# TEN YEARS' ADVANCES OF RESEARCH ON KNOTTY TYPHOONS IN CHINA

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ABSTRACT

The forecast and research skill of knotty typhoon tracks of various kinds is presented. It is a practical approach to raise the diagnosing ability of the forecasters and to improve the forecast of knotty typhoon tracks at the present stage by revealing and studying the causes of the erratic tracks, obtaining their characteristics and gradually perfecting the prediction models.

## I. INTRODUCTION

The subject of knotty typhoons has stemmed from the course of typhoon research work and operational forecasting. It can be seen that damage caused by typhoons over China in the past ten-odd years and samples of large errors occurring in various objective forecast models are predominantly caused by a small number of problematic typhoons with erratic movements, which are hereby defined as knotty typhoons. The knotty typhoons include both the typhoons with complicated abnormal tracks and those with normal tracks which, however, make large deviation angles with the flow direction at the "optimum or best steering layer"[1,2]. The author has investigated five peculiar phenomena of western North Pacific typhoons, such as the sudden change of direction and speed of movement, dawdling and circling, etc. The skills of various forecasting methods in the countries along the western North Pacific and in China are shown in Fig. 1. Only 15% of the sudden right-turning of the tracks (the difference between the subsequent 6 hr mean direction and that of the previous 6 hr $\geqslant 50°$) has been forecasted in advance and less than 6% for the prediction of 24 hr ahead (Fig. 1a). The skill for the forecast of the left-turning (the previous 6 hr mean direction minus that of the subsequent 6 hr$\geqslant 40°$) has been very poor, less than 6% (Fig. 1b). No successful prediction has been recorded in the past three years for the looping and dawdling tracks, and the best is only to make timely diagnose when a typhoon begins to dawdle (Fig. 1c). Fig. 1d shows the statistics of forecasting skill for typhoons with sudden reduction of speed of movement (from a mean of$>15$ km/hr in the previous 6 hr to$<5$ km/hr in the subsequent 6 hr) in the objective predictions of the various forecasting centers involved. It is shown that this kind of trajectory has not been predictable either and most of the diagnoses lag behind by 12—18 hours. Thus it can be seen that, for these deflections,

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both the empirical diagnosis of the forecasters and the various objective prediction models lack the forecasting skill. The most probable reason for this is the complexity of the formation mechanism for these knotty typhoon tracks which are quite different from ordinary typhoons. Little is known about this mechanism. Furthermore, as these knotty typhoons are diverse in variety, it is almost impossible to cover all the knotty typhoons with a single model. Comprehensive synoptic analyses of various kinds of knotty typhoons thus seem to be a more practical approach in solving the problem. Their mechanism of formation may then be investigated and the diagnostic skill of the forecasters may be improved. And numerical models may eventually be constructed on the basis of these studies to sum up the characteristics of different types of knotty typhoons.

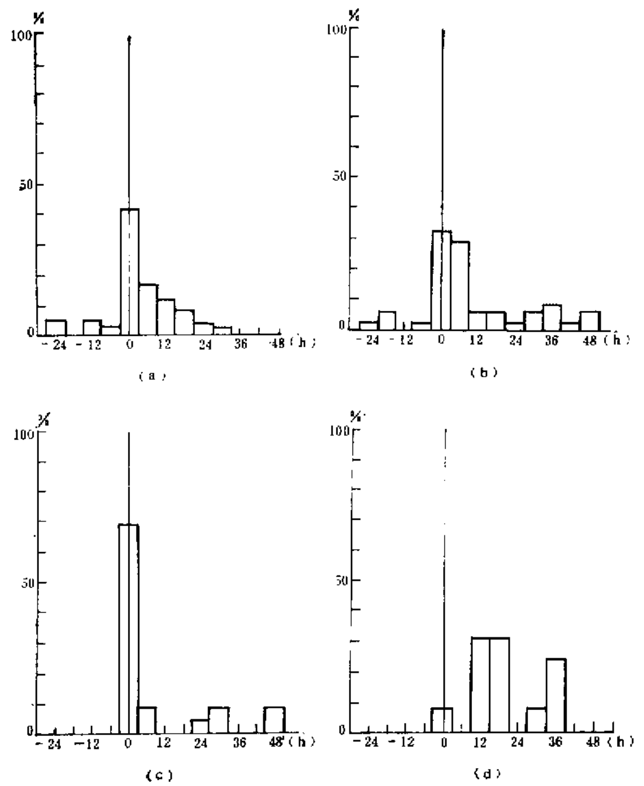
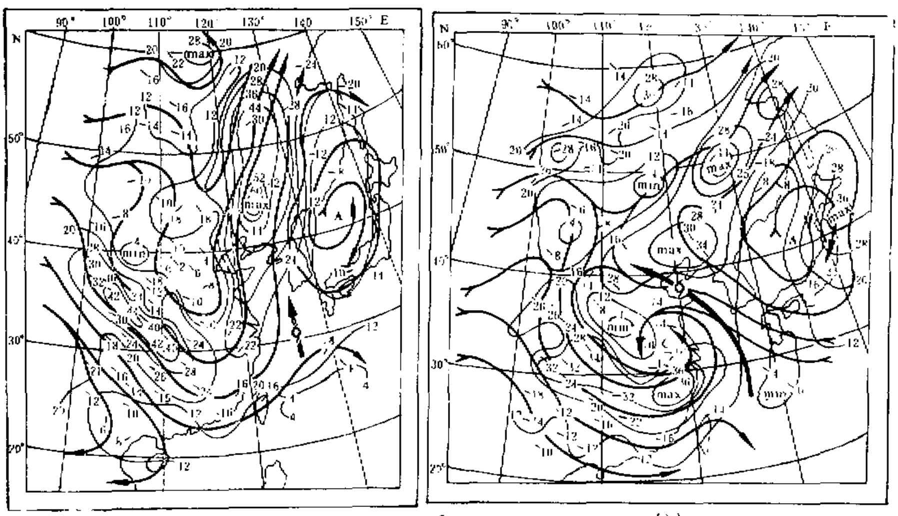



Fig. 1. Forecasting skills for different kinds of abnormal typhoon tracks over the western North pacific during 1976—1978 in various forecasting centers and by various objective prediction models.
(a) for sudden right-turning typhoon tracks (65 cases); (b) for sudden left-turning typhoon tracks (42 cases); (c) for dawdling tracks (23 cases); and (d) for sudden speed reduction (13 cases). Shown on the left of the abscissa zero (negative) is the forecasting skill for the actual predictions, and on the right (positive), for the posterior predictions.

## II. THE SUDDEN TURNING OF TYPHOONS

The sudden turning of typhoons forms the largest category of knotty typhoons influencing China. Typhoon No. 7203 turning west unexpectedly to strike North China after entering the Huanghai Sea on its northward movement arouse wide concern[3] for the first time. Fig. 2 gives the change of the synoptic-scale circulation as the typhoon moved northward. Note that the deep trough over Inner Mongolia had been replaced by a strong anticyclone within 24 hours and, the typhoon, steered by the strong southeasterly flow, accelerated to move northwest.

An important problem is to discern the real cause of the west-turning of the typhoon. Chen Lianshou[1] is the first to have noticed the influence of the strong cold vortex over North China on typhoon motion. He has also noticed that the west-turning for



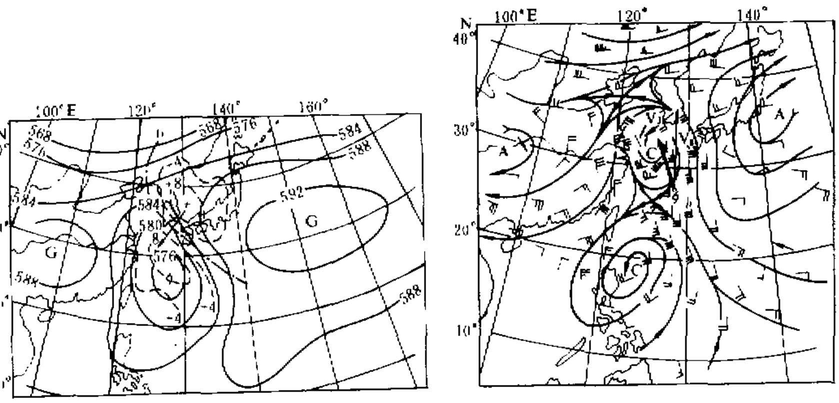
(a) (b)

Fig. 2. 300 hPa charts when Typhoon No. 7203 turned west over the Huanghai Sea. The thick solid lines are streamlines and the thin lines isotachs (m/s).
(a) 1200 GMT, 25 July; (b) 1200 GMT, 26 July.

this sort of typhoon occurs mostly in the sea area off the Cheju Island[4]. In order to make clear to what degree the upper tropospheric cut-off cold vortex influences the west-turning of the typhoon tracks, special investigations have been made. The typhoon research group of Liaoning Provincial Meteorological Bureau[5] reveals that it is the high pressure ridge in the westerlies that greatly influences the latter part of a typhoon's northward track. The author et al.[6] once emphasized that the building-up of a high ridge between Northeast China and Korea together with the weak vertical shear and relatively barotropic structure within the ridge plays a decisive role in the west-turning of a typhoon over the Huanghai Sea. It is no doubt that the continental cold vortex and the quasi-stationary low-pressure system also have their contributions. The existence of this system is favourable for the setting-up of the warm anticyclone over Northeast China. When the cold vortex is active to the east of 115°E, the typhoon will be forced to turn further west. This indicates that the cold vortex will attract the typhoon when these two systems are close to each other. Wang Dawen[7] has made a simple numerical experiment by using a primitive barotropic equation model of spline function. Results show that when a cold vortex and the Northeast-China High exist simultaneously, the ridge of the high will play a main part in a typhoon's west-turning, but when there exists no strong anticyclone over Northeast China or the anticyclone is quite weak, the typhoon will be found to move to the right side of the predicted track instead of moving west due to the presence of a cold vortex to its west. It is shown from his experiment that the attraction of the vortex to a typhoon is present only when the two systems are close enough to each other, and the two systems will finally combine. If the separation is more than 9 degrees of latitude, the cold vortex will have nothing to do with the typhoon. It can thus be seen that the effect of a cold vortex on a typhoon is second to the rapid development of a warm anticyclone to the north of the typhoon, the latter causing the basic flow to change its direction. A typhoon in the Huanghai Sea turns west in the following procedure: When it enters the Huanghai Sea, the ridge of a warm high in the upper tropospheric westerlies over Northeast China develops rapidly and superimposes on the subtropical high over Korea to combine into a new strong high pressure belt. The typhoon is forced to move northwest under the strong southeast-steering current on the western side of the newly-established high. When the typhoon center, under this favourable environmental circulation, moves within 7—9 degrees of latitude of the cold vortex to the west, the attraction of the vortex to the typhoon in turn shows up and causes the typhoon to further deviate to the west.

For those typhoons already moving northeastward ahead of the westerly trough over the East China Sea, it also remains a problem to forecast its sudden west-turning and the subsequent landing at China. Typhoons 7708 and 7504 are two typical cases belonging to this category. Typhoon 7708, however, is more complicated in the mechanism of its west-turning. On the one hand, the typhoon encountered a dramatic change of the general circulation as the cell of the Pacific subtropical high had advanced west by 15 degrees of longitude within 2 days[8]. On the other hand, the ageostrophic wind component also played an important role. It is well known that the track forecast using geostrophic steering current is dependent greatly on the stability of the circulation pattern. When this typhoon turned west, the track prediction by using the 500 hPa steering current resulted in directional errors of −28° and −43° respectively for 12 and 24 hours (Fig. 3a). The author reveals[8] that the adjustment of the circulation is closely related to the periodic intensification of the Pacific subtropical high while the allobaric wind acting on the typhoon as the subtropical high rapidly stretched westward, causing considerable difference between the typhoon movement and the steering current (Fig. 3b). Liu Jingxiu[9] has analysed the causes of the west-turning of this typhoon and revealed that the west-turning of this typhoon is dominated by the subtropical high steering current at first. And, as the typhoon moved west to an area within 7 degrees of latitude of the cut-off cold low, the two vortices rotating around each other anticlockwise, added to further westward deviation of the typhoon track. The Weather Forecasting Center of Zhejiang Province[10] has obtained a similar conclusion after analysing the west-turning of Typhoon 7504 over the southern East China

Sea. In fact, the cutting-off itself of the cold vortex from the mid-latitude westerly trough reflects the dramatic growth of the subtropical high and the rapid weakening and subsequent dissipation of the westerly trough. A layer of easterlies rapidly reestablishes to the north of the typhoon, thus the typhoon, together with the cold vortex, moves westward, being steered by the easterly flows. As a cold vortex and a typhoon occupy different positions relative to the high, their directions of movement would also differ, with the former steered by the northeasterly flows and moving southwest and the latter dominated by the southeasterly flows and moving northwest. This large-scale phenomenon of general circulation is often mistaken to be the mutual rotation of the two systems when they are far apart. However, it is still quite significant if we simply take the cut-off of the upper tropospheric cold vortex from the westerly trough as an indication that the typhoon will deviate to the west.




(a) (b)

Fig. 3. (a) 500 hPa isallohypses (dashed lines) at 1200 GMT, Sept. 9 (The arrow represents the allobaric wind).
(b) 500 hPa geostrophic-steering current, isallobaric wind and the typhoon track.
When Typhoon 7708 turned west over the northern East China Sea, its trajectory deviated greatly from the geostrophic-steering current. The direction of the typhoon is basically the resultant of the geostrophic steering current and the direction of the isallobaric winds.

But more complicated phenomena will be found if an expanded sample of data is analysed. Fei Liang et al[11]. have investigated the movement of 24 pairs of cut-off cold vortices and typhoons which are less than 10 degrees of latitude apart off the east coast of China. It is shown from the statistics that only 32% of the typhoons will turn west, being affected by the cold vortex when the two systems move around each other cyclonically; the remaining 68% of the typhoons will not be influenced and therefore recurve to the north or northeast as the two systems depart from each other anticyclonically. What is more, the west-turning of the typhoon is quite independent of the distance, intensity and horizontal dimension of the cold vortex. Wang Dawen[7] has also found from his numerical experiment that even when a cold vortex is linked with a typhoon circulation, the two systems might later move separately along their own environmental current, i. e.

the typhoon recurves towards the northeast and the cold vortex moves to the northwest. In a word, the interaction between a cold vortex and a typhoon in real atmosphere needs to be further investigated.

Chen Delin[12] has studied two kinds of knotty typhoon tracks to the east of Taiwan Province: one is the west-going typhoon though it ought to have recurved from the analysis of the synoptic stituation; the other kind is the recurving track over the sea though it should have been moving west. All these are caused by the drastic readjustment of the large scale circulation. The west-going typhoons are resulted from the westward stretch and intensification of the subtropical high under the smooth mid-latitude westerly circulation, and the alternation and retrogression of the long-wave trough over the China coast while the recurving typhoons are associated with southward displacement of frontal zone under the blocking action and the weakening of the subtropical high.

Over the South China Sea, the mean basic current is rather weak and the movement of typhoons is slower than that over other sea areas. Knotty typhoons occur in this area frequently and their mechanism is complicated. There are mainly two categories of typhoons that might cause severe failure of the forecasts due to their sudden directional changes: The first category includes typhoons that turn north suddenly after entering the South China Sea from the Pacific. The landing point therefore evidently deviates to the east of the expected position, resulting in the unpreparedness for precautions against the typhoon. The second type involves typhoons which tend to have rather northern-deviated tracks but suddenly turn west when approaching land. High costs might have to pay by unnecessary precautionary measures taken due to undue warnings. The second type of typhoons will be discussed in the next section and the results of study of the first category are presented here.

The north-turning typhoons differ from the normal west-going ones over the South China Sea in both the circulation characteristics and the nature and structure of the pressure systems. Xue Hongkuan has indicated from a detailed comparative analysis that, for the west-going typhoons, there usually exists a strong zonally-distributed subtropical high to the north of the typhoon with positive isallohysic field and negative vorticity prevailing from west to east along 30°N, the lower troposphere being nearly barotropic with small temperature difference, and slight zonal and meridional winds. On the contrary, for the north-turning typhoons, all the parameters indicate that the subtropical high to the north of the typhoon is quite weak while the ridge to the east of the typhoon is apparent. The latter circulation pattern causes the strong meridional flow and favours the northward turning of the typhoon. Chen et al.[1] have revealed that the typhoon track will turn north when the typhoon enters into the monsoon convergence zone, the easterly wave superimposes on the typhoon, the India-Burma trough moves east, the South China high weakens and the equatorial anticyclone intensifies or the subtropical high retreats to the south. The Chief Hydro-meteorological Forecasting Office of the State Oceanographic Bureau[13] has selected weather predictors from the parameters causing the north-turning of the typhoon to design a set of practical forecasting procedures. Niu Xuexin has developed prediction equations to diagnose the west-turning of the northward track and the sudden north-turning of the west-going track over the East China Sea on the basis of historical sample of many years.

It can be seen from above that most of the sudden turning of the typhoon trajectories happen when the large-scale circulation undergoes dramatic changes. Therefore, in addition to updating and improving numerical prediction models, it is necessary to study seriously the change of the circulation system from synoptic aspects so as to improve the prediction of such knotty typhoons.

## III. THE PARTICULAR STERRING LAYER

The basic method of using steering current to predict the typhoon movement is supported widely by the forecasters, but the problems arise as which level or levels can be taken as the steering layer and how the steering current can be best calculated. Almost all the studies agree on the point that the 500 hPa and 700 hPa or the weighted average in a thick layer would be most effective as a steering layer for western North Pacific typhoons[14,15]. This is the so-called "best steering layer". However, the "best steering layer" is in the sense of statistics of large sample of data or of composite mean and is not necessarily appropriate for some individual typhoons. Large deviations may occur. Fei Liang et al. have found that when an upper tropospheric cold vortex occurs in the subtropical region, the subtropical high will have a special structure: the negative anticyclonic vorticity is confined to the middle and lower troposphere below 500 hPa, and a cold vortex lies in the upper troposphere, especially at 300 hPa (Figs. 4 and 5). The typhoon in this case does not move with the "best" steering layer current but is significantly affected by the strong southerly winds in the upper troposphere. Dong Keqin et al.[16] have discussed in detail the prediction of the first portion of the trajectory of Typhoon 7303 which is one of such cases. On the contrary, other typhoons move under the control of the lower tropospheric flow instead, mostly in autumn and winter. Summer typhoons will not be affected by the low-level flow unless strong cold air bursts south along the east coast to directly influence the north side of the typhoon. Forecasters in South China have already had such experiences[17]. It is shown from the statistics of Chen Lianshou et al.[1] that, when the 500 hPa air flow differs from the 850 hPa flow to the north of the typhoon after the cold air breaks to the south, the lower tropospheric steering becomes more important. 13 out of 14 typhoons of this category move with the direction of the 850 hPa flow. The sudden west-turning of the originally north-, ward moving typhoon is the result of this lower tropopsheric steering[1,18]. As the cold air pushes southward, the zonally-distributed Pacific subtropical high markedly weakens and

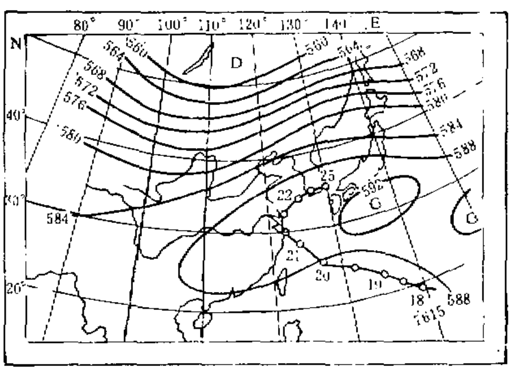



Fig. 4. Mean 500 hPa chart at 0000 GMT, 18—21 August, 1976 (Heavy lines are contours and the typhoon track is marked with dates).

retreats to the east. In general, when a westerly flow is seen at 500 hPa to the north of the typhoon, it is most likely to predict that the typhoon will continue to move northward and land at the coast of South China or even recurve northeastward. However, as the typhoon moves northward and approaches the strong low–level easterly winds, e. g. the wind speed at 850 hPa reaching 12 m/s or more, the typhoon immediately turns west. The cold air reaching the coast of South China can maintain strong easterly winds only when the surface pressure center of the cold–core high and the 850 hPa contour center near the Great Bend of the Huanghe River reach the intensity of 1030 hPa and 162 geopotential decameters respectively.

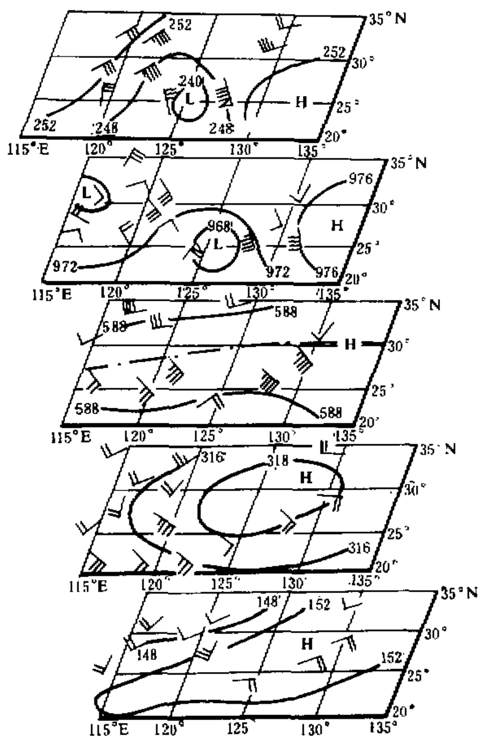



Fig. 5. Vertical struture of the subtropical upper tropospheric cold vortex (Dotted and dashed line denotes the axis of the subtropical ridge).

## IV. INTERACTION OF BINARY TYPHOONS

It is well known that strange tracks such as looping are likely to occur under the circumstance of binary typhoons. When two typhoons are close to each other, the two systems will undergo mutual rotation and mutual attraction, the so–called "Fujiwhara effect", which was found half a century ago but the study of many problems involving binary typhoons has achieved little progress since then. Rules that can be applied to operational forecasts are scarce. In recent years, much work has been done in China in both the synoptic study and theoretic analysis of the binary typhoons, which enables us to understand them better. From their laboratory simulations, Wei Dingwen et al.[19,20] have obtained the initial distance and rotating angular speed when the two typhoons begin to rotate around each other under ideal conditions. For the amalgamation of the two typhoons, diverse conclusions have been reached by theoretical analysis and by laboratory simulation. Wu Zhonghai[21] holds that the two vortex centers do not amalgamate, as the distance between the two systems reduces to a certain critical value $r_1$, they will start to separate again. He also discussed several possible trajectories of binary typhoons. In the simulation experiment[19], however , the amalgamation and the dissipation of one circulation system can be clearly seen as the two vortices gradually approach each other. Actually, the so-called amalgamation of two typhoons is, in a sense of fluid dynamics, the process in which one center maintains while the other dissipates as the two typhoon centers get nearer. It is impossible for the two systems to really coalesce. In the real atmosphere, the activities of binary typhoons are much more complicated due to the varying intensities and to the concurrent acitons of the environmental currents. In order to obtain definite conclusions applicable to the forecast, more investigations into historical samples of binary typhoons are needed as well as further simulation experiments and theoretical analyses.

Chen Qigang[22] has made a statistical analysis of the synoptic-climatological characteristics for binary typhoons over the West Pacific in the 30 years from 1949 to 1978 and found the 10-year quasi-periodical frequency of occurrence of binary typhoons and their relative high concentration near the Ryukyu Islands. It has also been shown that when the eastern one of the two typhoons moves into the area within $\pm 10°$ due east of the western one, the western typhoon would start to dawdle. In other words, as the eastern typhoon moves to the same latitude as the western one or to a point 1—2 degrees of latitude lower, the latter will begin to stagnate or loop. An earlier study by Luan Baochu[23] indicates that when a closed low occurs at 500 hPa in the northeast quadrant on the periphery of a typhoon, even though the low may be quite weak with surface wind below Beaufort force 8 and may be as far as 25 degrees of longitude away, the typhoon to the west may also take a looping track. The two studies mentioned above have derived generally similar results. This phenomenon is generally considered to be an indirect interaction between two typhoons, that is, as the eastern typhoon moving northward separates the western one from the deep large-scale main current of the subtropical high, the western typhoon is thus dominated by the surrounding weak and variable flows and hence begins to dawdle[24]. But what is the maximum distance between the two typhoons at which the direct rotation around each other initiates? This is a complicated and controversial issue. Wang Zuoshu et al.[25] have established from their investigation of 92 pairs of binary typhoons that the maximum distance of interaction is 12 degrees of latitude; binary typhoons have no evident mutual rotations farther away. Chen Ruishan et al. have found from an analysis of the well-known Typhoons 6413 and 6414 which coalesced near the Ryukyu Islands that the distance at which the typhoons started to rotate around each other is much less, being 7 degrees of latitude which doubles the radius of strong winds over force 6 for Typhoon 6414. Dong Keqin[26] has pointed out that the anticlockwise relative rotation of two typhoons is largely determined by the environmental basic current. If the basic current favours the clockwise mutual rotation, the two typhoons, even though they are close to each other, say, being separated only by 2.6 degrees of latitude, will not rotate anticlockwisely. Therefore it can be seen that the contribution of "Fujiwhara effect" could not be overestimated. It can also be inferred that the role of environmental circulation has been incorporated in the statistical results of previous investigations so that the distance of interaction has been exaggerated.

Up to the present the study of binary typhoons is confined to a rather narrow scope. Further investigations should be carried out on various aspects, such as the movement characteristics of the eastern typhoon under binary typhoon circumstances, the motion of the western typhoon for different relative locations of the two typhoons, the stagnation duration of the western typhoon, the mechanism for the varying curvatures of the looping track, the trajectory after ending of the stagnation period of the western typhoon, the amalgamating process and intensity variations of the two typhoons, and the tracks of multiple typhoons.

## V. THE SUDDEN CHANGE OF MOVING SPEED

The sudden change of the moving speed for typhoons is another knotty problem for forecasters. No systematic research has been undertaken except some case studies[1] and a general survey of the sudden slowing-down of the South China Sea typhoons. The author[2,7] has analysed Typhoons 7810 and 7806 which suddenly slowed down and stagnated when approaching the coast of East China. Preliminary knowledge has been obtained of the background circulation that leads to the sudden change of the moving speed, of the location of decreasing center of the contour field round the typhoon and of the specific conditions for the initiation of sudden deceleration. As for the circulation characteristics, the stability of main part of the subtropical high and the transformation into a col area to the north of the typhoon (which can be seen from the strong convection development in the originally subtropical-high controlled region in the north part of hte satellite images) play an important role in the sudden deceleration. A typhoon decelerates simultaneously with pressure fall in the entire layer from the surface to 300 hPa to the north of the typhoon.

The improvement of typhoon track forecast has become sluggish. This is due to a small amount of extremely knotty typhoons in addition to the fact that various prediction models have reached a plateau. It might be expected that this situation will last a considerable time since the complicated causes for the sudden change of typhoon movement can not be really and fully understood without a pesistent period of study. Of course, a model to accurately predict different kinds of knotty typhoons can not be constructed without a solid foundation. Therefore only when detailed studies of the mechanism of knotty typhoons and analyses of their physical processes are made can we expect new prospects for typhoon track forecasts. The study of knotty typhoons in China fully demonstrates this. Persistence means greater achievements.

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