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Orography Effects on the Structure of Typhoons: Analyses of Two Typhoons Crossing Taiwan

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ABSTRACT

Taiwan is a unique place to study typhoon-orography interactions. On the average, four typhoons encounter the high Central Mountain Range (CMR) per year. This study analyzes the hourly surface wind and pressure structure over the Taiwan area during typhoon Nadine (1971) and typhoon Betty (1961). The results show the center of Nadine passed over the CMR continuously. On the other hand, secondary circulation and a secondary low formed over western Taiwan when typhoon Betty moved close but still to the east of the CMR. The original center and the secondary circulation/low moved in different directions. When the original center of Betty weakened over the east side of the CMR, the secondary circulation/low became the dominating system. This situation is very different from a typhoon track over an open ocean. The formation of the secondary circulation/low started from a pronounced wind shift from northerly to southwesterly over southwestern Taiwan. The southwesterly wind blew against the CMR and induced a ridge in the southern part of the existing lee trough. If the ridge was strong enough, the low pressure zone over the west side of the CMR was separated from the original center over the east side. The southwesterly near the CMR was further deflected to northward by the mountain to form a cyclonic circulation over the west side of the CMR.

(Key words: Typhoon-orography interactions, Continuous/discontinuous track, Secondary circulation/low)

1. INTRODUCTION

Prediction of typhoon tracks and intensities is one of the major forecasting problems in Taiwan. A data-void problem upstream of the island makes the forecast task difficult. The steep and high Central Mountain Range (CMR) causes track deflections and structure modifications. It makes the forecast even more complicated.

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Significant typhoon intensity, structure and track modifications by the CMR of Taiwan were first reported by Wang (1954). He showed the CMR caused the formation of a secondary low over its west side when typhoon Phyllis invaded Taiwan from the east in 1953. The interesting phenomena of CMR-induced typhoon track deflections and structure modifications were later summarized by Brand and Blelloch (1974). They concluded that weak or shallow storms will tend to dissipate over Taiwan. Moderate typhoons will tend to produce secondary lows that may take over the primary circulation. These storms may appear to jump forward through the island. The strong storms will follow a continuous track even if secondary lows do form. In a technical report, Wang (1980) showed many cases of formation of secondary low(s) when typhoons were in the vicinity of Taiwan. He also classified the typhoon tracks according to the formation and development of the secondary low(s). Chang *et al.* (1993) showed that the secondary low is most apt to form when the typhoon is over southeastern Taiwan and its adjacent ocean.

Numerical simulations have also been employed to study the CMR effect on typhoons. Formation of a secondary circulation to replace the original center was first simulated by Chang (1982). However, the discontinuous track produced by Chang was in the unusual circumstances of suppressed cumulus heating and surface friction effects. The simulated vortex is able to move across the CMR-like topography if cumulus heating is included. The vortex with the continuous track re-intensifies as the simulated storm center moves over the topography. However, the observed typhoons were generally weakened after moving over the CMR.

Bender *et al.* (1987) simulated a storm approaching the central Taiwan with a speed of 5 m/s westward. They found that the storm was weakened and deflected around Taiwan from the north. No secondary center was reported in this simulation. Track discontinuity was simulated when the translation speed of the storm was increased to 10 m/s. However, the track was divided into three pieces. A secondary low center developed and remained over the high mountain area before a third low center was formed over the ocean west of the island.

Similar results were reproduced by the simulation study of Yeh and Elsberry (1993). They explained that the formation of secondary low near or over the mountain area is due to the subsiding warming effect of flow over mountain. The terrain induced subsidence flow has a maximum near or over the mountain area. Therefore, the secondary low will be found over or near the maintain area and it is terrain locked. The third low, however, is a result of system reorganization after the vortex passes over the mountain. Yeh and Elsbery (1993) also discussed two different types of vortex reorganization processes depending on whether the "remnants" of the original vortex can effectively pass over the mountain.

As simulation, the results of Bender *et al.* (1987) and Yeh and Elsberry (1993) showed similarity, but both conclusions on whether the secondary low can move and develop to replace the original center are different from the earlier observations (e.g., Brand and Blelloch, 1974; Wang, 1980). Moreover, Yeh and Elsberry (1993) noticed that under the significant topography influence, a simple balanced relationship between the winds and pressure fields such as the earlier observational studies applied is not valid especially in the area near the mountain. Therefore, it is worthwhile re-examining the detailed structure of typhoon-CMR interaction from surface observations.

In this study, two cases of typhoons crossing Taiwan are discussed. Typhoon Nadine in 1971 is a typical example of typhoons crossing southern Taiwan in a continuous track. On the other hand, typhoon Betty in 1961 induced a secondary center over the west side of the CMR. It is an example of discontinuous track. We first present Taiwan's topography and the distribution of its surface observation stations in Section 2. Analyses and discussions of the structure of typhoons Nadine and Betty are then given in Section 3. Section 4 is the summary and concluding remarks.

2. TAIWAN'S TOPOGRAPHY AND THE OBSERVATION STATIONS

Taiwan is located in the Western Pacific. The island has a banana-shape with a major axis of about 3 degrees latitude extending in a north-south direction and a minor axis of about 1.5 degrees longitude in an east-west direction. The CMR, with peaks higher than 3000 m, dominates the island. The 500 m isoline is very close to the east coast, while there is a band of flat land along the west (Figure 1). 22 surface observation stations operated by the Central Weather Bureau and 15 surface observation stations operated by the military spread over all of Taiwan and the nearby small islands. Most of the stations take hourly observations during the period of typhoon warnings. Details of the name, location, and elevation of the stations are given in the Table 1.

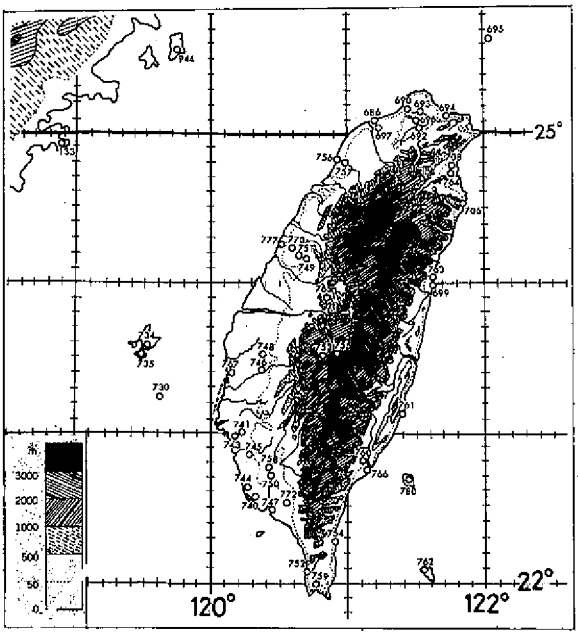

Fig. 1. The topography and the distribution of surface stations in Taiwan area. The name of the stations are given in Table 1.

3. ANALYSES AND DISCUSSIONS

3.1 Continuous Track: Typhoon Nadine

Typhoon Nadine invaded Taiwan in late July of 1971. According to the annual typhoon report of the Joint Typhoon Warning Center in Guam (JTWC), Nadine formed an organized system on 17 July. The maximum wind reached the typhoon intensity (30 kts) at 12 UTC of 20 July when it moved to the west of Guam. Nadine then moved toward Taiwan directly in a northwest direction and landfalled at 18 UTC of 25 July.

Table 1. List of surface stations in Taiwan area.

Station No	Station Name	Latitude (N)	Longitude (E)	Altitude (M)
46695	Peng-chia-yu	25°38'	122°04'	101.7
46693	Chu-tz-hu	25°10'	121°32'	607.1
46690	Tan-shui	25°10'	121°26'	19.0
46694	Kee-lung	25°08'	121°44'	26.7
46692	Taipei	25°02'	121°30'	5.5
46757	Hsin-chu	24°48'	120°58'	34.0
46708	I-lan	24°46'	121°45'	7.2
46749	Tai-chung	24°09'	120°41'	84.0
46699	Hua-lien	23°59'	121°36'	16.1
46765	Ji-yueh-tan	23°53'	120°54'	1014.8
46735	Peng-hu	23°34'	119°33'	10.7
46753	A-li-shan	23°31'	120°48'	2413.4
46748	Chia-yi	23°30'	120°25'	26.9
46755	Yu-shan	23°29'	120°57'	3844.8
46730	Tung-chi-tao	23°16'	119°40'	43.0
46721	Cheng-kung	23°06'	121°22'	33.5
46741	Tai-nan	23°00'	120°12'	13.8
46766	Tai-tung	22°45'	121°09'	9.0
46744	Kao-hsiung	22°34'	120°18'	2.1
46754	Ta-wu	22°21'	120°54'	8.1
46762	Lan-yu	22°02'	121°33'	324.0
46759	Heng-chun	22°00'	120°44'	22.3
46696	RCSS	25°04'	121°33'	7.3
46697	RCGM	25°03'	121°13'	46.0
46756	RCPO	24°48'	120°53'	14.6
46764	RCMS	24°44'	121°45'	10.4
46770	RCMQ	24°18'	120°36'	207.9
46751	RCLG	24°11'	120°36'	115.5
46763	RCYU	24°01'	121°37'	14.3
46734	RCQC(Ma-kung)	23°33'	119°37'	28.9
46746	RCKU(Chia-yi airport)	23°28'	120°23'	28.0
46743	RCNN	22°57'	120°12'	16.0
46745	RCAY	22°47'	120°15'	11.2
46760	RCQS	22°46'	121°06'	10.8
46758	RCSQ	22°42'	120°28'	30.8
46750	RCDC(Peng-nan)	22°40'	120°27'	30.4
46752	RCKW	22°00'	120°41'	17.1

Nadine reached its maximum intensity (lowest surface pressure of 898 hPa) at 12 UTC of 24 July. At that time, Nadine was about 300 nm to the southeast of Taiwan. Although Nadine weakened afterward, it still was a strong typhoon with maximum wind of 110 kts at 12 UTC of 25 July (six hours before landfall). The radius of the 100 kts wind extended 100 nm, and the radius of the 30 kts wind was more than 300 nm to cover the entire Taiwan area. By the time of landfall at 18 UTC, Nadine had weakened to a moderate typhoon; it was a weak typhoon 5 hours later when it left the island from the west coast. The tracks of Nadine in the vicinity of Taiwan given by JTWC and this study are shown in Figure 2.

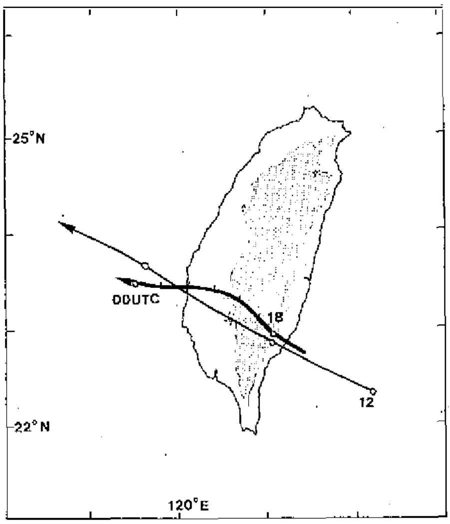

Fig. 2. The tracks of typhoon Nadine in the vicinity of Taiwan given by JTWC (thin solid line in 6 h interval from 12 UTC of 25 July to 00UTC of 26 July) and by this study (heavy solid line in 1 h interval from 18 UTC of 25 July to 00 UTC of 26 July). Grid intervals are 1 degree.

The surface winds and pressure fields over the Taiwan area at 12 UTC of 25 July when the center of Nadine was about 100 nm east of station Tai-tung are shown in Figure 3. The figure shows most of the winds on both sides of the CMR were northerly along the mountain. Strong winds were found to the east of the CMR and at the offshore islands to the west of Taiwan (Peng-hu and Tung-chi-tao) . The surface isobars (Figure 3b) over the Taiwan area did not circle around the typhoon center. This shows the significant influences of Taiwan's orography on the typhoon. Over northeastern Taiwan, the flow was against the CMR and produced a pressure ridge. The lee trough was found over the western slope. The air in the lee trough was very dry especially near station Tai-chung where the difference between temperature and dew point temperature (dew point depression) was greater than 7°C. Meanwhile, the wind at Lan-yu was 40 kts northerly. One hour later, the wind shifted to 55 kts southerly. The surface pressure also decreased from 968.9 hPa to 968.3 hPa. These phenomena suggest the center location of Nadine at 12 UTC was closer to Lan-yu than the position (22.4°N and 122.3°E) observed by JTWC.

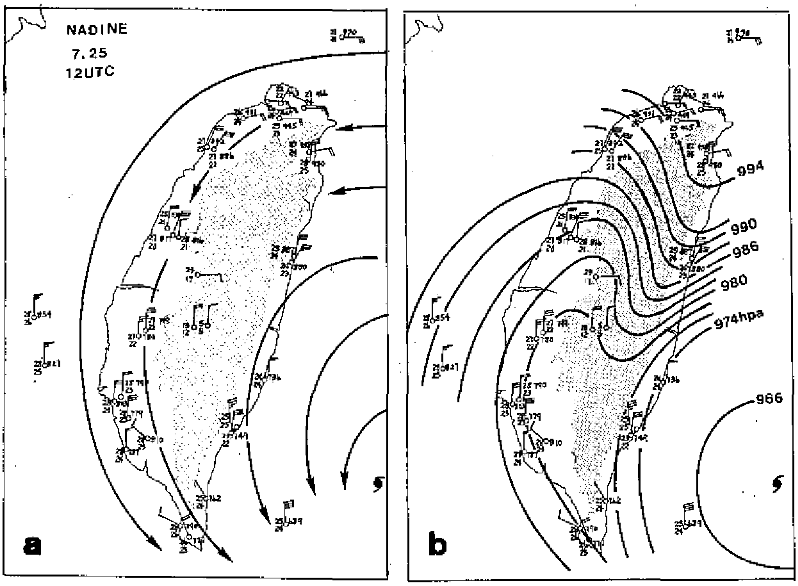

Fig. 3. (a) Surface winds and simplified streamlines, and (b) surface pressure analysis (2 hPa intervals) over Taiwan (hashed area is higher than 500 m) at 12 UTC 25 July 1971. Typhoon symbol indicates typhoon center.

The time sections of surface winds and pressure along Lan-yu, Tai-tung, Yu-shan, A-li-shan, Chia-yi, Tung-chi-tao, Ma-kung and Peng-hu are shown in Figure 4. At Tai-tung, the wind shifted from northerly to southerly between 17 UTC and 18 UTC of 25 July. The surface pressure also decreased to its minimum value in the same period. Similar wind shift and pressure decrease were reported by Cheng-kung (not shown). These wind and pressure changes indicate the center of Nadine had landfalled and passed Tai-tung between 17 UTC and 18 UTC.

The surface winds and pressure distributions at 18 UTC are shown in Figure 5. As the center moved closer to the land, the wind over the east coast (e.g., Hua-lien) became stronger. But, due to the sheltering effect of the CMR, winds over southwestern Taiwan (Chia-yi and Tai-nan area) were weaker than those in Figure 3. An important difference between Figure 3 and Figure 5 is that the wind near Ping-tung has shifted from northerly in Figure 3 to southerly in Figure 5. This wind direction change started at 16 UTC (not shown) and was accompanied by the formation of a weak pressure ridge. The pressure near Ping-nan was about 2 hPa higher than the nearby station at 18 UTC. The blocking effect of the CMR deflected the low-level flow toward the north instead of allowing it to climb over the CMR. But at this time, whether the low pressure had been separated into two centers by the pressure ridge was unclear from the observations.

The wind speed at Yu-shan increased to 30 kts at 19 UTC (Figure 6a). The cyclonic circulation in Yu-shan, Cheng-kung and Tai-tung indicates that the center of Nadine at 19 UTC was still to the east of the mountain ridge. One hour later (Figure 7), the wind at Yu-shan changed to 50 kts easterly. In the same period, the wind direction at A-li-shan also shifted from northerly to southerly. The changes of the wind directions indicated the circulation center of Nadine had passed over the CMR at 20 UTC.

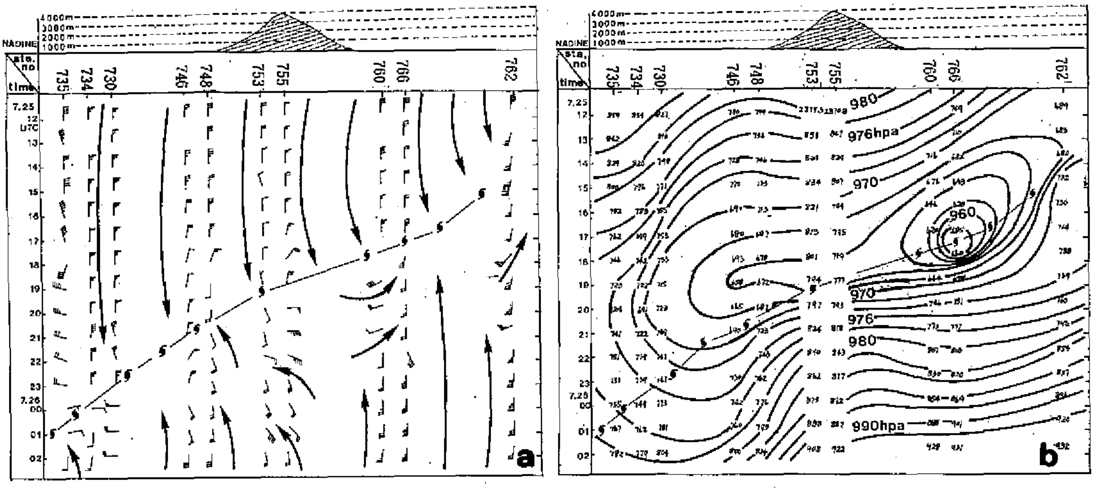

Fig. 4. Time sequences of (a) winds and (b) pressure (hPa) at stations given in the top of the diagrams. The station height are also showed. Line connecting typhoon symbols highlight the passage of center.

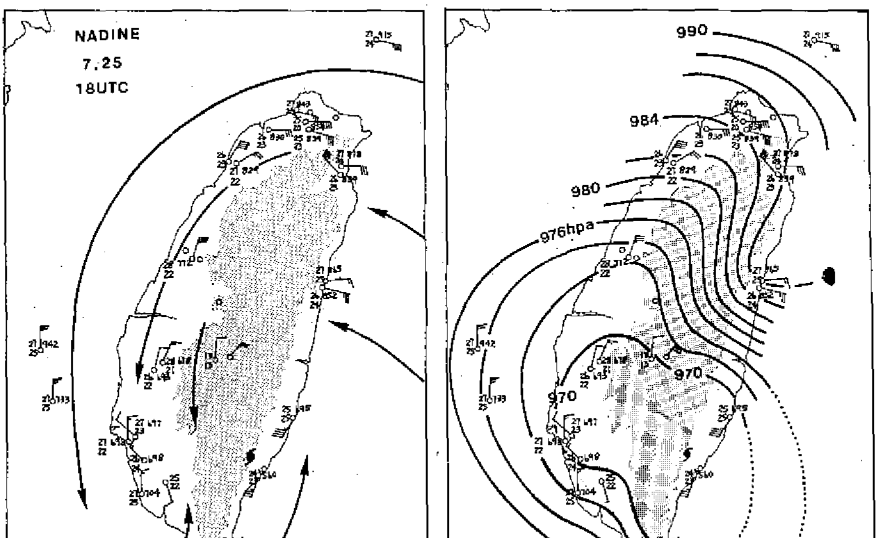

Fig. 5. Same as in Figure 3, except at 18 UTC.

It is rather difficult to determine the exact location of the low center from Figure 6. It is similarly difficult to determine whether there were separated centers. That is because the minimum isobar (968 hPa) enclosed a broad area extending southeast-northwest. Figure 4 shows that the surface pressures at both Yu-shan and A-li-shan reached minimum at 19 UTC. And, the decrease of surface pressure had a continuous trend from east to west, which indicates that the pressure center was moving across the CMR continuously. Since typhoon

Nadine was filling when it moved over the land, a station might observe its minimum pressure before the low center passed.

The pressure difference between east and west coasts to the north of the typhoon center became larger as Nadine moved closer to the land. At 19 UTC (Figure 6), the pressure difference between Hua-lien and Tai-chung increased to 16 hPa. As the pressure difference increased, the air over the western lee trough became even drier (dew point depression = 9°C). Similar warm and dry air over the lee trough was found from the simulation study of Yeh and Elsberry (1993). The dew-point depression in the region closer to the center, however, was small, for example, Chia-yi was only 2°C. This different air property suggests that the pressure decrease over the Chia-yi area was caused differently from that over the Tai-chung area. The downslope warming caused the deepening of the lee trough over the Tai-chung area, while the approach of the low center caused the pressure decrease over the Chia-yi area. One may notice that the wind directions at Chia-yi were significantly different from those at Chia-yi airport. Actually the difference lasted for several hours beginning from 19 UTC to 23 UTC (Figure 3). In this period, the wind at Chia-yi maintained about 10 kts southerly when the wind at Chia-yi airport was about 10 kts northerly. As these two stations are only 5 km apart and the circulation (if it existed) did not move, these differences may be due to observation errors.

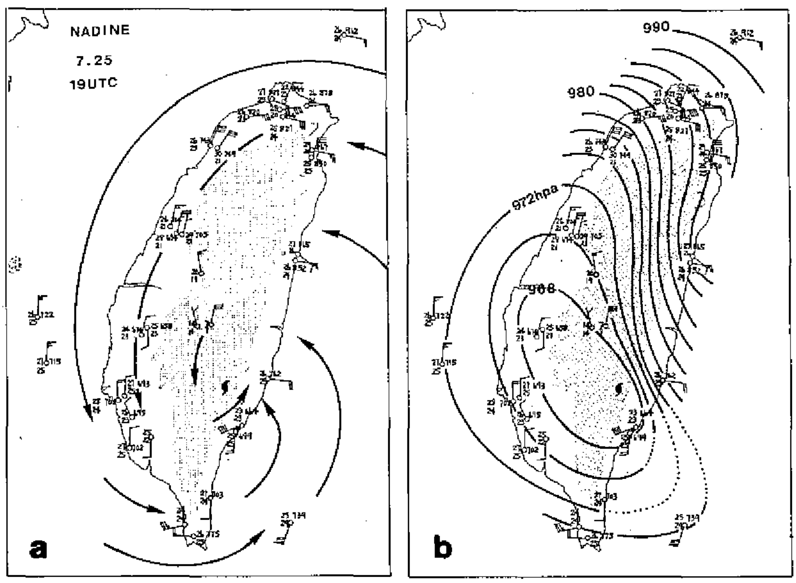

Fig. 6. Same as in Figure 3, except at 19 UTC.

At 20 UTC (Figure 7), winds at Yu-shan and A-li-shan shifted clockwise to easterly and southeasterly, respectively. The wind speed at Yu-shan also increased to 50 kts. These indicate the passage of the circulation center. Meanwhile, the wind over the western coastal area were mainly along the mountain. Over the eastern coast, especially to the north of Cheng-kung, strong upslope winds were observed. These strong upslope winds produced a pressure ridge/trough over the upstream/downstream of CMR. The isobar of 970 hPa enclosed a broad area over central Taiwan. It is difficult to identify the exact location of the low center from the isobars. The time section diagram of Figure 3b shows the surface pressures at Yu-shan, A-li-shan, Chia-yi, Chia-yi airport, and Tung-chi-tao all reached their minimum at 19 UTC. The pressure then increased (2 hPa) from 19 UTC to 20 UTC at Yu-shan. In the same period, the pressure increases were very small west of A-li-shan. Therefore, the center at 20 UTC was believed still east of Chia-yi station. Because Nadine was weakening, all the stations west of the CMR should have observed the minimum pressure before the center passed by.

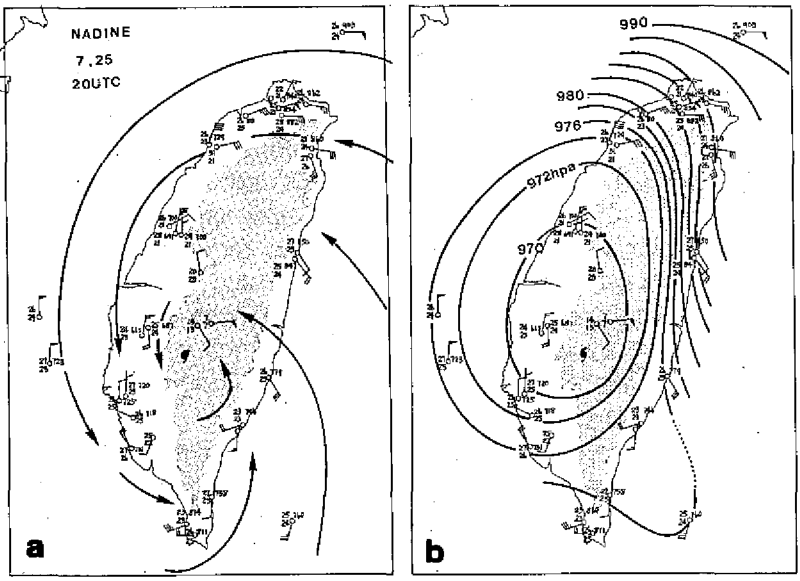

Fig. 7. Same as in Figure 3, except at 20 UTC.

Significant wind direction changes at both Tai-chung and Tai-nan were found at 21 UTC (Figure 8). The winds changed from northerly to northeasterly at Tai-chung, and the winds at Tai-nan changed from northerly to northwesterly. These wind changes suggested that the typhoon circulation center was located near Chia- yi at 21 UTC. The pressure fields in Figure 7b show a similar pattern to those in Figure 6b, except that the minimum isobar contour (increased 2 hPa to 972 hPa) has shifted westward slightly and extended northward to cover Hsin-chu. The decrease of pressure at Hsin-chu is very special as the typhoon was weakening and all the other stations showed pressure increase. The very dry (dew point depression=9°C) and warm (temperature=31°C) air at Hsin-chu indicates the pressure decrease was mainly caused by the downslope warming effect, not the approaching of the low center. It is still not possible to analyze a separated low at this time. However, it could be a result of not enough data coverage.

Some additional observations in southwestern Taiwan (Figure 9) help to locate the circulation and pressure centers at 22 UTC. A pronounced cyclonic circulation to the east of Tung-chi-tao was shown. The center of the circulation was located at about 120.1°E, 23.3°N. It was very close to the location given by the JTWC. The surface pressure fields remained very similar to those in Figure 8b, except that the lowest isobar contour was 2 hPa higher and the low pressure area had shifted slightly westward. To the north of the primary circulation center, there was a secondary cyclonic shear between Hsin-chu and Tai-chung. The slightly higher pressure to the north of the primary circulation center also separated the low pressure area into two regions. The southern low pressure center was located very close to the primary circulation center, but the northern low pressure center was not clearly located.

At 23 UTC (Figure 10), the northerly at Tung-chi-tao and Ma-kung suggest the center was still to the east of these stations. At 00 UTC of 26 July (detail fields not shown), the easterly at Ma-kung and the westerly at Tung-chi-tao (Figure 3) suggested the circulation center was located between the two stations. This location was to the south of the location given by JTWC. The wind at Ma-kung then turned to southerly later at 01 UTC (Figure 3). It showed the passage of the center. But the center location was not easy to identify after it moved to the open ocean.

In summary, the intensity of typhoon Nadine decreased significantly as it encountered mountainous Taiwan. The center pressure was filled 36 hPa from 12 UTC of 25 July when it was near Lan-yu to 00 UTC of 26 July when it was near Tung-chi-tao. About half of the pressure filling (10 to 15 hPa) was found before the center landed on the eastern coast. Over and near Taiwan, significant asymmetry of isobars was found even though the center was still far away from the island. A pressure ridge was located east of the CMR with upslope flow. A trough was found over the lee-side of the CMR with very dry and warm air. The winds were also changed by the mountain. Instead of circling around the typhoon center, the flows were generally along the CMR over western Taiwan and south of the center when Nadine was still east of the CMR.

Although the locations of the circulation/pressure center couldn't be identified exactly, the time section plots do show Nadine passed over the CMR continuously. The center landed north of Tai-tung between 17 UTC and 18 UTC of 25 July then it moved over the ridge of

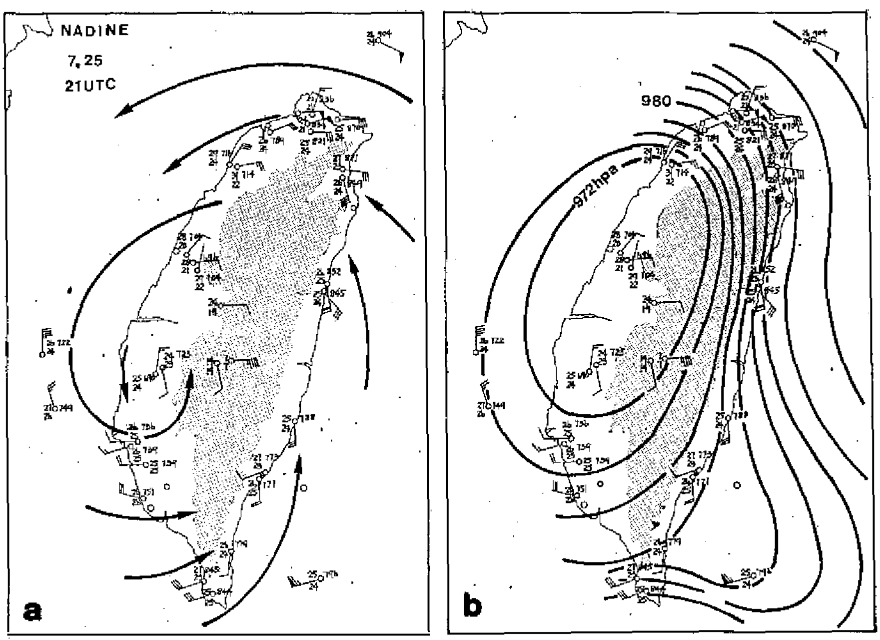

Fig. 8. Same as in Figure 3, except at 21 UTC.

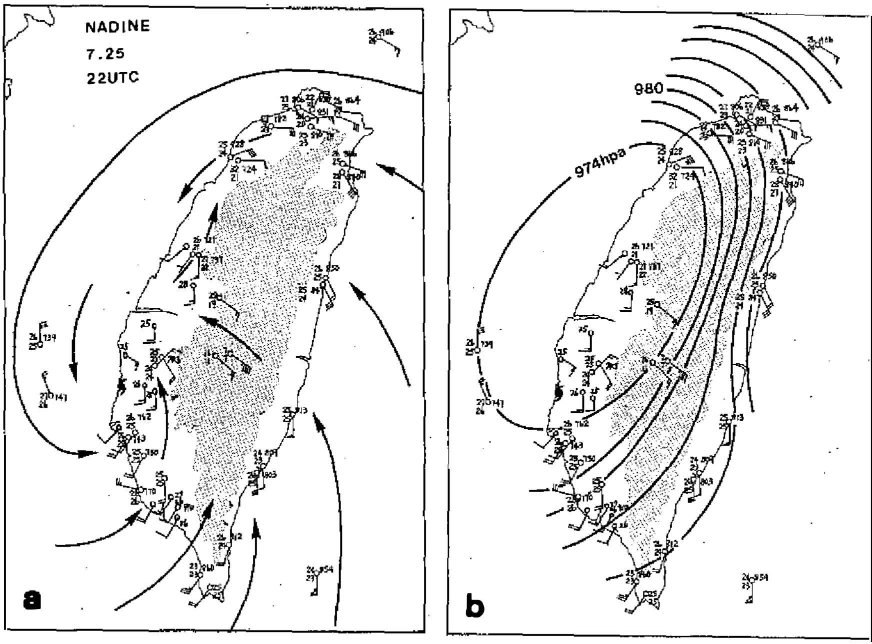

Fig. 9. Same as in Figure 3, except at 22 UTC.

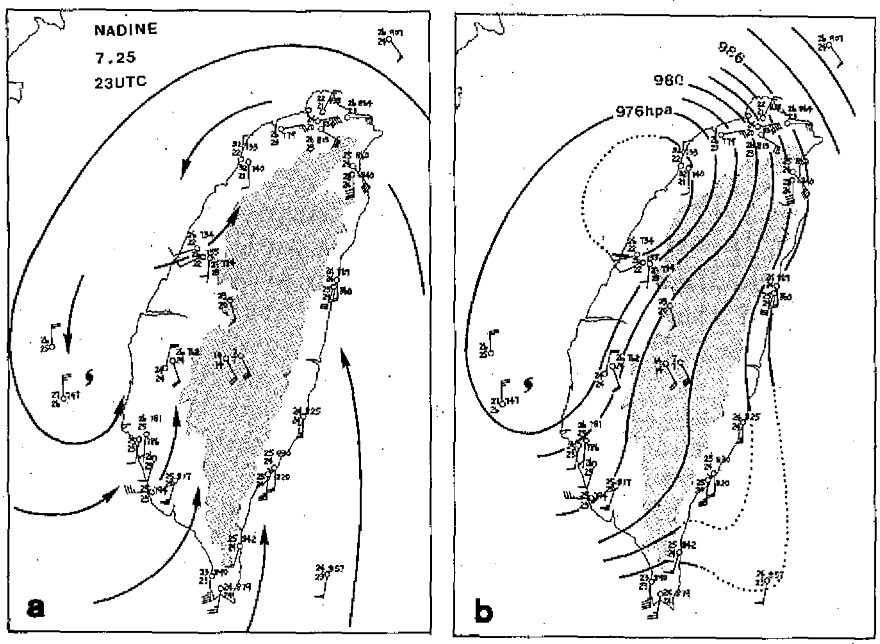

Fig. 10. Same as in Figure 3, except at 23 UTC.

the CMR about 2 hours later. After the center passed over the CMR, it moved to the western coast at 22 UTC and moved southwestward to near Tung-chi-tao at 00 UTC 26 July. The track was to the north of the track given by the JTWC (see Figure 2). The 6-hour interval best track of JTWC was obtained by using synoptic data only and fitting the centers smoothly. It may represent the motion of a typhoon without the effect of the CMR. The northward (southward) deflection of the track before (after) the typhoon center passing the CMR is similar to the simulation results of Bender *et al.* (1987) and Yeh and Elsberry (1993). Whether the ventilation flow discussed by Yeh and Elsberry related to the surface track deflection remains to be examined.

The very warm and dry air over the northwestern slope lasted for several hours even after the center had passed the CMR and moved over the western coast. The observations in Figure 9 and Figure 10 suggested that a secondary circulation and low pressure center was formed over the northwest coastal area after the center had passed over the CMR. Similar phenomena was simulation by Yeh and Elsberry (1993). Unfortunately, the detailed structure of the newly formed secondary centers, and re-organization of typhoon Nadine were not well observed (due to the sparsity of the observations). Therefore, a comparison of the simulation results and the observation is not possible.

3.2 Discontinuous Track: Typhoon Betty

Typhoon Betty reached typhoon intensity at 06 UTC on 22 May, 1961. At that time, it located to the east of the Philippines near 147°E, 11°N. Then it followed a smooth track north-northwestward and made landfall in southern Korea at 12 UTC 28 May. The tracks of Betty in the vicinity of Taiwan by JTWC and this study are shown in Figure 11. The track given by the JTWC shows Betty invaded Taiwan on 26 May. The typhoon intensity reached its maximum with wind speed of 110 kts at 06 UTC on 26 May (about 12 hours before landfall on Taiwan). The maximum wind speed decreased to 60 kts when the center landed between Hua-lien and Tai-tung at 18 UTC on 26 May.

The surface winds and pressure distributions over the Taiwan area at 09 UTC are shown in Figure12. The wind at Lan-yu decreased from 55 kts northerly at 08 UTC (not shown) to 15 kts easterly, then increased to 30 kts southerly at 10 UTC. These wind changes showed Lan-yu was near the eye of Betty at 09 UTC. The streamlines both over the east and west of the CMR were generally along the mountain. Strong winds were over the southeastern coast and the southern tip of Taiwan. A calm area with wind speed less than or equal to 10 kts was over western central Taiwan where lee trough with relatively warm and dry air was found. The temperature was 26°C at Tai-chung and 25°C at Chia-yi. Those temperatures were about 2 to 3 degrees higher than the temperatures at eastern stations. Another calm wind area was over northeastern Taiwan where a surface pressure ridge was found. A similar calm area over the upwind side was simulated by Yeh and Elsberry (1993).

The time section of wind and pressure along Lan-yu, Tai-tung, Cheng-kung, Yu-shan, A-li-shan, Chia-yi airport, Ma-kung and Peng-hu are shown in Figure 13. The winds at Ma-kung and Peng-hu were maintained northerly from 09 to 16 UTC, while the wind at Chia-yi airport changed from northeasterly to westerly to southerly. The pressure at Chia-yi decreased during this wind-shift period and reached a minimum at 16 UTC. After 16 UTC, a steady southerly and a pressure rise were observed at Chia-yi. The wind shift and pressure decrease were later found at Ma-kung and Peng-hu at about 20 UTC. These phenomena show that the cyclonic low pressure center moved westward from Chia-yi at 16 UTC. However,

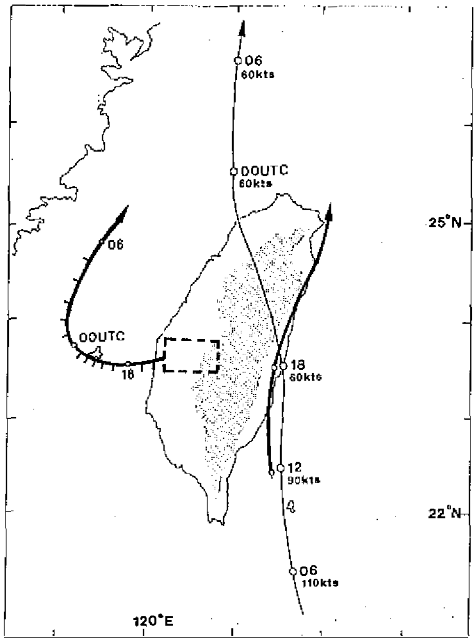

Fig. 11. The track of typhoon Betty in the vicinity of Taiwan given by JTWC (thin solid line in 6 h intervals from 06 UTC of 26 May to 06 UTC of 27 May) and by this study (heavy solid line). The rectangular area over western Taiwan show the uncertain location of the formation of secondary center.

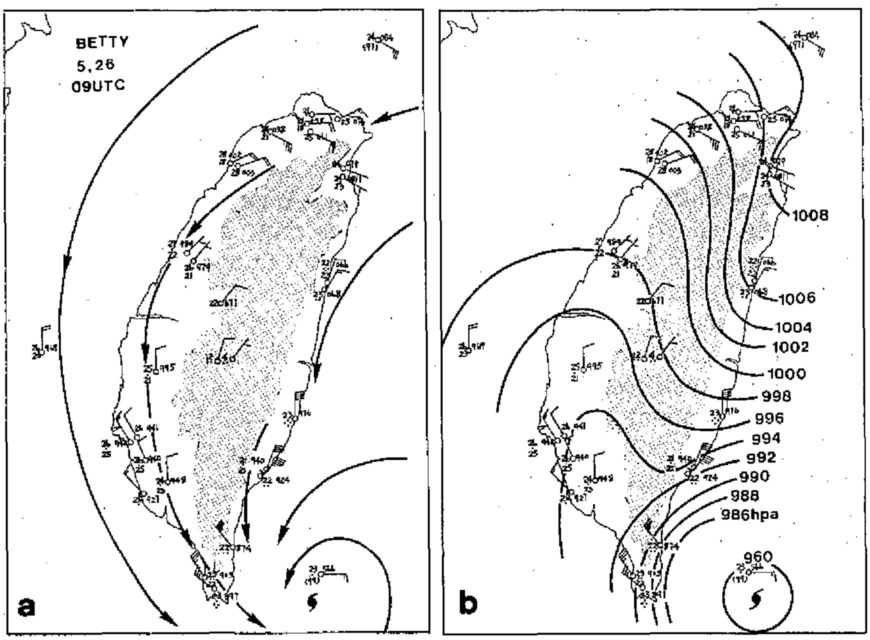

Fig. 12. Same as in Figure 3, except at 09 UTC 26 May 1961.

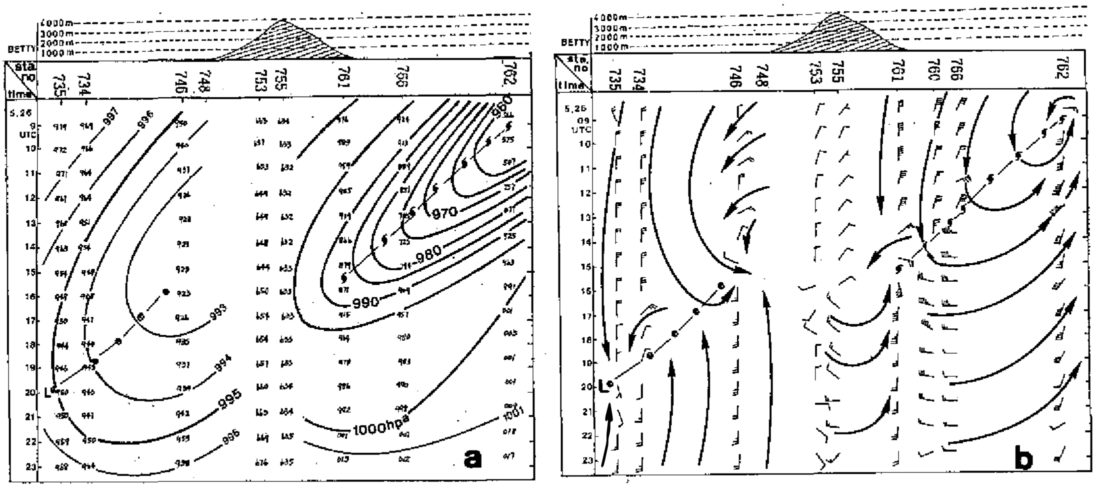

Fig. 13. Same as in Figure 4, except from time period from 09 UTC to 23 UTC 26 May 1961.

the time section diagram shows that the original typhoon center at 16 UTC was still near Cheng-kung, where the strongest wind of 70 kts and the lowest pressure of 871 hPa were found. The wind shift at Yu-shan started at 17 UTC, but, the southerly wind component did not appear until 22 UTC. This indicates the original typhoon circulation center did not pass over the CMR before 22 UTC. The track of the cyclonic low pressure center shown in Figure 13 was discontinuous from the eastern to the western the CMR. The cyclonic low center over the west side of the CMR was not the original typhoon center. Winds near the secondary center were weaker than in the surroundings, and the pressure gradient near the secondary center was much smaller than that of the original center. These differences also show the secondary center had different properties from the original typhoon center. The details and the evolution of the secondary centers will be discussed in the following sections.

Figure 14 shows the surface winds and pressure distributions at 15 UTC, about the time of typhoon landfall on the eastern coast. The typhoon center was within the most favorable area to form a secondary center as shown by Chang *et al.* (1993). Both the flow and the pressure patterns over northern Taiwan remained very similar to those in Figure 12, but the wind was stronger and the pressure was lower at this time, as the typhoon center moved closer. Over southeastern Taiwan, a cyclonic circulation and low pressure center was found near the coast. The wind speed over the high mountain area (e.g., at A-li-shan) was very weak. Another important difference between the flow structure in Figure 14 and that in Figure 12 was the wind over southwestern Taiwan. It shifted from northerly or northwesterly at 09 UTC to westerly or southwesterly at 15 UTC. These wind changes increased the cyclonic curvature of the streamlines over western central Taiwan and the nearby ocean area. A pressure ridge formed over the southwestern slope. This ridge changed the 994 hPa isobar to a dipole-shape. The center of the east pole includes the typhoon and the west pole is over the Chia-yi area. The air in the west pole was relatively dry (dew point depression=3°C) and had different characteristics from that in the east pole.

The center of Betty moved and landed very close to Cheng-kung at 16 UTC (Figure 15). The wind at Cheng-kung increased to 70 kts and shifted to southerly. This center location is to the west of that given by the JTWC (Figure 13). At the same time, the wind over the

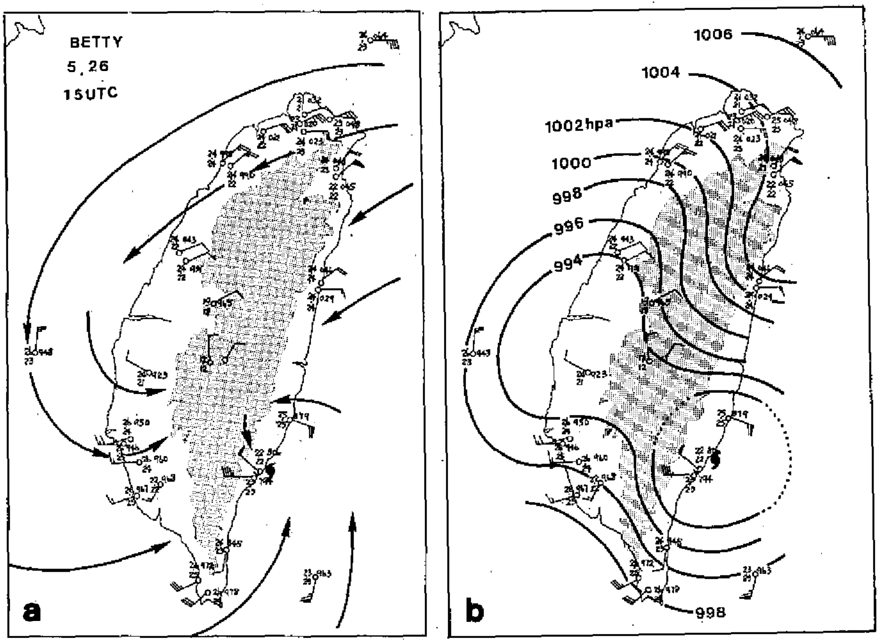

Fig. 14. Same as in Figure 12, except at 15 UTC.

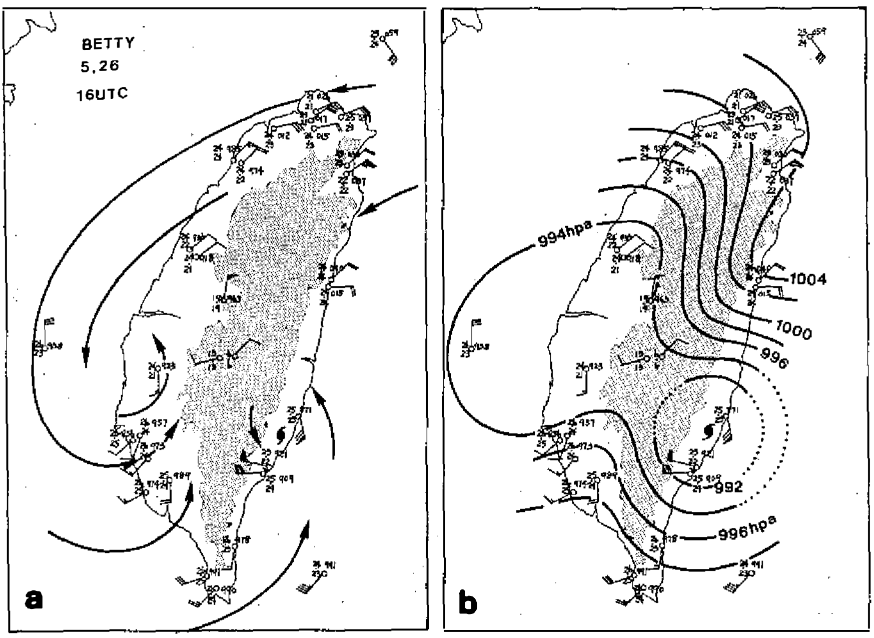

Fig. 15. Same as in Figure 12, except at 16 UTC.

northeastern coast became stronger and the ridge became more pronounced. Over the west of the CMR, the 994 hPa isobar shifted westward and extended northward to cover a broad area including Tai-chung, Peng-hu and the Chia-yi area. The pressure ridge produced by the flow over southwestern Taiwan was stronger. The dipole pattern of the 994 hPa isobar was clearly shown.

The winds over southwestern Taiwan gradually shifted from westerly to (Figure 14) southwesterly (Figure 15) to southerly (Figure 16 and Figure 17). The change in the wind direction increased the cyclonic curvature of the streamlines in that area. The area of southerly flow also extended northward. At 16 UTC (Figure 15), the southerly was already found at Chia-yi. The northerly flow over the northwestern coast and the southerly flow along the southwestern slope of the CMR formed a closed circulation (secondary circulation) in the west of Chia-yi. At 18 UTC (Figure17), the southerly extended to the Tai-chung area. Ji-yueh-tan also reported 15 kts southerly. Meanwhile, the cyclonic circulation over the west of Taiwan moved slightly westward.

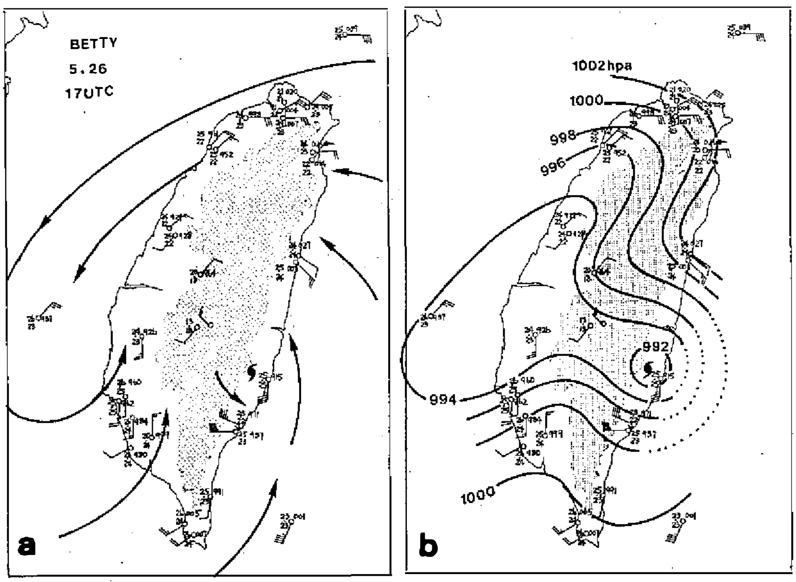

Fig. 16. Same as in Figure 12, except at 17 UTC.

The original typhoon circulation center over the east of the CMR could still be identified at 17 UTC (Figure 16), but, the detailed pressure distribution was not exactly known after it passed Cheng- kung and moved into a data-void area between Cheng-kung and Hua-lien. The 994 hPa isobar over the west of the CMR narrowed in an east-west direction but extended northward. The gradual development of the ridge over southwestern Taiwan and the southerly flow at Chia-yu, Ji-yueh-tan and Tai-chung area suggest that the cyclonic low over the western coastal area had completely separated from the original typhoon center at 18 UTC (Figure 17), but, the exact location of the secondary low center was unclear.

Also noticed is that the north-south extended low pressure pattern in Figure 17 is similar to the situation when typhoon Nadine was in the west of CMR (e.g., at 23 UTC on 25 July in Figure 10). However, the air properties in the two low pressure regions are quite different.

The air over northwestern Taiwan in the case of Nadine was very warm and dry, caused by subsidence flow passing over the CMR. In the case of Betty, no strong flow over the CMR was found. The air in the west bank of the CMR was blown from the ocean as part of the typhoon circulation. The flow was then blocked by the CMR and deflected northward along it. Therefore the air was not very dry.

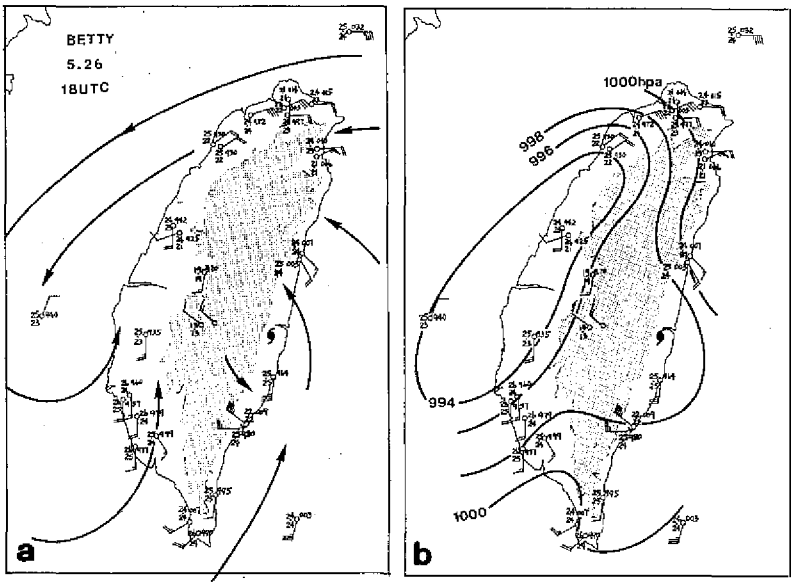

Fig. 17. Same as in Figure 12, except at 18 UTC.

Figure 18 shows wind observations (selected stations only) from 20 UTC on 26 May to 06 UTC on 27 May. The change of wind direction at Ma-kung (northerly at 18 UTC to southerly at 20 UTC) shows the secondary circulation has passed Mar-kung at 20 UTC. The gradual increase of the southerly flow at Mar-kung (wind speed increased outward in the secondary circulation) shows the secondary circulation center was moving westward. The wind at Ma-kung then shifted gradually from southerly (at 00 UTC) to southwesterly (at 02 UTC) to westerly (04 UTC and 06 UTC). This wind shift indicates that the secondary circulation center recurved northward. The center was located near 120 degrees E and 25 degrees N at 06 UTC. Over the other side of the CMR, the original circulation moved northward along its east slope. The gradual shift of the wind direction at Hua-lien shows the center was east of Hua-lien at 20 UTC and was between Hua-lien and I-lan at 22 UTC. The center then moved to the ocean and passed the northeast tip of Taiwan to a location northeast of Kee-lung at 04 UTC. The original center had already lost its properties at this time as the wind speed near the center (such as at Kee-lung) was very weak. The tracks of both the original and the secondary circulation centers are shown in Figure 11. The study of the later stage of typhoon Betty's reorganization requires more observations over the Taiwan straits.

In summary, the structure of typhoon Betty in the vicinity of Taiwan was very different from the simple circled isobars or streamlines around the center. A lee trough formed over the west of the CMR before the typhoon center landed on Taiwan. As part of the Betty circulation was blocked on southwestern Taiwan, flow was deflected northward along the west slope of

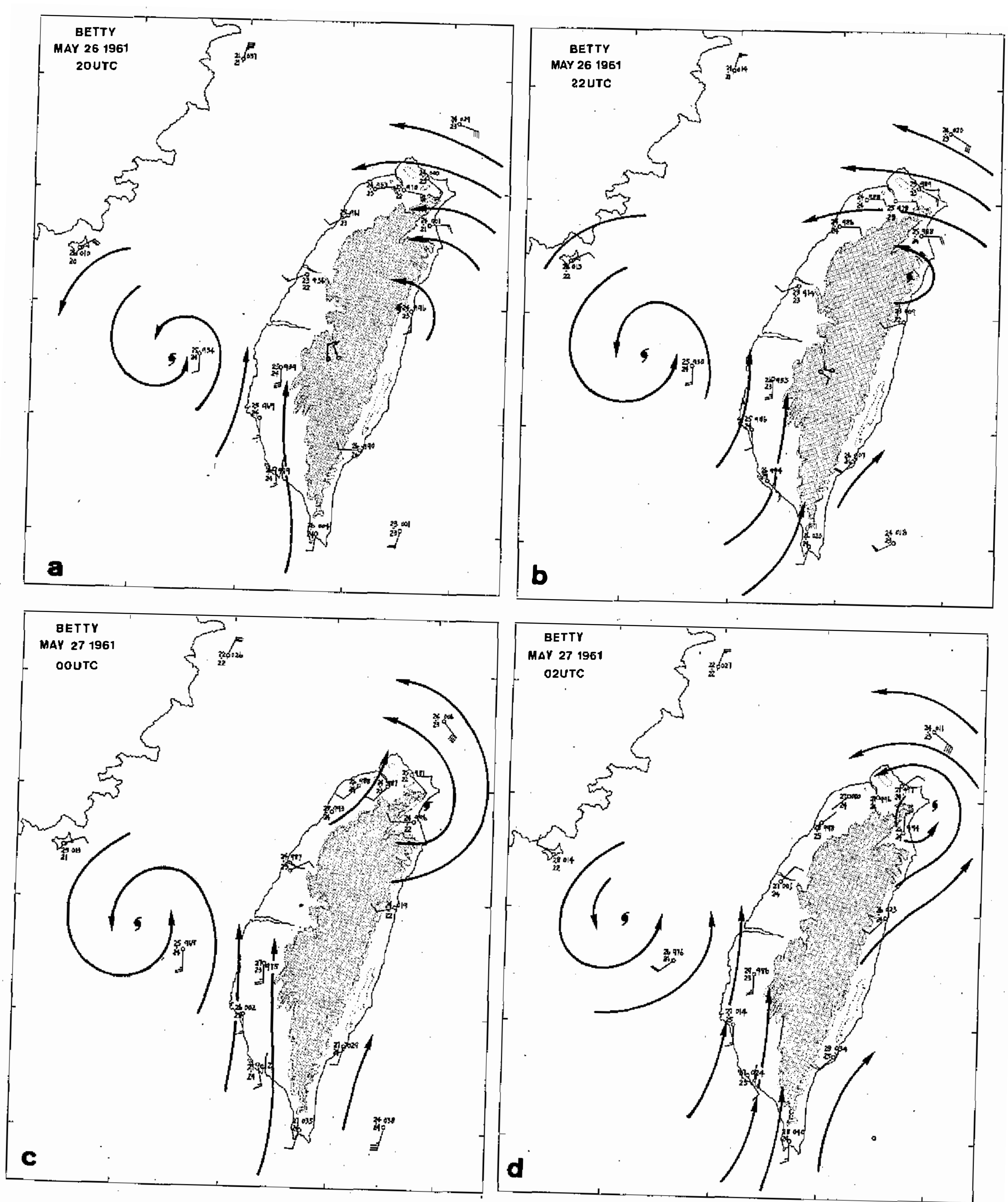

Fig. 18. Surface winds and simplified streamlines near Taiwan area (background) at (a) 20 UTC, (b) 22 UTC 26 May, and (c) 00 UTC, (d) 02 UTC, (e) 04 UTC and (f) 06 UTC 27 May 1961.

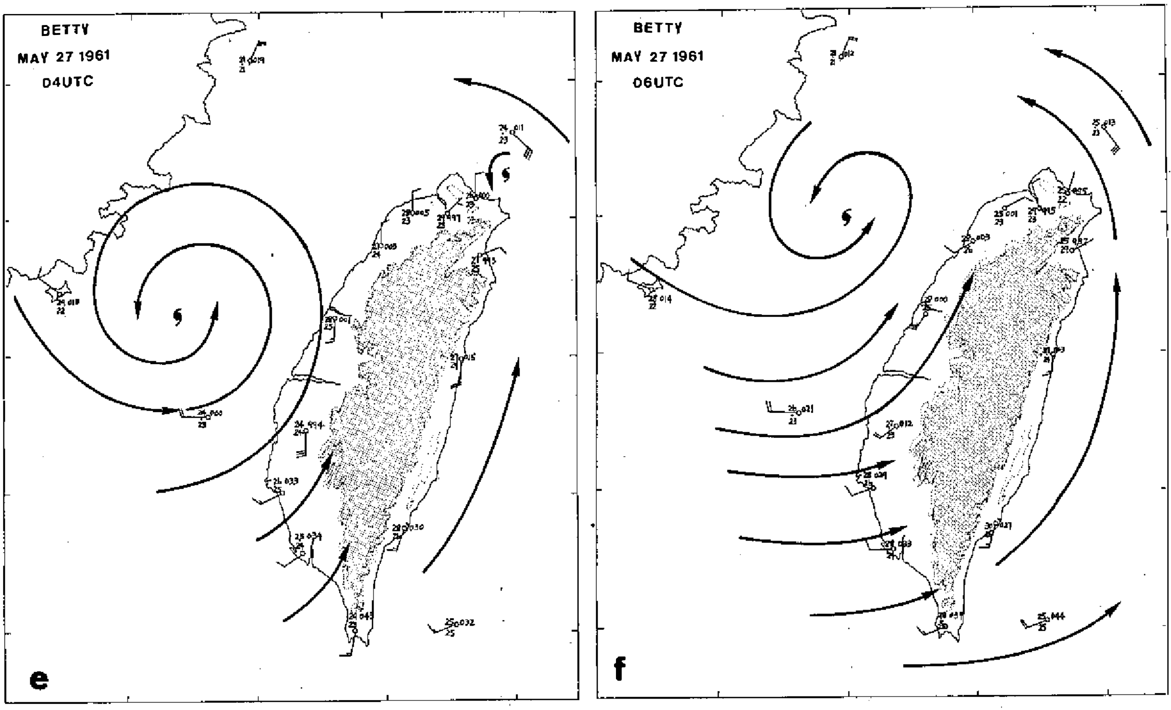

Fig. 18. (Continued.)

the CMR to form a secondary circulation. The accompanying development of the ridge over southwestern Taiwan later separated the low pressure region over the west of the CMR from the original typhoon center. When the original circulation center was weakening and moving northward along the east slope of the CMR, the secondary circulation center was moving westward to pass Mar-kung. The detailed track in the vicinity of Taiwan (Figure 11) is completely different from the smoothed best track of JTWC.

The secondary center of typhoon Betty was found embedded in the lee trough at the formation stage. A similar result was found by Chang *et al.* (1993) in their climatology study. They showed that the pre-existing lee trough (their mode 2) became an isolated secondary low when the onshore flow produced a ridge over southwestern Taiwan (their modes 1 and 4). After the formation, the secondary center moved westward. As Betty approached Taiwan from the southeast, the motion of the secondary center had a leftward component related to the meanflow. Similar leftward motion deflection of the secondary center was obtained in simulation W6S of Yeh and Elsberry (1993). The reason for the southward motion deflection may related to the strong northerly flow over the west of the Taiwan. However, most of the simulation studies were focused on the westward moving typhoons. The northwestward-moving typhoon Betty provides another interesting case for future simulation study.

4. SUMMARY AND CONCLUDING REMARKS

This paper has shown the detailed surface wind and pressure distributions over the Taiwan area when typhoons Nadine in 1971 and Betty in 1961 were invading Taiwan. The center of Nadine passed over the Central Mountain Range (CMR) continuously although an orography-induced local ridge/trough was found. The center of Betty, however, was weakening over the east slope of the CMR when it was moving northward. The secondary circulation and low system formed and developed over the west side of the CMR. It later became the dominant system and resulted in track discontinuity.

In both typhoons Nadine and Betty, the CMR induced a pair of upslope ridges and lee troughs when the typhoon centers were still far away from Taiwan. The ridge and trough intensified when the typhoon center moved closer to Taiwan. In the case of typhoon Nadine, the wind direction over the west side of the CMR was generally parallel to the CMR. Strong winds was also found at the top of the mountain stations. Therefore, the center circulation was able to pass over the CMR. On the other hand, the wind over southwestern Taiwan shifted to the western slope of the CMR when typhoon Betty moved to the eastern coast. A pressure ridge was induced and strengthened to separate the lee-side low pressure zone from the typhoon center. The wind speed at the mountain top was very weak during the invasion of Betty. The flow over southwestern Taiwan was unable to climb over the CMR but was blocked and deflected northward to form a secondary circulation. The wind speed near the center of the secondary circulation was very weak. The pressure gradient of the secondary low was also very small. These are the differences between a secondary center and a regular typhoon center.

The exact locations of the secondary low center and secondary circulation center were often not easy to define from the current surface observation networks. Rather weak wind speed near the secondary circulation center and the small pressure gradient in the secondary low made the center determination even more difficult. Increase of surface observations over western Taiwan will help the identification of these secondary centers in western Taiwan. The numerical simulation is another alternative for study of Taiwan-typhoon interactions.

The time-section plots for stations along the center track were proven to be useful in determining whether the original center had passed over the CMR. The diagrams are also helpful in the identification of center(s) location. The time-section plots for typhoon Nadine show continuous change of wind and pressure fields along the track. On the other hand, discontinuity between the east and the west of CMR stations were found in the time-section diagrams for typhoon Betty. The low wind speed near the secondary circulation and the small pressure gradient near the secondary low were also shown in the time-section diagrams.

This study has shown the surface wind and pressure structure when the centers of the typhoons were over or near Taiwan. Very complicated orographic effects on a typhoon still occur even after the center has passed Taiwan. For example, very warm and dry regions were found in Tai-chung and Hsin-chu area after Nadine had moved away from the west over the coast. Re-organization processes after the secondary circulation of Betty passed around Ma-kung and moved toward the original smoothed track were also briefly noted. However, more observations over the Taiwan strait or numerical simulations are required to further address these phenomena.

From this study, we learn that secondary centers do develop over the west side of the CMR. The motion of the secondary center (such as in typhoon Betty) may significantly differ from the original direction (such as the smoothed track of JTWC). Therefore, a poor track forecast downstream of the Taiwan may occur if not considering these effects. In addition, the CMR can also induce other complicated wind modifications. For example, strong corner flow was observed over the south and the north tips of Taiwan, while a calm area was found over western central Taiwan. Understanding of these detailed surface wind modifications is very important for issuing a correct typhoon warning.

In this study, only two types of typhoons crossing Taiwan have been discussed. Several other types of typhoon tracks crossing Taiwan have been suggested by Wang (1980) and Yeh and Elsberry (1993). For example, Wang showed some typhoons may make a loop before the center passes the CMR. Possibility of dual centers moving parallel westward was also suggested by both observation and simulation studies. The structure modifications also depend on the location of the approaching typhoon. Examination of the surface structures of these types of typhoon crossing Taiwan are ongoing.

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