NUMERICAL SIMULATION STUDY OF THE EFFECTS OF TERRAIN AROUND TAIWAN ON TYPHOON DOT (1990)

Yang Jinghua (阎敬华)

Guangzhou Institute of Tropical and Oceanic Meteorology, Guangzhou, 510080

and Dong Keqin (董克勤)

Chinese Academy of Meteorological Sciences, Beijing, 100081

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ABSTRACT

With the use of analyzed TCM-90 data, Typhoon Dot (1990) and complex evolutions are successfully reproduced in numerical simulation as it travels over the island of Taiwan. The simulation includes the formation of secondary highs in both circulation and geopotential fields, trajectory jumps during mergence with main centers, anomalous northward movement of a low center west of Taiwan, evolutional process of a low-level jet over the Taiwan Straits and significant deviations of circulation center from geopotential center between upper and lower levels. By examining evolutions of 3-h interval simulated results, detailed processes of changes in structure and track before and after Dot's passage of Taiwan is given, whose evolutional images are otherwise impossible with conventional observations at intervals of 6 h. A number of control experiments are conducted in the end of the work for understanding causes and mechanisms behind various properties.

Key words: Typhoon Dot, terrain effects, numerical simulation

I. INTRODUCTION

As early as in the 1950's and 1960's the work on the effects of Taiwan terrain on tropical cyclones began (Hsu, 1960; Li, 1963). Some forecasting rules taking account of the effects were further discussed in the viewpoint of statistics and weather prediction in the 1970's (Brand and Blelloch, 1974; Putian Weather Services, 1974) and part of the features, e.g. appearence of secondary maxima, were even reproduced in experiments (Zhang, Wei and He, 1975). More advances were made in the 1980's. Initially, well-defined behavioural patterns of the tropical cyclone over Taiwan were drawn up by summarizing years of observed data (Wang, 1980). Then, the reproduction was first successful by numerical approach in which elaborate conditions of 60-km horizontal grids and idealized topography were designed (Chang, 1982).

Additionally, a triply nested model of a resolution of 0.16° in real size of Taiwan gave changes in tropical cyclone passing over the island in two basic air currents. The study has outlined a framework that needs further development because i) the previous observations are temporally and spacially too coarse to analyze changes in structure, which is just made possible by the data collected in American Tropical Cyclone Motion Experiment in 1990 (TCM—90), ii) difference exists between distributions of meteorological elements and the reality in the past numerical modelling that takes idealized field as initialization, iii) the isolated island is focused in the past treatment of Taiwan in expense of the terrain in mainland China west of the straits, which might contribute to the results simulated, and iv) in previous attempts, detailed changes either as regard to the storm's passage over the island, especially the process and mechanism for generation of secondary centers and their mergence, or efforts trying to distinquish those of the circulation from the geopotential field, are absent. The present work analyzes the intensive observations from TCM—90 and simulates the changes in Dot's characteristics over a period prior to and post landfall of Taiwan using both observed data and real terrain, with stress on the formation and mergence of the secondary centre and its mechanism. Topographic effects of the mainland on the west side of the straits are also discussed.

Ⅱ. BRIEF DESCRIPTION OF THE MODEL

Necessary improvements are added to selected mesoscale of PSU/NCAR (MM4). The model has been shown in much modelling research at home and abroad to be of reliable performance and suitable platform for simulations on meso-α through meso-β scales. The current work allows for in the model 55×55 grids at intervals of 45 km horizontally and 10 layers vertically to top at 100 hPa. Physical processes include Kuo's convective parameterization, large-scale condensation, radiation, bulk kinetic boundary scheme, dry convection adjustment and horizontal/vertical diffusion etc. Observations at 6-h intervals are applied to the boundary to materialize time-dependent lateral conditions of inflow/outflow.

The model terrain is available by averaging an area of 0.5°×0.5°. It is shown in Fig. 1 that the extreme model height is 1910 m in conjunction with strip-shaped distribution of hilly regions (highest at 1050 m) in the mainland west of the Taiwan Straits in close parallel with the mountain ranges in the island. By aligning just between the two high topographic features, the straits is of funnelling.

The data in use is from the international typhoon experiment TCM—90 in 1990 with grid interval at 0.5°.

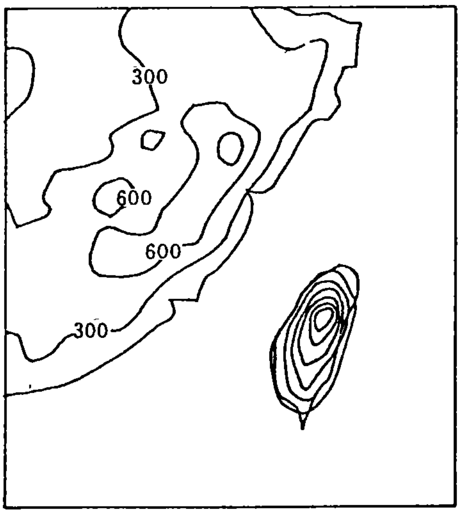

Fig. 1. Model terrain height around Taiwan at intervals of 300 m. The thick, solid line is the coastline and the thin, solid line the contour.

Ⅲ. ANALYSIS OF CASE OBSERVATIONS

The case selected is the life cycle of Typhoon Dot (1990). According to the *Typhoon Yearly Book*, the tropical cyclone is formed on September 3 over the western Pacific and keeps moving towards NW after September 4 in the direction of the southeastern part of Taiwan. Its landfall near Xingang, Taiwan at 1300—1400 GMT on September 7 is followed by mergence of the main center with the secondary one in motion of jumps over the southwest of Taiwan. The merged center further advances to NW until its second landfall on the southeast of Fujian at 1600 GMT on September 8. Fig. 2 gives variation in time of the center's position of Dot both before and after the passage of Taiwan. In the position multiply located (Fig. 2a), the secondary center formed at 1200 GMT September 7 on the southwest of Taiwan starts moving to NW while the main center rapidly jumps to join it after landing on the island and reach-

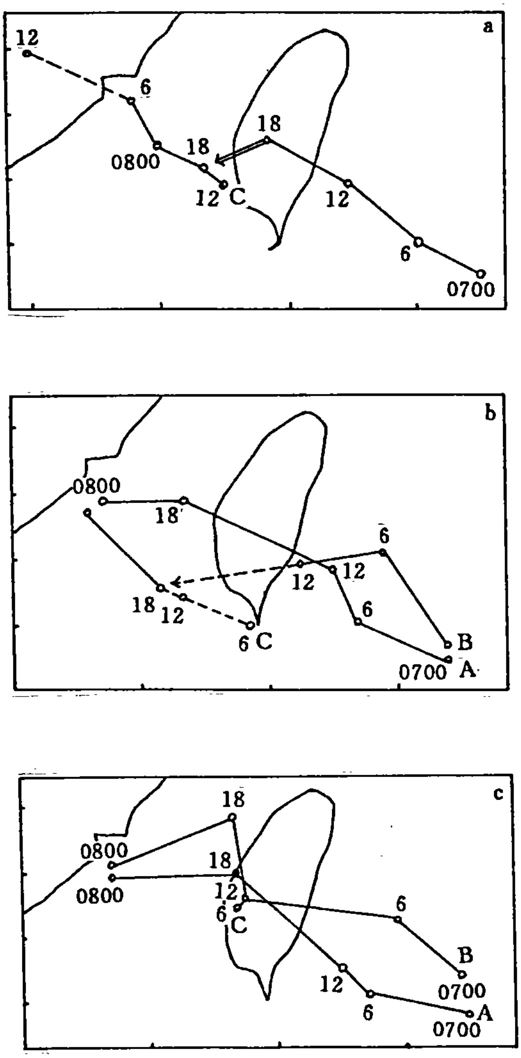

Fig. 2. Temporal evolutions of the centre of Dot around passage of Taiwan as positioned by comprehensive data in *Typhoon Yearly Book* (a), analysis of flow field from TCM-90 observations (b), and analysis of geopotential field from TCM-90 observations (c). A and B denote the main centres at 500 and 1000 hPa, respectively and C the secondary centre.

ing the west part, completing the mergence by 1800 GMT. The merged center further travels to NW to make a fresh landfall on the province of Fujian. Though the center of flow field is determined by subjective analysis of a $0.5°\times0.5°$ mesh, it meets the requirement on errors defined in this work. It is seen in Fig. 2b that the center is featured by ① large deviation of certers between the upper (500 hPa) and lower levels and an opposite tendency of northward (southward) location of the center before (after) the landfall, with the distance of deviation the largest at about 150 km (1800 GMT September 7), ② formation of a secondary center (as marked by "C") beginning from 0600 GMT September 7 in general agreement with what Fig. 2a shows, ③ merging of main and secondary centers by 1800 GMT September 7 in identity with the Fig. 2a illustration, and ④ gradual reunion of centers at upper and lower levels after clearance of the island. In parallel, the center of geopotential field (Fig. 2c) is characteristic of ① constant northward location of lower center against the higher one and by a maximal deviation of 100 km 0600 GMT through 1800 GMT on September 7, ② formation of a secondary center at the lower level at 0600 GMT and mergence with the main center at 1200 GMT, ③ good allocation of centers between the geopotential and flow fields at upper level in contrast to sharp difference at lower level after the landfall on Taiwan, being over 250 km at 1800 GMT at maximum, and ④ a tendency of merging of both centers towards a location consistent with the center of circulation when the tropical cyclone moves out of Taiwan.

It has been clear by now that on the upper level a smooth track is dominant that is accompanied by allocated centers of the circulation and geopotential field while complicated changes have taken place in the structure of the lower level, which is displayed by

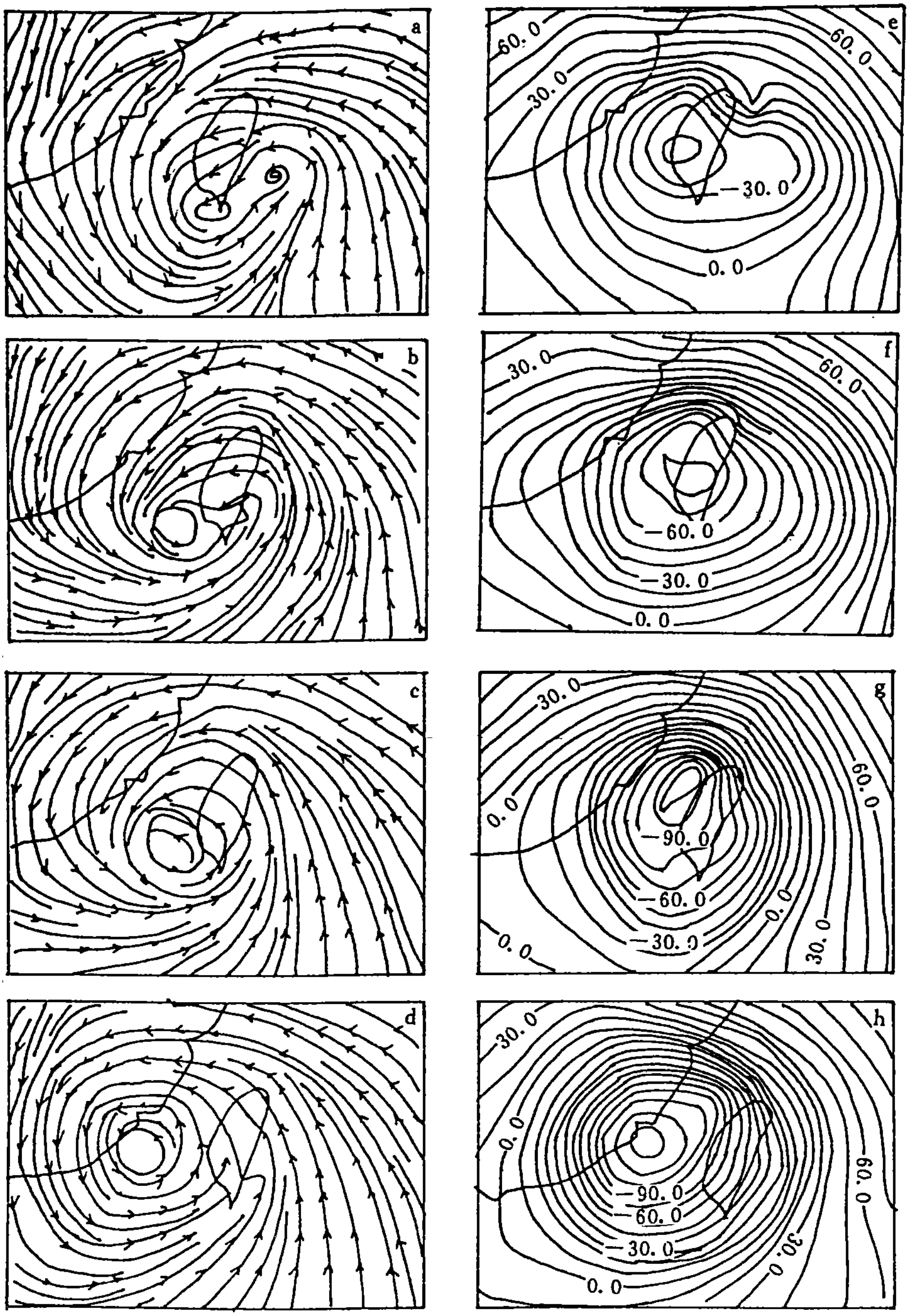

Fig. 3. Analyses of TCM−90 data at 1000 hPa shown in the flow and geopotential fields at 0600, 1200, 1800 GMT 7 September and 0000 GMT 8 September 1990 as denoted by a, b, c, d and e, f, g and h in th figure. The thick solid line is the coast.

severe deviation between the two centers and formation of secondary centers and mergence with main ones in relavant distribution, though in different time, location and manner. Hence, discussion focusing on the lower level is worthwhile.

A clear picture is revealed by evolutions of observed flow (Fig. 3a—d) and geopotential (Fig. 3e—h) near the southeast of Taiwan, a secondary center has appeared south of the island (1); a well-defined secondary geopotential center has formed by 0600 GMT September 7 and is more active than the main one that is filled-up (2); difference is found both in time and location concerning the formation of both secondary centers and subsequent mergence with the main one (3); and the northwest deviating turn of the geopotential center arriving at the west of Taiwan between 1200 1800 GMT has parted itself substantially from the circulation center (See Fig. 3c). The phenomenum, known as anomalously northward shift of low center west of Taiwan, is common (Putian, 1974) and representative in the area.

It is thus inferred from the above that inconsistency is always found with *Typhoon Yearly Book* if only the geopotential or flow field is based in determination of the center of tropical cyclone. Meanwhile, no information of the mergence between the main and secondary centers is available even with detailed analyses of the 6-h interval intensive observations, which is just supplemented by numerical simulations.

IV. RESULTS OF NUMERICAL EXPERIMENTS

The simulation experiment undergone here is initialized at 0000 GMT September 7 for study of variations every 3 hours over an integration of 24 h. By the analysis in the preceding section, one knows that complicated changes have taken place in the tropical cyclone observed during the period 6th through 18th h of integration. For comparison, a number of numerical experiments are done as shown in Table 1.

Table 1. Schematic results of schemes of numerical experiment.

Experiment names (codes)	Model terrain	Physical processes
CONTROL	Real terrain	All included
SEA	Taiwan as sea surface	All included
NHS	Taiwan as flat ground	All included
NHSC	Hills west of Straits as flat ground	All included
DRY	Real terrain	Wet process absent

1. *The CONTROL experiment*

All variations in the structure of Dot are successfully modelled with fine resolution in the experiment CONTROL concerning the passage through Taiwan. The simulation is agreeable to the observation at the upper level with smooth trajectory of motion and no generation of any secondary center, which takes no text to elaborate here. Fig. 4a is a graphic time-dependent variations of 950 hPa centers of the circulation and geopotential height in the CONTROL experiment, which is marked by ① general agreement with analyzed observations in terms of the storm structure simulated, ② presentation of variations in finer resolution than analysis of observations (at intervals of 3 hours), e. g. successful reproduction of the landfall of the main circulation center on Taiwan and its migration to the west of the island in the period 1200-1500 GMT before mergence with the

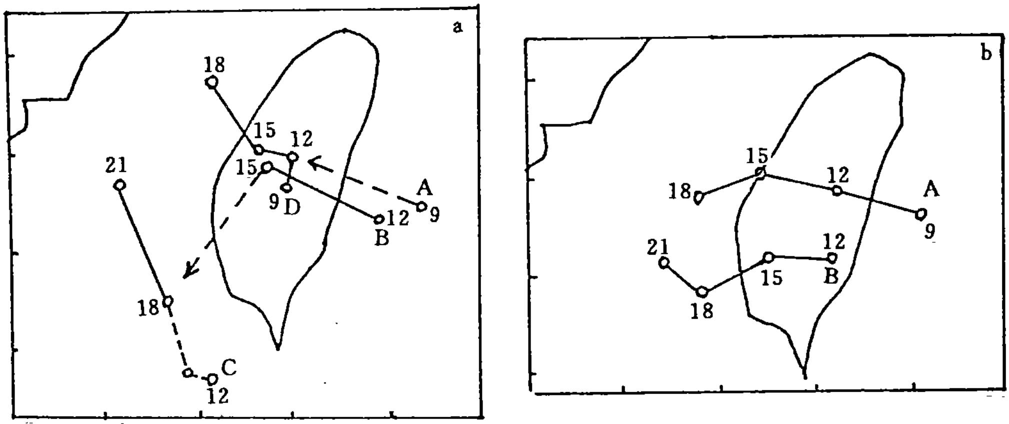

Fig. 4. Graphic evolutions of the center of Dot at 950 hPa in the CONTROL (a) and SEA (b) experiments. The main centers in the circulation and flow field are denoted respectively by A and B and the secondary centers by D and C. The numerals stand for Greenwich mean time on 7 September 1990.

secondary center 1500 through 1800 GMT, being coincided with what is located by multiple factors, ③ simulation of anomalously northward dislocation of the geopotential center 1500 through 1800 GMT to be situated much away from the circulation center, ④ revelation of consistency of comprehensively located storm position as given in *Typhoon Yearly Book* with that of the main (secondary) center in the lower-level flow field, but of sharp inconsistency with that in the lower-level flow field, suggesting inadequacy in the employment of surface pressure center for determining the storm center in the area of Taiwan, and ⑤ appearence of the modelled secondary geopotential center which is late by 3 hours but coincident in the time of occurrence.

Fig. 5 gives the flow field at 950 hPa at intervals of 3 hours at the 12nd-21st h of prediction in CONTROL. It is known that concurrently with the shift of the main center to the southeast of Taiwan at 1200 GMT on September 7, the secondary center has formed on the southwest side of the island to constitute a dump bell shape that is consistent with Fig. 3. Three hours later at 1500 GMT, the secondary center tends to be stationary while the main one has landed on Taiwan. Analyzing maxima in the flow field at the σ-plane on the bottom layer of the model (figure omitted), the main center has by now moved to the central-and western-part of the island, maintaining an enclosed circulation and the dump-bell linkage with the secondary center. In the 3 hours afterwards, it rapidly shifts to the south to merge with the secondary center to form a circulation center. At 2100 GMT three hours away, the merged center again moves further towards NW, which coincides with the observation.

The changes in the complicated structure of low-level geopotential field is also well simulated (figure omitted) except for a weak, late (by about three hours) appearence of the secondary center than the analyses, which may be attributable to lower model terrain (the highest at 1910 m against >3000 m in reality). Fortunately, it does not affect the simulations effectively.

In addition, in 21 hours into the integration, a tendency is found for all centers, including those on each layer in the circulation and flow field, to superimpose, being in agreement with the observation.

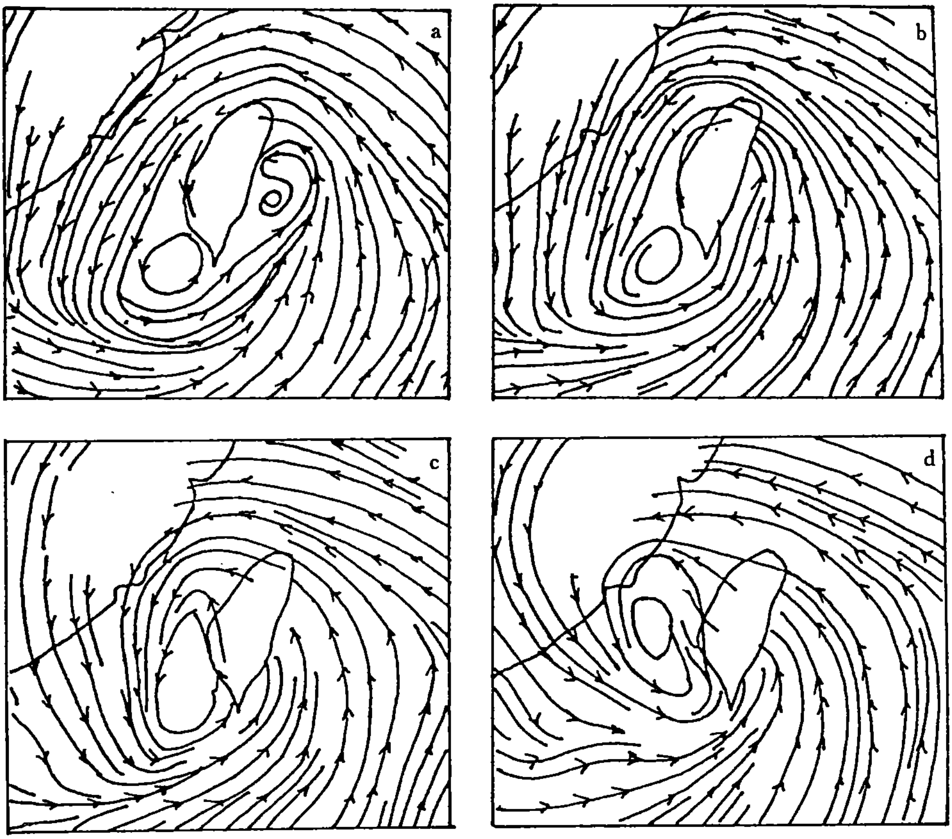

Fig. 5. Evolutions of 950 hPa flow field in the CONTROL experiment as predicted at 1200, 1500, 1800 and 2100 GMT on September 7 denoted by a, b, c and d, respectively.

2. *The SEA experiment*

Except for an assumption of sea for Taiwan, the rest is identical to CONTROL in this experiment. Observing the evolutions of the flow and geopotential fields in SEA (figure omitted) and variation of the low-level center (Fig. 4b), points that differ from CONTROL include that ①there is not any secondary center in the circulation and geopotential height; ② the point on which the low-level circulation center lands in Taiwan is a little more to the south, suggesting the role of the presence of topographic features in the island in diverting it more to the north, which is duplicated in idealized numerical experiments by Bender, Tuleya and Kurihara (1987) and extensive observation, just further proof of the results with a real case in this work; ③ the path has been smooth rather than jumping over the coarse of low-level circulation center migrating out of Taiwan; and ④ There is absence of northward deviating movement of the low-level geopotential center as witnessed in CONTROL and the observation, indicating that the phenomenum is caused by the particular terrain of Taiwan.

3. *The NHS experiment*

Almost identical results (figure omitted) with that of SEA are obtained, with the only significant difference in more northward point of landfall in Taiwan than in SEA. It conforms with the experimental results with an idealized field by Chang (1982). The suggestion is that no changes in structure and track is expected if the local land-sea difference or effects of the boundary layer (of friction and transport of sensible and latent heat) is considered without realistic terrain of the island.

4. *The DRY experiment*

The secondary centers in both the circulation and geopotential height are formed and merged with the main ones in this experiment though with difference from CONTROL (figure omitted). In respect of the geopotential field, a secondary center appears at 0600 GMT at the low-level and by 0900 GMT a typical dump-bell distribution is formed between the main and secondary centers respectively in the east and west of Taiwan, the former being weaker than in CONTROL. By filling up, the main center has at 1200 GMT completed the mergence with the secondary one west of Taiwan. It is concluded that the formation of the secondary center and its mergence with the main one is realized by kinetic action of the terrain in the island. However, the lack of maintenance of heating by latent heat in the DRY experiment has greatly weakened the main geopotential center and the merged center as compared with CONTROL that leads to a gradual deviation of pattern from CONTROL. For instance, by 1200 GMT it has elongated into a strip towards SW in the west of Taiwan, a phenomenum that is caused by too weak the merged center, as is known in comparison with CONTROL. As a matter of fact, precipitation over 1000 mm exists in the east of the island both in the observation and CONTROL experiment during the coarse of this 24 h (figure omitted) to maintain and intensify Dot. It is then concluded that the dynamics by the local terrain contributes to the formation and mergence of the secondary center while the thermal mechanism is responsible for how the main and secondary centers distribute, merge and move by way of increasing the intensity of low pressure.

With regard to the flow field, a low-level secondary center has appeared by 0900 GMT in DRY, though with a location just more to SW than in CONTROL. It develops more vigorously at 1200 GMT when the circulaton around Dot is much weakened till close disappearence of the main center while the secondary center grows in size, resulting in earlier mergence than in CONTROL. Besides, the low-level center makes landfall on the island later than in CONTROL and keeps moving to SW rather than NW after the mergence, differing from the observation.

It is suggestive in the aforementioned analysis that due to much decreased intensity in DRY it is reasonable to expect some difference in structural change and distributional pattern of a tropical cyclone as compared with a controlled experiment and the observation, although the formation and mergence of secondary centers are simulated for the flow and geopotential field. It is then inferred that the period in which properties change in a tropical cyclone in passage of Taiwan is actually the co-action by topographic dynamics and thermodynamics.

V. NHSC EXPERIMENT

In view of previous numerical treatment of Taiwan as an isolated island with ignorance of peripherical terrain west of the straits (Chang, 1982; Bender et al., 1987), the topographic features of interest will be looked into in this experiment. The result has shown (figure omitted) that the evolutions of the secondary center in terms of formation, mergence and track are almost identical with that in CONTROL with the only significant difference in higher intensity than in CONTROL at all layers that is gradually obtained as Dot is out of Taiwan at 1800 GMT and afterwards. It may attribute to absence of dissipation by physical blocking of the mainland terrain. It is, therefore, inferable that no other than the isolated-island effects are obviously exerted on changes in properties of the tropical cyclone by the terrain west of the Taiwan Straits as it is shifting over the island. The presence of the terrain in question does have essential roles on the by-passing jet stream oner the straits at low-level.

VI. LOW-LEVEL BY-PASSING STREAM OVER THE STRAITS

The lifecycle of Dot is also marked by appearence at 1800 GMT on September 6 of a strong low-level northerly jet over the Taiwan Straits some 20 hours before its landfall on the island. It keeps staying there until 1500 GMT on September 7 after the landfall (See Fig. 6), which has drawn much attention from the forecaster and Taiwan researchers (Putian, 1974; Wang, 1991). The jet stream is related with a so-called "angular stream" and "opened channel stream" (Chang, 1991). The air current is strong right over the straits against weak winds along the west side of Taiwan due to frictional and blocking effects, giving rise to large wind shear between them. In accordance with the vorticity equation, a positive growth of vorticity, or, a secondary flow center, is naturally possible where the cyclonic shear gets the strongest southwest of Taiwan. The center, increasing outwardly in wind speed, takes on an entirely reversed distribution with that of the main center of Dot. It is easily understood that the nature and structure are different between the two centers—the former is driven by dynamical forcing in the absence of either dominant wet process or forced precipitation while the latter is maintained by CISK mechanism accompanied by heavy rains. It is worth noting that the mergence with the landfall has led to a display of features of strong outward range against weak central core in the distribution of air current (Fig. 6e), typical of secondary center, which is resulted from much dissipated flow of the original main center and does not restore resolvable structure of a tropical cyclone until after the shift out of Taiwan. The maintenance of the jet stream is well simulated in CONTROL (Fig. 6b) but not reproduced in NHSC due to wider wind zone, suggesting an important role of terrain west of the straits in keeping the low-level jet by-passing over it. In SEA, the wind belt expands to Taiwan in inconsistence with reality (figure omitted). It is obvious then that the formation and maintenance of the jet is resulted from the coaction of terrain on both sides of the Taiwan Straits.

The jet disappears with the landfall to replace with a maximal wind value of 35 m/s formed north of Taiwan (Fig. 6e). It is a typical "angular stream" (Fig. 6e), caused by dynamic forcings of terrain in the island. Good simulation is found in CONTROL and NHSC, though with a more westward position of the center (Fig. 6f, g) while being totally ignored in SEA (figure omitted). It is then argued that the so-called "angular stream" activates due to the blocking effects of the terrain.

It becomes clear now why the secondary center of circulation is formed and the low pressure center moves anomalously to the north 1500 through 1800 GMT. With the terrain in action, a stream of northerly low-level jet is maintained over the straits, but the speed is mild just to the west of Taiwan due to frictional and blocking effects. A wind shear is then generated southwest of the island to be favourable for positive vorticity. When Dot moves near the southeast of the island at 0600 GMT on September 7, a south-

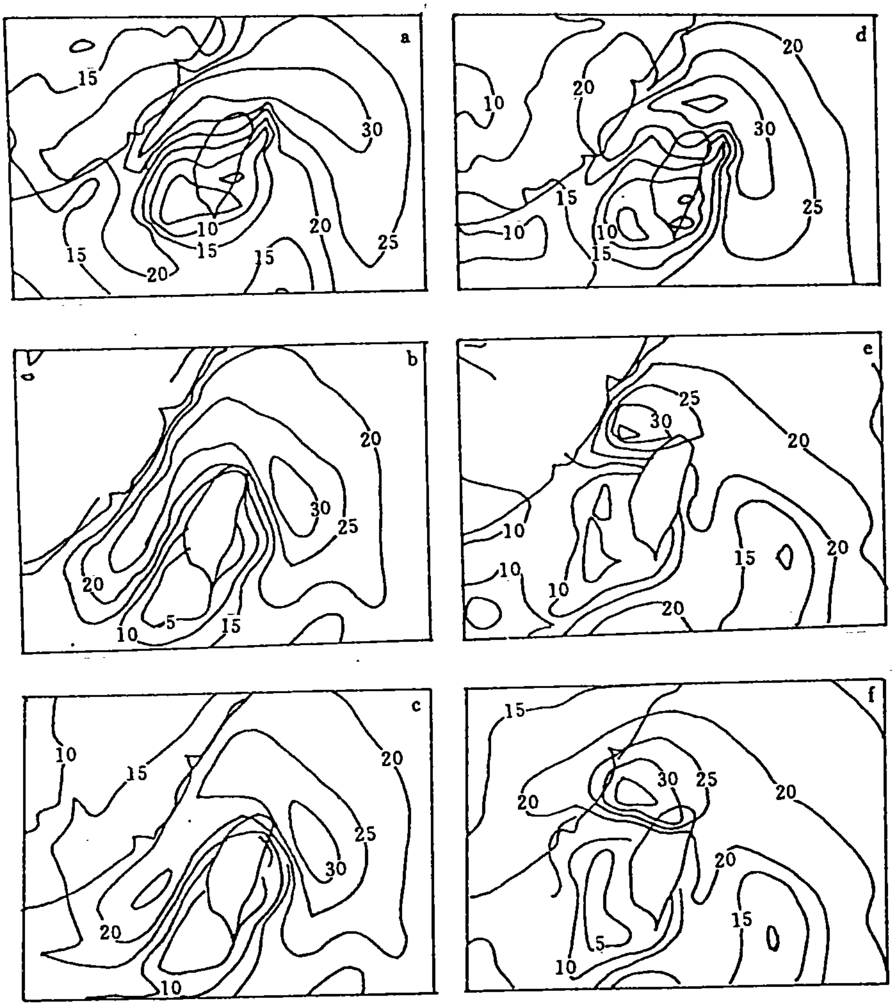

Fig. 6. Distribution of low level wind speed. Top panel: observed, middle: CONTROL, Bottom: NHSC. Left: 1200 GMT & right: 1800 GMT, 7 September 1990.

westerly circulation is seen to its south in conjunction with a cyclonic wind shear to the southwest, facilitating an enclosed secondary circulaton center under combined effects of the straits jet. Similarly, the "angular stream", or the jet, is formed by topographic forcings with the landfall, accompanied by a strong easterly center on the northwest of Taiwan (Fig. 6e), resulting in a strong shear in winds south of Dot. According to the theory of adaptation, a strong low-pressure center is expected to be adjacent here. On the other hand, a forced structure of getting strong outwardly from the merged circulation center does not require any allocation of a center of low pressure. The result: the latter moves north at 1800 GMT in effective deviation from the former.

Ⅶ. CONCLUSIONS

a. All processes of changes in properties of Dot in travelling over Taiwan is successfully simulated by numerical experiments in the current work.

b. There are abruptive mergences with the main centers of the secondary ones after formation in both the flow and geopotential fields, though differing in time, location and mechanism. The secondary circulation center is formed due to the coaction of the cyclonic shear effects of an "opened channeled" jet stream at low level of the Taiwan Straits and the southwesterly storm circulation south of the island, while that in the geopotential field is caused by a lee pressure trough forced dynamically.

c. Although these centers are resulted from the dynamics of the Taiwan terrain, the manner in which they present themselves are changable through heating by latent heat. The changes in the property realistically shown are therefore results of coaction between the local topographic features and thermodynamics.

d. The geographic point at which Dot makes landfall on Taiwan has shifted little more to the north in the presence of frictional effects of the boundary layer and the terrain of the island.

e. The topographic effects on Dot is mainly effective during the few hours both before and after the landfall of Dot and experimental results tend to be consistent with each other as it is considerably away from the island.

f. The lower level jet active just prior to the circulation of Dot is jointly produced by the terrain on the island and the west side of the Taiwan Straits.

g. The anomalously northward shift of a low-level pressure center west of Taiwan from 1500 to 1800 GMT on September 7 is caused by adaptation of pressure field to flow field in response to appearence of a strong easterly center of the "angular stream" northwest of Taiwan.

h. On the merging of centers in the circulation, a forced structure typical of non-tropical cyclone, i. e. intensity increasing in the outward direction, is shown that has no center of low pressure in allocation.

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