and mesocyclone has been studied numerically using hydrostatic models (Sun *et al.*, 1991; Lin *et al.*, 1992). Sun *et al.* has calculated the relative importance of contributions from individual terms of the vorticity equation. They found that the formation of lee vortices comes mainly from stretching, tilting, and artificial numerical friction. It is noteworthy to mention that the vorticity stretching can only contribute to the later development of lee vortices, but cannot contribute to their initial formation, according to the vorticity equation.

Figure 9 shows the streamlines and pressure perturbations for an inviscid stratified flow past the real topography of Taiwan after 15 h. The basic flow is from the west with a speed of 5 ms^{-1} . The Froude number and Coriolis parameter are 0.125 and $5.8 \times 10^{-5} \text{ s}^{-1}$, respectively. A stagnation point forms upstream of the island and one lee vortex forms over the eastern slope of the CMR at an earlier time (not shown). The formation of this lee mesovortex may be explained by the baroclinically-induced vorticity tilting as the gravity waves steepen, overturn, and break (Lin *et al.*, 1992). A mesohigh forms to the northwest of the CMR, while a major mesolow forms to the southeast (Lin *et al.*, 1992). The accompanying downslope wind passes through the center of the mesolow. This mesolow is formed by the adiabatic warming associated with the downslope wind (Lin *et al.*, 1992). The upstream mesohigh and the leeside mesolow can be explained by the hydrostatic mountain wave theory. An anticyclonic vortex also forms to the north of the existing vortex. The northern vortex forms at a later time than the southern vortex because it takes a longer time for the fluid parcel to reach the northern part of the mountain. This result is similar to the observations of Kuo and Chen (1990) and the numerical simulation of Sun *et al.* (1991). Notice that the cyclonic mesovortex develops into a mesocyclone at 15 h (Figure 9) which may explain the mesocyclone formed to the east of Taiwan as observed during TAMEX field experiment by Kuo and Chen (1990, also see Figure 1). Similar experiments indicate that a mesolow tends to form to the northwest of Taiwan in a northeasterly wind which often prevails behind the Mei-Yu front. Using a hydrostatic model, Sun and Chern (1993) showed that mesoscale vortices are able to form successively on the lee of the CMR. The intrinsic period of this type of vortex shedding is about 54 h in an inviscid adiabatic flow, which is reduced to 24 h in a diabatic flow with diurnal forcing. The reduction of the vortex shedding is no surprising since it is dominated by the forcing mode. In addition, they found that tilting is important to the generation of the vertical vorticity over the CMR and the stretching is responsible for amplifying the lee vorticity and is directly related to the initial development. The finding of vortex shedding on the lee of CMR in an inviscid flow is interesting, although there are no available observational data to confirm its existence.

With the above numerical results and the observations of Kuo and Chen (1990, also see Figure 7), Lin *et al.* (1992) proposed a conceptual model for the formation of the Taiwan mesolow and mesocyclone as shown in Figure 10. This conceptual model suggests that a stationary mesohigh forms on the upstream side of the mountain range while a mesolow forms to the southeast of the CMR under a prevailing westerly or southwesterly flow. A moving mesocyclone develops to the east of the CMR if the impinging angle of the prevailing wind is large enough.

3.3 Discussion

Using hydrostatic numerical models, Sun *et al.* (1991) and Lin *et al.* (1992) are able to reproduce the mesolow and mesocyclone observed to the southeast of Taiwan during TAMEX (Kuo and Chen, 1990). Lin *et al.* (1992) suggests that the distinction between the Taiwan mesolow and lee vortex should be made because they do not necessarily collocate. Thus, more careful data analysis for the Taiwan mesolow is needed. This is an important finding since some traditional synoptic analysis in this area often relate closed cyclonic circulations with mesoscale low pressure centers (e.g., Wang, 1986; also see Figure 16). However, the formation of lee mesovortices still needs to be investigated due to their transient features which occur for both idealized and real topographies. Even though Smolarkiewicz and

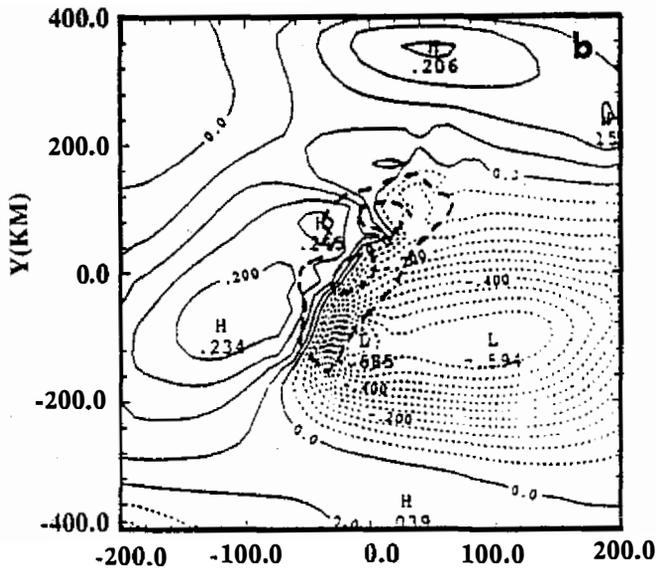
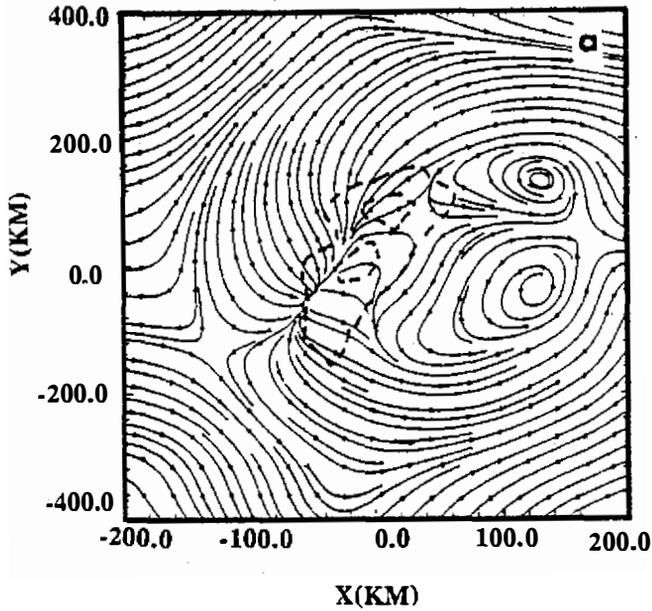


Fig. 9. Streamlines and perturbation pressure for a westerly flow over the real topography of Taiwan after 15 h of a numerical simulation. The Froude number is about 0.125. The basic flow speed and Brunt-Vaisala frequency are 5 ms^{-1} and 0.01 s^{-1} . The Coriolis parameter is $5.8 \times 10^{-5} \text{ s}^{-1}$. Contours of 500 and 2500 m of the mountain height are depicted by heavy dashed curves. (after Lin *et al.*, 1992)

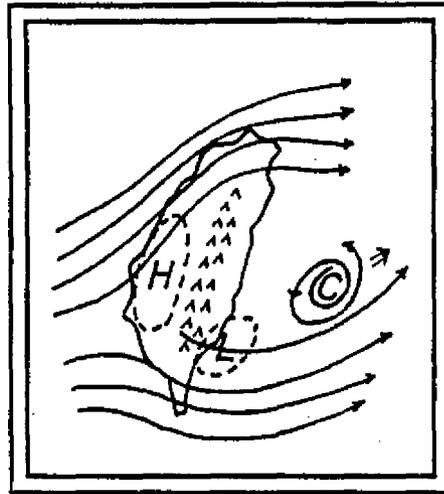


Fig. 10. A conceptual model of the Taiwan southeast mesolow and mesocyclone. A stationary mesohigh forms on the upstream side and a mesolow forms to the southeast of the CMR under a prevailing westerly or southwesterly flow. An additional moving mesocyclone develops to the east of the CMR if the impinging angle of the prevailing wind is larger. (after Lin *et al.*, 1992)

Rotunno (1989) stated that the only source of vertical vorticity in their numerical experiments is the baroclinically-induced vorticity tilting, the contribution of the stretching term to the vertical vorticity at later times, such as that found in Sun *et al.* (1991), cannot be ignored once the vertical vorticity has developed. The relative importance of this stretching term to the tilting term still needs to be investigated. The formation mechanism of the midlevel vortex proposed by Chen and Liang (1992) has no solid evidence in the data analysis and still needs to be examined. In addition, due to the disagreement between Smolarkiewicz and Rotunno (1989) and Smith (1989), the interpretations of the generation of lee vortices as simulated by Smolarkiewicz and Rotunno should also be addressed by future work. Again, one should keep in mind that the lee vortex does not necessarily produce mesolows with it.

Due to the steepness of the CMR, the work of Sun *et al.* (1991) and Lin *et al.* (1992) should be extended by adopting a nonhydrostatic numerical model to study the detailed flow circulation around the island. This may be accomplished by nesting a nonhydrostatic model for a particular region of interest in a hydrostatic model, which has a smaller domain and finer resolution.

It appears that the southeast mesolow forms under a prevailing westerly or southwesterly wind, while the northwest mesolow forms under a prevailing northeasterly or northerly wind. Thus, it will be helpful to distinguish different frequency distributions of the mesolow and mesocyclone formations based on the basic wind directions. In addition, the mechanism proposed by Chen and Chi (1980), in which the formation of the northwest mesolow tends to strengthen the southwesterly monsoon current and then produce heavy or torrential rainfall, is interesting, but needs to be examined using both data analysis and numerical simulations with moisture effects included. According to Lin *et al.* (1992), the northwest mesolow is produced

by the northeasterly current behind the frontal passage. It is observed that the southwesterly current often turns northwesterly after the Mei-Yu front passes over Taiwan from the north (e.g., Chen and Hui, 1992). It appears that the northwest or west mesolow is an effect of the frontal passage, instead of a cause of heavy rainfall. Therefore, the relationship between the mesolow and the enhancement of the southwesterly still remains to be clarified. Effects of the planetary boundary layer and vertical wind shear on the formation of lee mesolows and mesocyclones also need to be investigated.

4. EFFECTS ON THE PASSAGE OF FRONTS OVER CMR

4.1 Frontal Distortion

When an east-west or southwest-northeast oriented Mei-Yu front impinges on the CMR from the north or northwest, it splits into two branches. The eastern branch moves southward much faster than the western branch. On the western side of the CMR, the southwesterly wind prevails before the frontal passage. The wind turns to the northeast or north after the passage of the Mei-Yu front. The deformation of the Mei-Yu front over Taiwan has been documented in Chen (1980) and Wang (1986) among others. Observational analyses of the passage of Mei-Yu fronts over Taiwan during TAMEX have also been performed by Trier *et al.* (1990) and Chen and Hui (1992). Since a significant portion of heavy rainfall events during the Mei-Yu season occurs when a Mei-Yu front and its embedded mesoscale convective systems pass over Taiwan, it is essential to understand the deformation mechanisms of the Mei-Yu front as it passes over the CMR.

Figure 11 shows the surface positions of a Mei-Yu front during the period from 0000 UTC 11 June to 1800 UTC 12 June 1986 (Chen, 1978). At 1100 UTC, the eastern branch

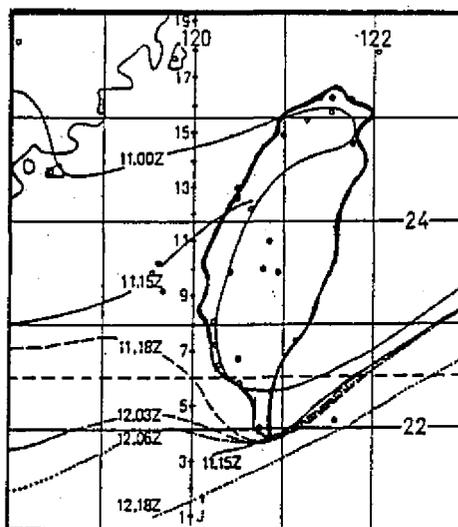


Fig. 11. The surface locations of a Mei-Yu front during 0000 UTC 11 June and 1800 UTC 12 June 1986. (after Chen, 1978)

has already propagated to a location near the southern tip of Taiwan, while the western branch is still located in northern Taiwan. After 1100 UTC, the eastern branch became more or less stationary. These two branches eventually merged at about 0300 UTC on June 12. Figure 12 shows the surface wind field and frontal locations of a Mei-Yu front on 13 May 1987 (Chen and Hui, 1992). At 0600 UTC 13 May, the prevailing wind in western Taiwan is from the southwest. This southwesterly current splits at the southern tip of the CMR. A mesolow formed to the southeast of Taiwan at this time. The formation mechanism of this mesolow is explained by the adiabatic warming associated with the downslope wind (Sun *et al.*, 1991; Lin *et al.*, 1992). Notice that the cold front observed to the north of TAMEX region was often shallow (1-2 km deep) and moderately baroclinic (Chen *et al.*, 1989; Chen and Hui, 1990; Trier *et al.*, 1990; Chen and Hui, 1992). These observational analyses also indicated that the leading edge of the shallow front has a structure similar to a density current. At 1200 UTC, the front reached the northern tip of Taiwan and started to split into two branches. It can be inferred from the figure that the eastern branch propagated at a faster speed than the western branch. At 0000 UTC 14 May, these two branches merged at the southern tip of Taiwan. It has been suggested that the retardation of the western branch of the Mei-Yu front is due to the prevailing southwesterly monsoon current (Wang, 1986). This hypothesis still needs to be examined.

This type of deformation of the surface front has also been observed in other parts of the world, such as that over the Alps (Kurz, 1990), and over New Zealand (Sturman *et al.*, 1990). The dynamics of orographic distortion of fronts can be understood by taking the passive scalar approach in which an initially straight front comes under the influence of the anticyclonic mountain circulation and experiences an anticyclonic turning. Using the passive scalar approach in a stratified linear steady flow over and around obstacles, Smith (1982) obtained very realistic isochrones of a frontal passage over an elongated mountain with anticyclonic turning of the front and retardation in the vicinity of the mountain (Figure 13a). The anticyclonic turning of the front over a mountain has also been produced using semigeostrophic theory (Blumen and Gross, 1987; Figure 13b) and in a shallow water model (Haderlein, 1986; summarized in Egger and Hoinka, 1992). As soon as the front impinges on the mountain, an anticyclonic circulation, associated with the mountain-induced high pressure, relative to the mountain is induced in the cold air and the front is retarded by the mountain. Concurrently, the front advances faster on the left side of the mountain and is retarded on the right side if one faces the direction of frontal movement. Frontolysis is dominant on the left side and lee side facing the direction of frontal propagation, while frontogenesis prevails on the right side.

Based on the theories discussed above and observations of the Mei-Yu front distortion, we propose that the distortion of the Mei-Yu front is due to the general anticyclonic circulation induced by the CMR. The retardation of the western branch is by the prevailing southwesterly monsoon current, while the eastern branch is accelerated by the formation of the orographic jet or Kelvin wave which will be discussed in section 4.3. A numerical modeling study of the Mei-Yu front impinging the CMR with sensitivity tests on the southwesterly wind speed is needed in order to help predict the frontal movement and the related weather phenomena in the vicinity of Taiwan.

4.2 Orographic Rain Induced by the Low-level Jet Associated with Mei-Yu Front

Torrential rainfall and convection during the Mei-Yu season in Taiwan are closely related to the low-level jet which has a velocity as high as 40 ms^{-1} and is located on the southern

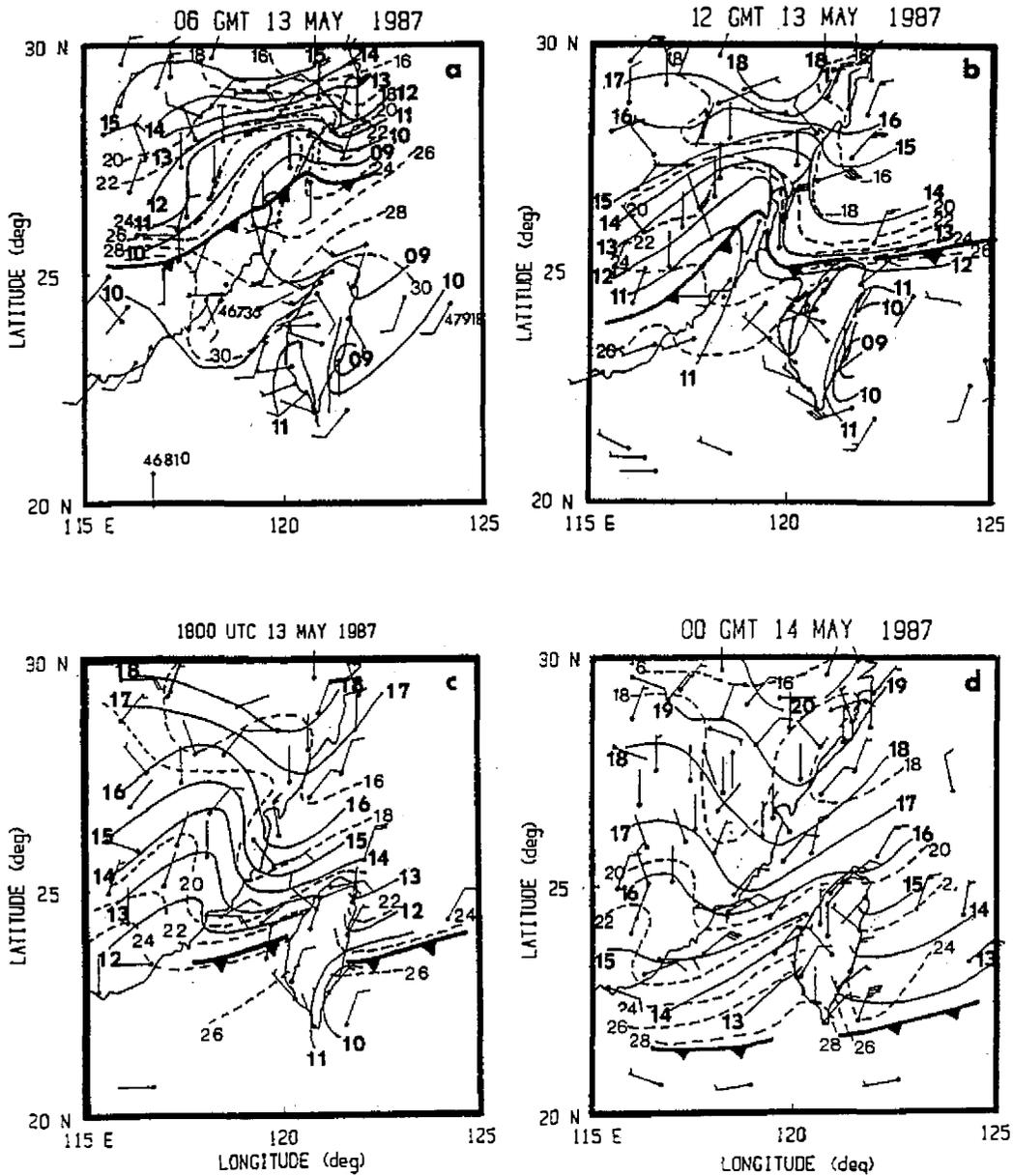


Fig. 12. Surface maps of the passage of a Mei-Yu front during TAMEX (1987). Four times are shown: (a) 0600 UTC 13 May (1400 LST), (b) 1200 UTC, (c) 1800 UTC, and (d) 0000 UTC 14 May. Winds (ms^{-1}) with full barb and half-barb represent 5 and 2.5 ms^{-1} , respectively. Sea level pressures (solid) are represented by the last two digits in mb and isotherms are denoted by dashed lines in $^{\circ}\text{C}$. (after Chen and Hui, 1992)

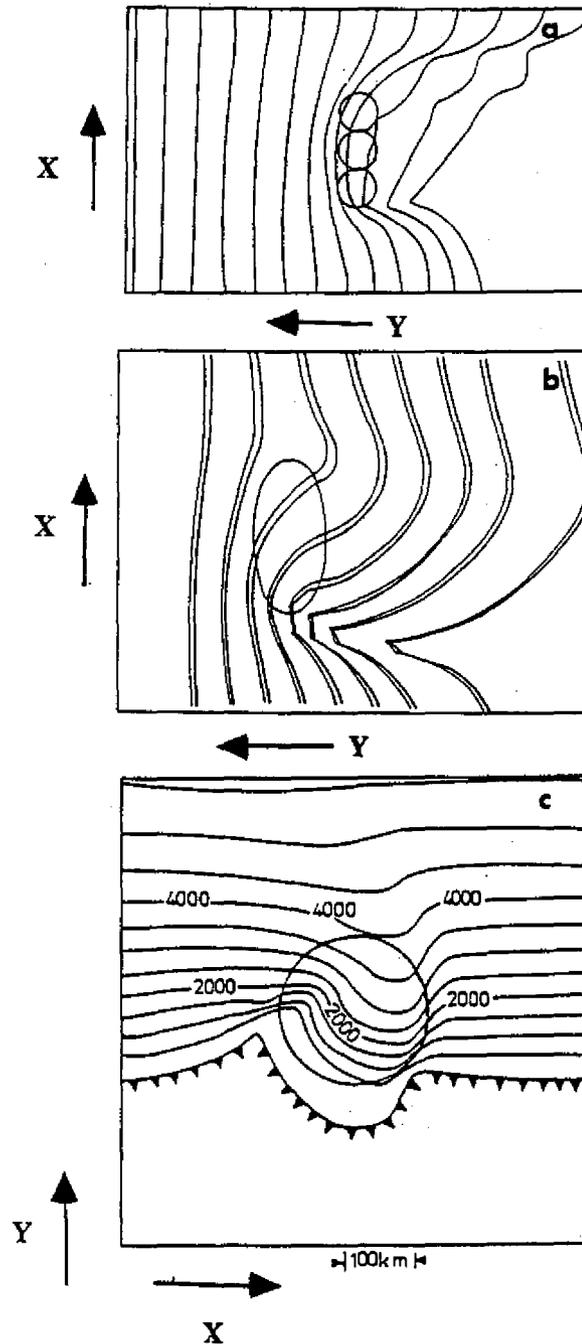


Fig. 13. Theoretical frontal distortion by a mountain for a north-south oriented front: (a) a stratified flow over an elongated mountain (after Smith, 1982), and (b) a semigeostrophic flow over an elongated mountain (after Blumen and Gross, 1987). The distortion of an east-west oriented front over a circular mountain in a shallow water model is presented in (c). (after Haderlein, 1986; presented in Egger and Hoinka, 1992)

side of the Mei-Yu front in the 850 to 700 mb layer (Chen, 1977; Chen and Yu, 1988; Jou and Deng, 1992). A similar phenomenon has also been observed when the Baiu front passes over Japan (Ninomiya and Murakami, 1987) and over China (Tao and Chen, 1987). The formation mechanisms of the low-level jet is beyond the scope of this study. One of them is the downward transport of momentum associated with cumulus cloud convection (e.g., Matsumoto and Ninomiya, 1969). However, the low-level jet associated with Mei-Yu fronts often exists before the convection starts and its location often determines the region favorable for the development of the mesoscale convective system. Therefore, Chen (1977) and Chen and Yu (1988) concluded that the low-level jet should be the cause of convection, instead of the effect. A low-level jet with velocities as large as 30 ms^{-1} at 850-900 mb together with anomalously high wet-bulb temperatures (Browning and Pardoe, 1973) are often associated with heavy rainfall as a vigorous cold front passes over the southwest facing hills of south Wales (Harrold, 1973). The low-level jet over south Wales serves as a conveyor belt of moist and warm air and is typically a few hundred kilometers wide and a few kilometers deep, which flows parallel to and immediately ahead of the surface cold front.

Thus, we may propose that the low-level jet ahead of the Mei-Yu front in Taiwan may serve as a "conveyor belt" which transports warm and moist air from the ocean to the upslope side of the CMR. Once the convective instability is released by orographic lifting, heavy orographic rain may be produced. A conceptual model of orographic rain induced by a low-level jet associated with Mei-Yu fronts over Taiwan is shown in Figure 6e. In order to numerically predict the orographic rain induced by the low-level jet, the frontal circulation has to be included in numerical modeling studies.

4.3 Cold Air Damming, Orographic Jet, and Kelvin Wave

When the Mei-Yu front of 13 May 1987 passed over Taiwan, the CMR blocked the shallow, stable northeasterlies in the postfrontal region (Chen and Hui, 1992; Wang and Wu, 1987; Figure 14). The surge of cold air moved rapidly southward on the eastern side of the CMR, while a pressure ridge built along the coast. Strong northeasterlies flowed along the coast down the pressure gradient of the ridge. Chen and Hui (1992) indicated that this phenomenon is similar to that observed for the same frontal passage over southeastern China (Figure 12b). They also indicated that a similar phenomenon has also been observed for other Mei-Yu fronts passing over Taiwan (Trier *et al.*, 1990; Chen and Hui, 1990; Wang and Wu, 1987; Chen and Liang, 1992). The phenomenon of cold air becoming entrenched along the eastern slopes of the Appalachian mountains in the U.S. during the winter is referred to as cold air damming (Bell and Bosart, 1988). The cold air is in the form of a dome moving southwestward along the Appalachian mountains. The dome is capped by a sloping inversion underneath a warm easterly or southeasterly flow. With a cold dome established in this way, strong northeasterly ageostrophic winds tend to develop parallel to the Appalachian mountains. During damming events, the generation of a quasi-stationary front is often observed. In addition, cold air damming depends critically on the configuration of the large scale flow, such as a synoptic high to the north of the Appalachian mountains. From the observations of frontal passage over the CMR (Trier *et al.*, 1990; Chen and Hui, 1990, 1992), there is no solid evidence for the existence of cold air damming on the eastern slope of the CMR. It appears that the formation of pressure ridge over southeastern China (Chen and Hui, 1992) is more related to cold air damming, compared to that over the CMR. To clarify this point, an east-west cross section analysis of the temperature and the along-mountain wind velocity is necessary. This will help to check if the two major features, the cold dome and stationary front in the along-mountain direction, are formed or not.

If the orientation of a front is such that the along-front geostrophic flow in the cold air is directed approximately normal to the mountain slope, a current must form in the boundary layer to accommodate the geostrophic flow into the slope (Egger and Hoinka, 1992). This boundary layer current exhibits a jet-like structure and is moving in a direction leaving the mountain to its right in the northern hemisphere. This type of boundary layer current is called an orographic jet or gravity current (Baines, 1980). The mountain slope must be sufficiently steep and the mountain must be high enough to block a substantial fraction of the flow normal to it. The speed of an orographic jet may be estimated by $(g'H)^{1/2}$, where g' is the reduced gravity and H the depth of the lower layer in a two-layer system (Stern *et al.*, 1982; Griffith, 1986). This type of phenomenon has also been observed in other parts of the world, such as the southerly buster in the coastal regions of New South Wales of Australia (Baines, 1980; Colquhoun *et al.*, 1985) and the alongshore surge of the west coast of North America (Mass and Albright, 1987). Figure 15 shows an example of an orographic jet simulated by a numerical model, which evolves along a mountain slope within 12 hours from a front which is initially perpendicular to the mountain (Egger and Haderlein, 1988). From the observations of the frontal passage over the CMR (Chen and Hui, 1992; Figure 14a), it appears that there exists a favorable condition for the formation of an orographic jet. The difficulty of examining this mechanism. The propagation speed of the eastern branch of the Mei-Yu front of 13 May 1987 is about 9.3 ms^{-1} as compared to 6.2 ms^{-1} propagation speed of the western flank (Figure 12). The difference in the case of 11 June 1986 is even larger (Figure 11). In the southerly buster cases observed by Coulman *et al.* (1985), the estimated speeds of the orographic jet are consistent with observations. However, there is no pronounced bulge of the cold air along the coast, as a characteristic of the orographic jet. The same hold true for the coastal ridging phenomenon (Holland and Leslie, 1986). Holland and Leslie argued that the coastal ridging cannot be regarded as an orographic jet since the ridge is moving faster than the wind along the coast. They interpret the ridging as a Kelvin-type

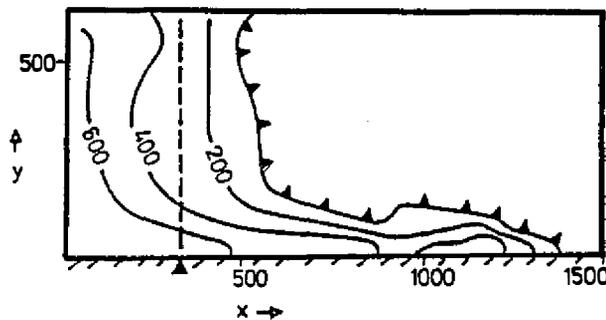


Fig. 15. An example from a numerical simulation of an idealized orographic jet which evolves along a mountain wall within 12 hours from a front which is initially directed perpendicular to the mountain. Both the position of the surface front and depth (m) of the cold air are denoted. The dashed line marks the initial position of the front. (after Egger and Haderlein, 1988)

edge wave. Although topographically trapped Kelvin waves and topographically trapped orographic jet (gravity current) are closely related and share many characteristics, such as phase speeds and decaying scale at the Rossby radius of deformation ($\sqrt{g'H}/f$), there are important differences (Mass and Albright, 1987). In topographically trapped Kelvin waves there are wavelike transverse displacements of a stable fluid; this fluid is capped by a layer of sufficient stability to maintain the blocking effect of a topographic barrier. It has been suggested by W.-D. Chen (1983) that the Kelvin wave may steepen into an abrupt surge, such as an orographic jet or gravity current, if the nonlinear effect is strong enough. To examine this phenomenon, a comparison of the propagation speed predicted by either theory or model simulations to observations and an analysis on a vertical cross section along the eastern slope of the CMR will be helpful. A sensitivity test on the Coriolis parameter may be helpful.

It is noteworthy to mention that both the cold air damming and orographic jet are orographic adjustment processes in that larger scale flow has to adjust to the presence of a barrier (Egger and Hoinka, 1992). However, the orographic jet is generated through the adjustment of a pre-existing cold front to the mountain, while a quasi-stationary front is generated by the damming process. Correspondingly, analysis of the orographic jet is performed on a plane parallel to the mountain ridge, while that of cold air damming is performed on a plane normal to the mountain ridge.

4.4 Mesoscale Frontogenesis and Cyclogenesis Associated with Frontal Passage

Wang (1986) reported that mesoscale frontogenesis and cyclogenesis may occur on both the western and eastern sides of the CMR when a front passes over Taiwan from north or northwest during the late winter monsoon season. As discussed earlier, the front is always retarded and split by the CMR when it passes over Taiwan. Figure 16 shows that mesoscale frontogenesis and cyclogenesis occurred to the southeast of Taiwan in connection with the front of 8 April 1975. Wang proposed that the mesoscale frontogenesis and cyclogenesis in this region is due to the local convergence of the northerly monsoon current and the southerly flow caused by the salient edge effect. The cyclogenesis on western Taiwan often occurs on the synoptic cold front, which may produce heavy rainfall. In addition, he also proposed that this type of mesoscale cyclogenesis is due to the convergence of the orographically enhanced southwesterly flow and the northerly or northeasterly flow along the cold front. This type of cyclogenesis may also be generated by the convergence between a cold front and the sea breeze.

The mesoscale cyclogenesis over southeast Taiwan may be closely related to mesocyclone formation as found in Lin *et al.* (1992). The edge effects proposed by Wang (1986) still need to be examined against other mechanisms by both observational analysis and modeling simulations. This may be accomplished by applying a mesoscale model with the boundary layer physics included in the simulation. Detailed analysis and more numerical modeling simulations are needed to help understand the processes of mesoscale frontogenesis and cyclogenesis in connection with the passage of a front over Taiwan. In addition, the existence of mesolows over the ocean (e.g., Figure 16) is questionable due to the lack of observational data, in which the readers should be aware of.

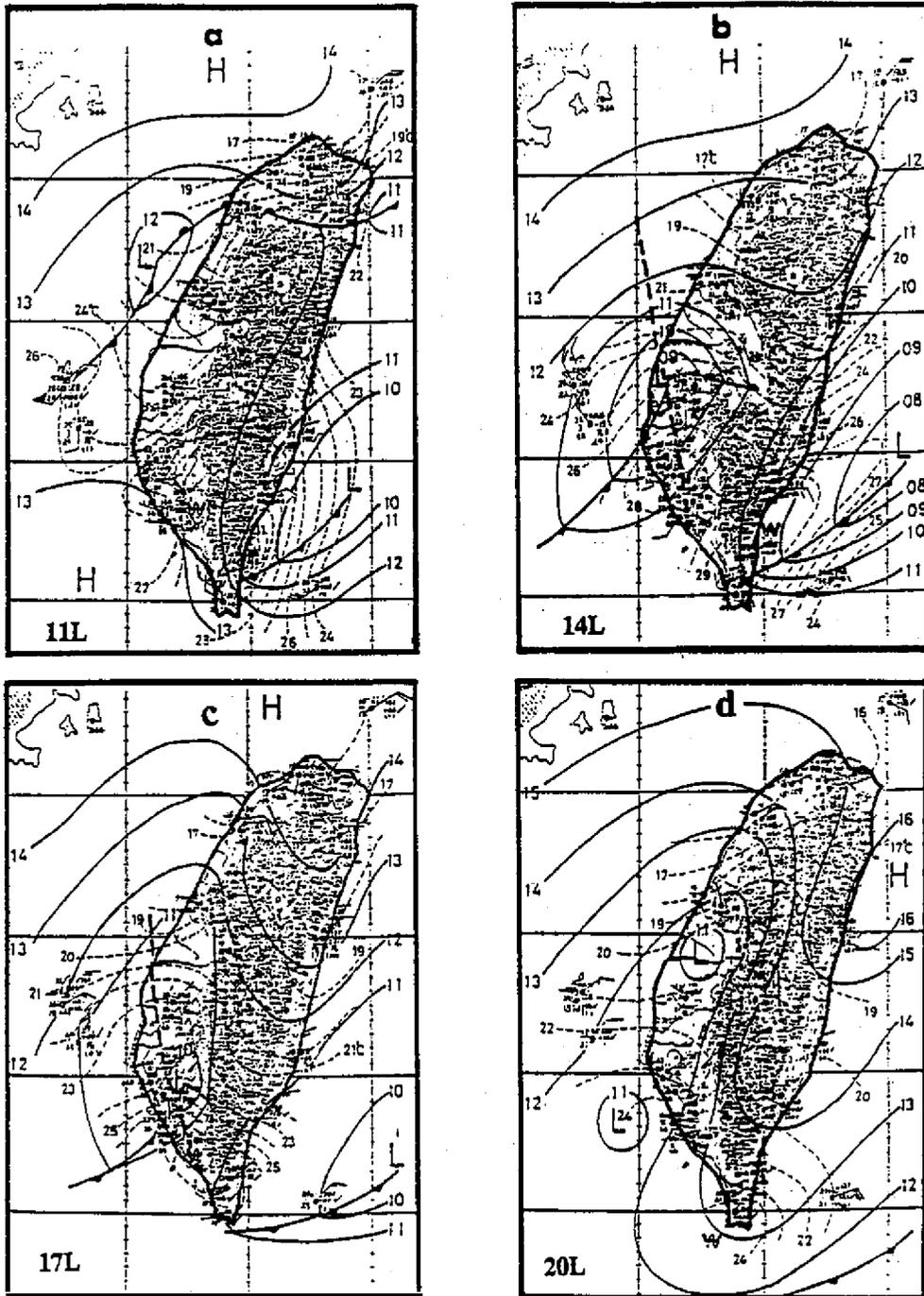


Fig. 16. Mesoscale frontogenesis and cyclogenesis in connection with the frontal passage of 8 April 1975. (after Wang, 1986)

5. INFLUENCE ON TYPHOON TRACKS AND CIRCULATIONS

5.1 Observations

When a typhoon approaches Taiwan, its circulation and track are significantly affected by the CMR. The change in typhoon tracks and the accompanying circulation proposes a challenging problem for weather forecasters in Taiwan. The orographic influences on the typhoon are many and include: (1) the movement of the storm, which includes the tracks, translational speeds, and the circulations, (2) the strength of the storm, and (3) the rainfall distribution. Orographic influence on tropical cyclones in other parts of the world has also been investigated, such as in the northern Phillipines (Brand and Brelloch, 1973; Kintanar and Amadore, 1974) and in the Caribbean islands (Hebert, 1980). In this review, we will place emphasis on the first two effects.

Brand and Brelloch (1974) found an average intensity (maximum surface wind) decrease of over 40% and a distinct northward deflection as the typhoons approach the island with a southward deflection after their passage over the CMR. The deflection of the typhoon track found by them is consistent with other observational studies (Wang, 1980 among others) and has been verified by numerical modeling experiments (e.g., Chang, 1982; Bender *et al.*, 1987) and tank experiments (Pao, 1976; Hwang *et al.*, 1977). However, as pointed out by Yeh and Elsberry (1993), the averaged cross-track velocities of the northward deflection are different among numerical simulations of Brand and Brelloch (1974), Chang (1982) and Bender *et al.*, (1987). In addition, the track deflection is found to be sensitive to the storm translation speed (Bender *et al.*, 1987). These differences may be caused by storm structures and the complexity of the environments. This problem should be addressed in future studies and may be investigated using a more systematic design of numerical experiments. Based on their strength and vertical extent (Z_t), typhoons may be classified as: (a) Category I typhoons ($V_{max} < 50$ kt or $Z_t < 3$ km): The typhoon tends to dissipate over the island, or (b) Category II typhoons (50 kt $< V_{max} < 100$ kt or $Z_t \sim 6$ km): The typhoon tends to produce secondary induced lows that may dominate the circulation at later times. These typhoons sometimes appear to jump forward or accelerate rapidly across the island. (c) Category III typhoons (100 kt $< V_{max}$ or 10.7 km $< Z_t$): The typhoon follows a continuous track even though the secondary lows form on the lee side of the mountain range. Yeh and Elsberry (1993) found that the CMR apparently decelerates the slow-moving storms upstream, but has a relatively small effect on typhoons moving faster than 6 ms^{-1} .

Extensive observational analysis of the orographic influence on typhoon tracks and circulations by the CMR have been performed by Wang (1980). When a typhoon impinges on the CMR at a certain angle, its track may remain continuous or become discontinuous (Figure 17). In the first category, the typhoon may (a) simply continue its path over the mountain range, (b) deflect southwestward and stay for some time on the eastern side of the CMR, then pass over the mountain, or (c) have its upper-level center propagated over the mountain range, while its low-level center is deflected southward and disappears. In the second category, two or three secondary lows tend to form on the downstream side of the CMR, one of which then develops and replaces the center of the parent typhoon. Thus, the typhoon appears to jump over the mountain range. The circulation is only modified slightly by the mountain range for typhoons with a continuous track (Figure 18), while it is modified significantly for typhoons with a discontinuous track (Figure 19). For typhoons which move in a direction parallel to the mountain range, their tracks are continuous. Wang

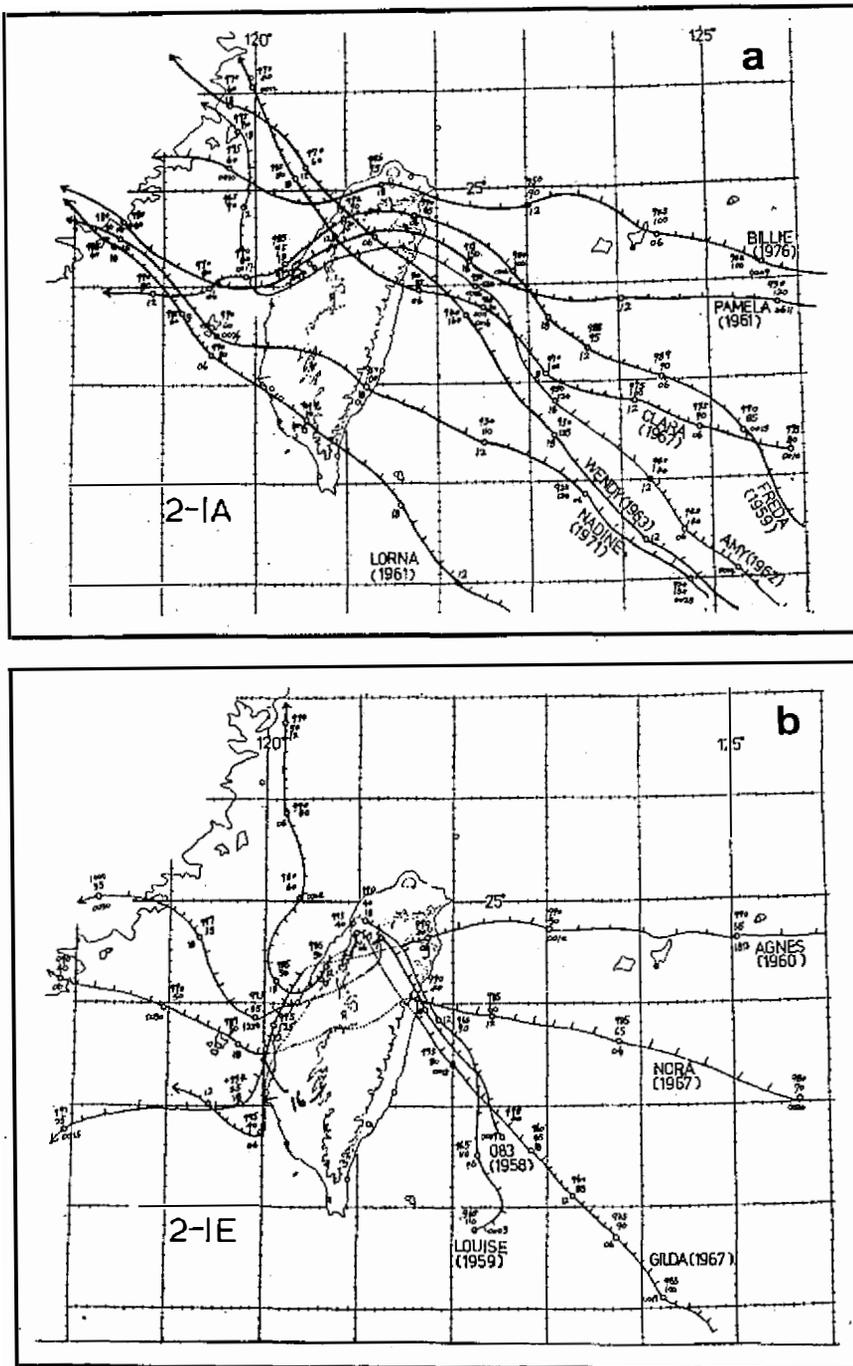


Fig. 17. Two types of typhoon tracks: (a) continuous and (b) discontinuous. (after Wang, 1980)

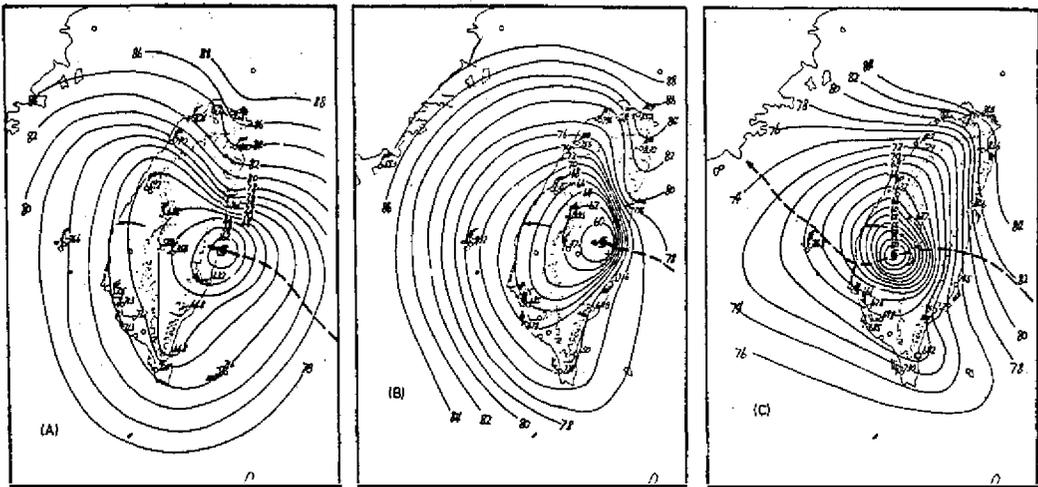


Fig. 18. Flow circulations associated with a typhoon which has a continuous track. (after Wang, 1980)

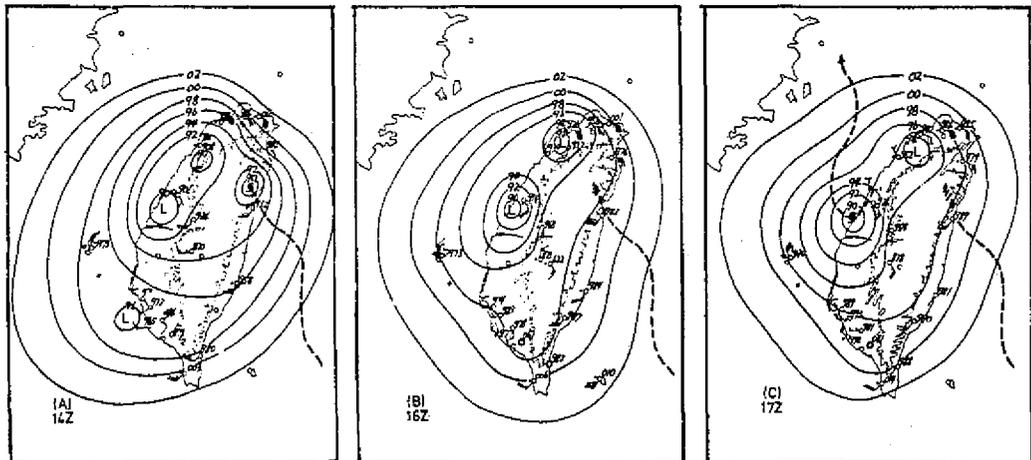


Fig. 19. Flow circulations associated with a typhoon which has a discontinuous track. (after Wang, 1980)

(1980) proposed a conceptual model for the change of typhoon track in the vicinity of a mesoscale mountain range (Figure 20). He suggested that the typhoon is steered by the rear part of the circulation and the basic flow (easterly in the figure) when the front part of the circulation is blocked by the mountain range. Therefore, the typhoon center will be deflected toward the north before it passes over the CMR. Similarly, the typhoon center will be deflected toward the south after it passes over the mountain range. However, it is noteworthy to mention that the flow circulations associated typhoon near the CMR may

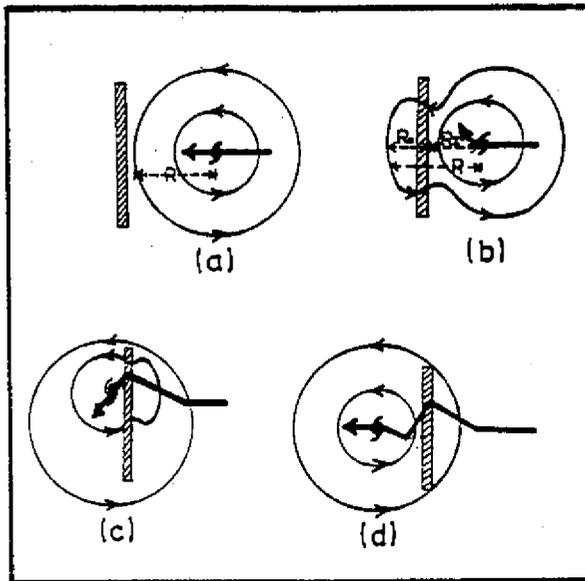


Fig. 20. Impact on the track of a typhoon due to the orographic influence on its circulation. Wang proposed that the typhoon center is steered by the rear part of the circulation when the front part is blocked by the mountain range. The typhoon center is deflected toward the north before it reaches the mountain range. See text for details and comments (after Wang, 1980).

become extremely complicated, such as the existence of flow blocking and hydraulic jumps, and behaves completely differently from those proposed by Wang (1980). A more systematic approach of numerical experiments may help in resolving this problem.

Both statistical analysis of observational case studies (Wang, 1980) and tank experiments (Pao, 1976; Hwang *et al.*, 1977) have shown that the formation of secondary lows is determined by the incident angle of the typhoon circulation and the Reynolds number. The incident angle (denoted as α in Pao and Hwang *et al.*) is defined as the wind direction at Pengchia-Yu, located at about (122°E , 25.5°N), before the typhoon impinges on Taiwan subtracted by the orientation direction of the CMR (20°). The secondary low forms farther to the north on the west coast of Taiwan for a larger angle α . In addition, these secondary lows may become either dynamically active or inactive (Figure 21). According to Wang (1980), a secondary vortex center may form in the wake zone through the corner effect. He also hypothesized that the inactive secondary low may develop into an active secondary low through the momentum exchange between the typhoon and the low, which may progressively replace the parent typhoon. Readers should keep in mind that the distinction between a mesoscale vortex and a low is necessary, which is not made in Wang's study. Chang *et al.* (1993) proposed that pressure troughs along the west coast are an inherent response of a west-moving typhoon approaching the north-south oriented CMR. It is important to make a distinction between the secondary low induced by the parent typhoon and the lee trough induced by the basic flow over a mountain. Notice that the latter is stationary, while the former is normally propagating.

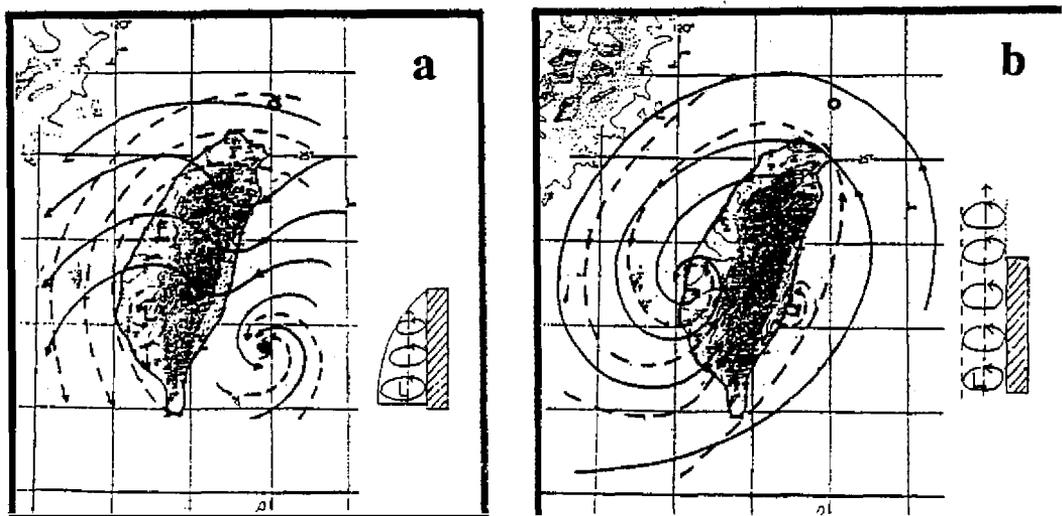


Fig. 21. A conceptual model for a developing secondary low from a shallow pressure center: (a) dynamically inactive and (b) active lows. Station Pengchia-Yu is denoted by "o". The streamlines at low levels are denoted by solid lines, while these at high levels are denoted by dashed lines. The vertical structure of these two types of secondary lows are also sketched. (after Wang, 1980)

The effects of Taiwan topography on typhoon circulation and convection has been investigated recently by Lee (1993) using data obtained by both conventional platform and Doppler radar at CKS airport. He found that the low-level circulation center of Typhoon Ofelia was blocked by the CMR and moved around the elevated mountain area, while the mid- and upper circulation centers moved across the CMR following the steering flow. Typhoon Yancy took a looping track after landfall due to the topographical effect. Both Ofelia and Yancy lost their eye structures shortly after landfall. However, both weak echo regions at the center reappeared when the circulation centers were located to the west of the CMR. It is also found that a typhoon rainband can be either blocked by the mountain range or enhanced by the terrain lifting.

5.2 Numerical Modeling Studies and Tank Experiments

Using a primitive-equation model, Chang (1982) found that the typhoon tends to translate at about twice the speed of the basic flow near the mountain, while its intensity is reduced. A majority of the airflow at low levels passes around the mountain range rather than is forced over it, which forms a ridge on the windward slope and a trough on the leeside slope. The tropical cyclone's passage induces a mean cyclonic circulation around the mountain with its strongest amplitudes at low levels. As a result, the model tropical cyclone acquires a cyclonic curvature in its path around the northern end of the CMR. This is consistent with the conceptual model proposed by Wang (1980; Figure 20). Chang also found that secondary vortex centers form in the lee trough, which may develop when they are in phase with the

upper-level vortex center (Figure 22). In addition, results indicated that diabatic processes associated with cumulus convection play important roles in maintaining the cyclonic circulation of the vortex associated with the typhoon. The horizontal advection of positive vorticity in conjunction with the leeside vortex stretching results in a mean positive vorticity around the mountain. This is consistent with the finding of Chan (1984). Chan showed a definite link between the local change in relative vorticity and tropical cyclone movement, which is contributed mainly by the horizontal advection of absolute vorticity and secondarily by the divergence term.

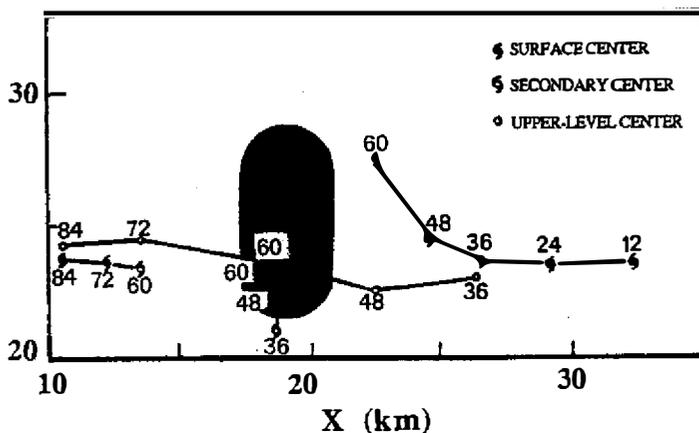


Fig. 22. The movement of the surface and 700 mb centers of a propagating typhoon in a numerical experiment. The movements of secondary centers are traced with a dashed line. (after Chang, 1982)

Bender *et al.* (1985) found that the typhoons fill much more rapidly in numerical simulations with a mountain included. The mountain range affects the decay rate through reduction in the supply of latent and kinetic energy into the storm circulation during, as well as after, passage of the storm over the mountain. In addition, a low-level, warm and dry region is produced where the storm winds descend the mountain slope. The results show that the effect of the mountain range is an enhancement of heavy precipitation to the right of the storm track immediately after landfall, which is probably related to increased coastal convergence. The orographic influence on tropical cyclones in other parts of the world has been studied using a triply nested, movable mesh numerical model by Bender *et al.* (1987). In a control experiment of an easterly flow over Taiwan without the vortex present, the basic flow field in the lower 4 km curves to the northwest well upstream of the island. It also directly influences the structure of the tropical cyclones when they pass over or nearby the region. Combination of these two effects yields changes in the movement and structure of the tropical cyclones. For the cases considered, the storm tracks show northward (cyclonic) deflection, sometimes after a small southward deflection. The northward deflection is generally larger and sometimes begins further upstream in the case of a weaker zonal flow. The translational speed of the storms also tends to increase along with the deflection. This result is similar to that found in other studies (Brand and Blelloch, 1974; Wang, 1980; Chang, 1982; Yeh and Elsberry, 1993a). After making landfall and encountering the high mountain ranges, the surface pressure minimum undergoes rapid filling. The surface low may continue to move

along with the upper-level vortex as it crosses the mountain range, or may become obscure before reforming on the lee slope. In one of the Taiwan cases, a secondary surface low or lows form behind the mountain range. In this case, it appears that the upper-level vortex becomes detached from the original surface low and eventually couples with the secondary one. The latent energy supply as well as the vertical coherence of the storm system are important factors in the determination of the intensity change of the storms near and over the island topography. The storm may be weakened by the advection of dry air from the mountain region into the storm area and the vertical tilting of the storm center. After leaving the island and moving over open sea, the storms generally reintensify if a vertically coherent structure is present.

Using a primitive equation model with 45 km horizontal resolution, Yeh and Elsberry (1993a,b) found that both the upstream track deflections and whether the track will be continuous or discontinuous across Taiwan depend on whether the typhoon approaches the northern end versus the central or southern end of the CMR. In general, the northern storms have smaller upstream track deflection and tend to pass continuously around the northern end of the CMR. By contrast, the typhoons approaching the southern or central region have larger upstream track deflections and are most likely to have a discontinuous track across Taiwan. As also found in other studies, the track deflection depends on both the basic flow and the typhoon circulation itself. Their numerical simulations also suggest two types of vortex reorganization occur downstream of the topography as the original vortex is dissipated on the upstream side. In one type, the low-level vortex is created from a downward extension of the circulation as the upper-level 'remnants' of the typhoon flow move downstream. In the second type, a secondary vortex that is formed at low levels on the lee side of the barrier is shed westward and develops upward. A new low-level pressure center that is separate from the original vortex or the terrain-induced pressure trough becomes the center about which the typhoon vortex reorganizes. The first type is consistent with the modeling results of Chang (1982), while the second type appears to be a new typhoon development to the east of the CMR and needs to be examined more carefully. The question is: Does the lee side, including the coastal plain and ocean, of the CMR provide a favourable environment for a completely new formation of typhoon?

Using a shallow water numerical model, Smith and Smith (1993) found that vortex interaction with ideal topography results in a pair of trailing banners of vorticity which get wrapped up into the vortex as it drifts away. Interaction with the actual Taiwan topography results in qualitatively similar effects, with the additional effect of a strong secondary eddy that remains northwest of the island for some time following the passage of the vortex. Observational analysis of vorticity distribution is needed to confirm this new finding.

The orographic influence of the CMR on typhoon tracks has been investigated by Pao (1976) and Hwang *et al.* (1977) using tank experiments with the real topography represented. The control parameters considered in their experiments are: the Rossby number, the ratio of mountain height to the water depth, and the angle (γ) between the upstream typhoon track and the CMR. When the typhoon impinges on the CMR at a right angle ($\gamma=90^\circ$), it passes over the mountain range gradually with the track deflected to the north upstream and toward the south downstream of the mountain. When the typhoon impinges on the CMR from a larger angle (e.g., $\gamma=130^\circ$), the primary center of the typhoon disappears just before it reaches the mountain range. In addition, a secondary vortex center forms in the wake zone. The secondary vortex center replaces the primary center whenever the latter disappears. Tank experiments have also been performed for typhoons over the Phillipines by Brand *et al.* (1982).

5.3 Discussion

The orographic influence on typhoon tracks and circulations is extremely complicated. In order to fully understand the problem, a systematic approach by combining the observational analyses, tank experiments, and numerical modeling experiments is necessary.

- The basic dynamics of a moving vortex over mountain is still not well understood. In particular, the relative importance between the deflection of a basic uniform flow over a mountain and the deflection of a circular flow associated with the typhoon over a mountain needs to be addressed. A simple type of primitive-equation numerical model may be helpful in studying the basic dynamics. To investigate the flow structures near the CMR, a nested nonhydrostatic modeling simulations may be needed since some phenomena, such as flow blocking and hydraulic jumps, may occur due to the steepness of the CMR.
- Both statistical analysis (Wang, 1980) and tank experiments (Pao, 1976; Hwang *et al.*, 1977) have shown that the deformation of typhoon tracks and the associated circulation is dominated by the formation and evolution of secondary lows on the downstream side of the mountain range. As discussed in Lin *et al.* (1992), the existence of a mesolow does not necessarily imply a closed circulation. By inspection of Wang's arguments concerning the development of the secondary low or vortex into a primary typhoon center (see Figure 21), the distinction between a low and a vortex is necessary. In addition, the mechanism of upward development of the secondary vortex on the lee (west) side of the CMR, as proposed by Yeh and Elsberry (1993a, b), is interesting, but needs to be examined more carefully since it requires a favourable environment on the lee side of the CMR for an almost new typhoon to develop.
- Results of tank experiments may be compared with that of shallow water modeling simulations, such as Smith and Smith (1993), to help understand the basic dynamics of the formation of secondary vortices. However, a direct application of these types of approach, both tank experiment and shallow water numerical modeling, to the real atmosphere is still limited due to the assumptions made in these experiments and models, such as a free surface and the lack of stratification.
- As mentioned earlier, Wang (1980) hypothesized that the inactive secondary low may develop into an active secondary low through the momentum exchange between the typhoon and the low, which may progressively replace the parent typhoon. In comparison with the results of numerical experiments (e.g., Chang, 1982), this hypothesis may be modified: When the secondary low at the surface is collocated with a cyclonic lee vortex, it may be regarded as a surface mesocyclone. This surface mesocyclone may develop and replace the parent typhoon when it is in phase with the upper-level vortex center. Notice that the secondary low is associated with the mountain waves which are produced by the circular basic flow associated with the typhoon, as the typhoon passes over the CMR. The formation mechanisms of the secondary vortex may be studied by an investigation of the response of a stationary circular flow to an idealized mountain range. In addition, the effects of impinging angle on the typhoon tracks may be investigated using a numerical model.
- Vertical structures of the circulations, storm center, and mountain waves for typhoons over Taiwan are not well understood and need to be investigated. Both observational studies and numerical modeling studies will be helpful. This type of analysis has been performed in an idealized numerical modeling study by Bender *et al.* (1985).

- As suggested by Chang (1982), diabatic processes are important in maintaining the cyclonic circulation of the vortex when the storm passes over a mountain. Experiments with a prescribed cumulus heating may be carried out to help understand this mechanism. In this way, the strength of the vortex can be sustained. In other words, the influence from the mountain range should be isolated from the typhoon evolution itself.
- Notable asymmetries in the wind, moisture and precipitation fields exist relative to the coastline at the time of tropical cyclone landfall. Roughness-induced, quasi-steady convergence and divergence zones are observed where onshore and offshore winds encounter the coastline (Tuleya and Kurihara, 1978). The latent energy release through condensational processes is initially augmented over land by greater moisture convergence in the planetary boundary layer which counteracts the lack of evaporation. Thus, the effects of boundary layer processes on the landfall of typhoons on Taiwan also need to be investigated.

6. SUMMARY

In this paper, we reviewed several prominent weather problems related to the orographic effects of the topography of Taiwan, which includes: (a) local rainfall enhancement by the CMR on prevailing winds and mesoscale convective systems, (b) the formation of mesolows and mesocyclones, (c) the effects on Mei-Yu fronts, (d) the effects on mesoscale convective systems, and (e) the influence on typhoon circulations and tracks.

Five different formation mechanisms of orographic rain (Figure 6) has been reviewed. In order to improve the understanding of the orographic rain problem in Taiwan, we suggest the following studies: (a) observational analysis of cross sections of rainfall distribution in the direction of the prevailing wind during different seasons, (b) effects of the amount and size distributions of cloud condensation nuclei, the applicability of the Bergeron process and the orographic lifting on the rainfall rate, (c) examinations of mechanisms c, d, and e by analyzing the observational data.

The formation of lee mesolows, mesovortices and mesocyclones during the Mei-Yu season has been successfully simulated by mesoscale hydrostatic models. However, some basic dynamics, such as the formation mechanisms of the lee mesovortex, still need to be investigated. Due to the steepness of the CMR, there is a need to adopt a nonhydrostatic numerical model to study the detailed flow circulation around the island. The following studies are recommended: (a) distinguish different frequency distributions of the mesolow and mesocyclone formations based on the basic wind direction, (b) examine the possible enhancement of the southwesterly due to the formation of the northwest mesolow as proposed by Chen and Chi (1980), and (c) investigate effects of planetary boundary layer, vertical wind shear on the formation of lee mesolows and mesocyclones.

We hypothesized that the Mei-Yu front distortion is due to the general anticyclonic circulation induced by the CMR. The retardation of the western branch is strengthened by the prevailing southwesterly monsoon current, while the eastern branch is accelerated by the formation of orographic jet or Kelvin wave. A numerical modeling study of the Mei-Yu front impinging the CMR with sensitivity tests on the southwesterly wind speed is needed in order to help predict the frontal movement. We propose that the low-level jet ahead of the Mei-Yu front in Taiwan may serve as a "conveyor belt" which transports warm and moist air from the ocean to the upslope side of the CMR (Figure 6e). Once the convective

instability is released by orographic lifting, heavy rainfall may be produced. In order to numerically predict the orographic rain induced by the low-level jet, the frontal circulation has to be included in numerical modeling studies. To clarify the possible cold-air damming on the eastern slope of CMR after the passage of the Mei-Yu front, an east-west section analysis of the temperature and the along-mountain wind velocity is necessary. To examine the phenomenon of orographic jet or Kelvin wave, a comparison of the propagation speed predicted by either theory or model simulations to observations and an analysis on a vertical section along the eastern slope of the CMR will be helpful. Detailed analysis and more numerical modeling simulations may be needed to help understand the processes of mesoscale frontogenesis and cyclogenesis in connection with the passage of a front over Taiwan.

The use of a shallow water model has greatly increased our understanding of the formation of some important phenomena, such as blockings, foehns, secondary vortices, and track deflection, associated with a vortex passing over a mountain range (Smith and Smith, 1993). Vertical structures of the circulations, storm centers, and mountain waves for typhoons over Taiwan are still not well understood and need to be investigated. Dependency of the typhoon path on strength also needs to be studied. By inspection of Wang's arguments (Wang, 1980) concerning the development of the secondary low or vortex into a primary typhoon center, the distinction between a low and a vortex is necessary. In addition, the formation mechanisms of the secondary vortex may be studied by an investigation of the response of a stationary circular flow to an idealized mountain range. Effects of diabatic and boundary layer processes on the typhoon circulation and tracks are not well understood and need to be investigated.

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