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# OPERATIONAL APPLICATION OF A TROPICAL CYCLONE RECURVATURE/NON-RECURVATURE STUDY BASED ON 200 MB WIND FIELDS


**BY**
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**NOV 1977**


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# OPERATIONAL APPLICATION OF A TROPICAL CYCLONE RECURVATURE/NON-RECURVATURE STUDY BASED ON 200 MB WIND FIELDS

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CAPT CHARLES P. GUARD, USAF

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## ABSTRACT

In his paper, Tropical Cyclone Motion and Surrounding Parameter Relationships, John E. George demonstrates the relationship between various 200 mb wind fields and recurvature/non-recurvature. Evaluation of the wind fields with data independent of George's study indicated that significant modification of his study was required to produce an operationally applicable recurvature/non-recurvature study. Synoptic analysis revealed two distinct environments affecting tropical cyclones, a Winter Regime and a Summer Regime. All tropical cyclones were stratified accordingly. By integrating the results of the evaluation with results from rigorous synoptic and statistical analyses, operationally applicable recurvature/non-recurvature techniques were developed for, both, Winter Regime and the Summer Regime tropical cyclones.

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# OPERATIONAL APPLICATION OF A TROPICAL CYCLONE RECURVATURE/NON-RECURVATURE STUDY BASED ON 200 MB WIND FIELDS

## I. INTRODUCTION

Since the advent of tropical cyclone forecasting, one of the most challenging problems has been that of accurately determining whether or not a tropical cyclone will recurve into the mid-latitude westerlies and, if so, when. When a tropical cyclone is forecast to recurve and does not, or when forecast to not recurve and does, the resulting errors can be very large, often exceeding 375 km at 24 hours, 750 km at 48 hours, and 1500 km at 72 hours. Errors of such magnitude can be costly, both in lives and dollars. Large errors also expand the range causing the "average" error to be less meaningful for operational decision making.

Most evacuation decisions must be made 36 to 48 hours prior to the anticipated arrival of destructive winds, or winds which would prevent ship sorties or aircraft evacuations. Unnecessary aircraft evacuations, ship storm-evasions, and local destructive wind preparations can amount to hundreds of thousands of needlessly spent dollars. Poor forecasts lower the operational user's confidence in subsequent warnings, and reduce the overall effectiveness of the tropical cyclone warning system.

Riehl and Shaffer (1944), Dunn and Miller (1964), Burroughs and Brand (1972), and George (1975), have considered the relationship between the tropical cyclone environment and recurvature. On the whole, however, little effort has been directed toward the recurvature/non-recurvature problem itself. Most investigators have approached it as merely a small segment of the overall problem of tropical cyclone track forecasting.

John E. George (1975), in his paper Tropical Cyclone Motion and Surrounding Parameter Relationships, has derived mean 200 mb and 700 mb wind, height, and temperature fields for the environments of both recurving and non-recurving western North Pacific tropical cyclones. The methodology used in obtaining his results limits their use in operational forecasting. The purpose of this study is to develop, using George's 200 mb wind field data, an operationally applicable technique for forecasting recurvature or non-recurvature, and subsequent timing.

## II. METHODOLOGY

### A. Original Study by John George

Twenty one pairs of tropical cyclone (TC) tracks were used; each pair consisted of one recurving TC and one non-recurving TC. The TC track pairs were selected such that the recurving TC and the non-recurving TC were within $5^{o}$ latitude of each other. A separation point (S) was selected for each pair of TC's. This point was "arbitrarily defined as the longitude where the recurving TC track begins to deviate significantly from the non-recurving track and acquires a northwesterly to northerly component" (George 1975). The S point time was always at a 00Z or 12Z synoptic time. Twelve-hourly rawinsonde data were composited for the recurving and non-recurving TC's at the S point time and at synoptic times before and after the S point time. The compositing scheme was applied to a radial band extending from $9^{o}$ to $20^{o}$ latitude from the TC center. The area inside $9^{o}$ latitude was assumed part of the direct TC circulation and not representative of the environmental flow. The size of the data sample was increased by compositing the S point data with data 12 and 24 hours earlier. Two mean composites designated S-12 were derived, one for recurving TC's and one for non-recurving TC's. Similarly, two S-36 and two S-60 mean composites were produced. (Henceforth, the original wind fields will be followed by an R, designating a recurvature wind field, or by an NR, designating a non-recurvature wind field; e.g., S-12 R, S-12 NR, etc.). Figure 1 depicts a TC track pair, the S point, and the compositing scheme used by George. From the composited data, 700 mb and 200 mb height, wind, and temperature fields were derived which distinguished the environments of recurving and non-recurving TC's.

### B. Modifications for the Operational Forecasting Technique

The wind fields at the 200 mb level were singularly used for the following reasons:

(1) Rawinsonde data in the western North Pacific is sparse. However, the 200 mb sounding data can be augmented with jet aircraft wind reports and meteorological satellite cirrus blow-off wind directions to provide a more detailed streamline and isotach analysis than at any other level.

(2) The range of wind speeds is much larger at 200 mb. Thus, significant changes in horizontal wind speeds are easier to detect at this higher level. The 200 mb wind regimes from George's study are shown in Figure 2.

In the line up of operational forecasting problems, the recurvature point (i.e., the point where the TC begins its easterly movement, being steered by the mid-latitude westerlies) is more significant than the S point. The recurving storms of the original study were examined to determine the time difference between the S point and the point of recurvature. The average time difference was 24 hours. Therefore, the wind profile at S-12 R was taken to be representative of the flow 36 hours prior to recurvature. The S-36 R and S-60 R patterns were considered representative of the flow 60 and 84 hours prior to recurvature, respectively.

The first part of the technique development evaluated the usefulness of the 200 mb wind profiles, obtained by George, in forecasting recurvature and non-recurvature. The second part used the evaluation to develop operationally applicable forecasting techniques.

For the evaluation, the original 200 mb winds, from George, were plotted on transparent overlays at the same scale as the JTWC daily synoptic charts (1:15,000,000 mercator). These original winds were compared to observed wind fields.

Storm data for 1974, 1975 and 1976 (Table 1) were used. This data set allowed the evaluation to be independent of the original data used by George, and permitted the use of synoptic chart series available at the Joint Typhoon Warning Center (JTWC), Guam.

The comparisons were accomplished by matching: the S-12 R overlay to observed data 36 hours prior to recurvature; the S-36 R overlay to data 60 hours prior to recurvature; and, the S-60 R overlay to data 84 hours prior to recurvature. Timing errors were calculated if "reasonable" matches were better at earlier or later data times. For example, if the first "reasonable" match of S-12 R occurred 12 hours prior to recurvature, the resulting error was -24 hours. The minus bias would indicate that the S-12 R wind field was too slow in anticipating recurvature.

## III. DISCUSSION AND RESULTS

Of the 49 TC's considered in the independent data set, 28 recurved. The recurvers are indicated in Table 1 by the date and time at recurvature point. All 28 TC's that recurved were forecast to do so by George's wind regimes. However, these wind regimes also forecasted significantly more recurvature cases than were observed: 10 more by the S-60 R wind field, 9 more by the S-36 R wind field, and 8 more based on the S-12 R wind field. Thus, the overall effectiveness of his study in forecasting recurvature correctly was approximately 75 percent. This result does not represent a significant improvement over methods now employed by JTWC in determining recurvature.

The errors shown in Tables 2 and 4 indicate that George's study consistently anticipated recurvature too slowly. Several of the recurving TC's exhibited large forecast errors (Table 4), while others displayed smaller errors (Table 2). The TC's with smaller forecast errors were found to occur during the winter and transition seasons. Those with large errors occurred during the summer and transition seasons. The 200 mb analyses were examined and revealed that distinct synoptic patterns distinguished the TC's with large errors from those with small errors.

The TC's with smaller errors were, for the most part, characterized by a direct link between the outflow circulation of the TC and the mid-latitude westerlies, 72 hours prior to recurvature. In this regime, winds continuously increased outward from approximately $9^{o}$ to $20^{o}$ latitude in the northern environment of the TC (Figure 3). This regime will be referred to as the Winter Regime (WR). The recurving TC's conforming to the WR are listed in Table 2.

All recurving TC's possessed this direct link prior to recurvature, however, the storms with large errors did not exhibit this link until about 24 to 36 hours prior to recurvature. During the major portion of the life span of these storms, the mid-latitude westerlies and the upper level outflow circulation of the storm were separated by the subtropical ridge and a Tropical Upper Tropospheric Trough (TUTT) (Sadler 1967) as shown in Figure 9. This synoptic regime will be referred to as the Summer Regime (SR). Recurving TC's with the SR are listed in Table 4. (Although Fran possessed small errors, it still exhibited the SR synoptic pattern.)

A. Winter Regime (WR)

The evaluation indicated that in nearly all cases of the WR there was a significant forecast timing problem, the average timing error being -15 hours at both S-12 R and S-60 R, and -12 hours at S-36 R. To modify the technique, twelve hours were added to each regime, reducing the average error to -3 hours at both S-12 R and S-60 R, and to -0 hours at S-36 R. The addition of the 12 hours rendered the S-12 pattern representative of flow 24 hours prior to recurvature instead of the original 36 hours. Likewise, the S-36 R and S-60 R regimes represent the flow 48 and 72 hours prior to recurvature, respectively. The need for the 12 hour adjustment arises, in part, from two reasons. First, the S point is selected relative to an arbitrarily chosen non-recurving TC, rather than relative to the point of recurvature. Second, some of the storms considered in George's original study were SR TC's rather than WR TC's. As will be seen later, this would contribute to anticipating recurvature more slowly than observed during WR situations.

It should be emphasized that the direct link between the mid-latitude westerlies and the upper level outflow circulation is contingent on a continuously increasing belt of westerly winds. This belt must be $10^{o}$ to $11^{o}$ wide, but occasionally may begin at a radius (from the storm center) less than $9^{o}$ of latitude. In such cases the recurvature wind profiles may be shifted toward the storm. If an isotach minimum is observed in the $9^{o}$ and $20^{o}$ radius, the link between the westerlies and the upper level outflow circulation is not considered direct. In this synoptic pattern the criteria of the recurvature wind fields will not be met.

There are two conditions under which TC's will not recurve, even if the criteria exceeds the wind profile at S-12 R. The first condition is illustrated in Figure 4. If the axis of a mid-latitude trough is stationary, and is more than 2000 km west of the TC, recurvature will not occur. This is most common in December and early January when a long wave trough is quasi-stationary over or near India. The trough in this position allows the mid-tropospheric subtropical ridge to exist, without interruption, well into Asia; TC's will move toward the west, south of the ridge, and dissipate over land.

The second condition occurs when a TC, still well south of the axis of the mid-tropospheric STR, collides with upper level westerlies. When this occurs an upper tropospheric trough is induced near the intersection of the westerlies and the TC's upper level outflow. Under such situations (when adequate mid-tropospheric data is available) the mid-tropospheric STR is observed to build southward, west of the TC (Figure 5a). This southward building of the STR may be in response to strong subsidence beneath the induced upper level trough. The TC is then subjected to a change in the vertical stacking of the steering current which causes a change in the normal vertical stacking of the TC. As a result, the TC is reduced to a weak low level circulation and continues westward with the low level flow while portions of the originally associated convective cloud mass remain to the east and ultimately dissipate (Figure 5b).

The winds north of a TC were found to have the most significant importance regarding recurvature. The influence of the winds north of a TC were generally dependent on the position of a mid-latitude trough relative to the TC. For example, if a trough were located west-northwest of a TC, recurvature would best be forecast when the appropriate wind regime overlay matched the observed winds northwest of the storm. If the trough were located north of the storm, best results were obtained when matching the appropriate wind regime overlay with winds observed north-northeast of the storm. Thus, the best correlation of observed winds and recurvature occurred by utilizing winds slightly east of the mid-latitude trough axis. This applied even though the trough of concern moved eastward, and recurvature occurred ahead of a subsequent eastward moving trough. Once a trough had moved to a position north-northeast to northeast of a storm, the wind regimes correlated poorly with recurvature.

Figures 6, 7, and 8 present the modified wind fields for the WR synoptic pattern. They will be designated R 72, R 48, and R 24, respectively. (Winds inserted in the north-northwest and in the north-northeast were obtained by averaging the original winds in the northwest and north, and north and northeast, respectively.) Table 3 lists the sequence and rules to be utilized when applying the wind regime overlays to WR situations.

## B. Summer Regime

### 1. Background

In the above assessment of the recurvature/ non-recurvature forecasting problem we found a relatively simple synoptic pattern, the Winter Regime (WR). The Summer Regime (SR), on the other hand, is tremendously complex. Figure 9 shows the major features of the upper troposphere in the SR. During the height of this period, the subtropical ridge (STR) is anchored near 30°N by the dynamic effects of the Himalaya-Tibetan Massif (Ramage 1971; Flohn 1968). Although there is little north-south fluctuation in its movement, the STR is highly variable, both in its intensity and eastward extent. Over the tropical North Pacific, a highly variable east-west ridge exists and is called the subequatorial ridge (SER) (Sadler 1972). This ridge lies over the spawning grounds of most tropical disturbances and tropical cyclones. The STR and the SER are separated by a trough, the TUTT. The TUTT can contain numerous cyclonic cells, some very intense, which generally migrate toward the west-southwest. Sadler (1974 and 1976) has shown the importance of the TUTT in initiating tropical cyclone development, and in providing channels for tropical cyclone outflow. Murakami and Sadler (1973) suggest that energy transferred from troughs in the mid-latitude westerlies is primarily responsible for inducing intense cyclonic cells within the TUTT. Pelissier (1975) hypothesizes radiational differences between cloud and cloud free regions as the mechanism responsible for the development and maintenance of these cyclonic cells. The TUTT may be continuous across the North Pacific, but is frequently segmented. The orientation of the trough may vary from north-south to east-west. The Mid-Pacific Trough (MPT) is the TUTT most often referred to in the Pacific. However, another TUTT is frequently observed in the western Pacific between 115E and 145E during July, August, and September. This TUTT will be referred to as the East Asian Trough (EAT) (Figure 9). The EAT is observed to develop in the manner described by Sadler (1976): A short wave trough in the westerlies moves into the longwave position, intensifies, penetrates southward, segments the STR and forms a cut-off low (south of the STR). Frequently, cyclonic cells segment from the MPT and, as they move westward, become associated with the EAT, intensify and extend the EAT well into the tropics.[1] As will be shown later, the EAT can greatly influence the movement of tropical cyclones approaching it.

During the spring-summer transition the westerly jet stream weakens and moves northward. By the height of summer the southern extent of the mid-latitude westerlies has been displaced some 20 degrees of latitude north of its winter position. Troughs within the westerlies are relatively weak, especially in lower latitudes, and retrogression is not uncommon.

Frequent vacillations of the above four major synoptic features, the STR, the SER, the TUTT's, and the mid-latitude westerlies result in a highly complex and fluctuating synoptic pattern. The pattern becomes even more complex with superposition of a fifth feature, the tropical cyclone.

2. Forecast Study

Table 4 lists the storms conforming to the SR. Also shown is the difference between the time of the earliest "reasonable" match of observed winds and overlay

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[1]Observed by the author during the 1974, 1975, and 1976 typhoon seasons at JTWC, Guam.

winds, and the time that the match would have occurred based on the S-12 R, S-36 R, and S-60 R wind fields. The average differences were -25 hours, -45 hours and -55 hours for the S-12 R, S-36 R, and S-60 R, respectively. The large negative bias indicates that the original wind fields were much too slow in anticipating recurvature.

Initially a 12 hour correction was added to the average errors for SR storms (Table 4) to make them consistent with the WR storms. This reduced the average errors to -13, -33, and -43 for the S-12 R, S-36 R, and S-60 R wind fields, and rendered these wind fields indicative of recurvature 24, 48, and 72 hours ahead of time, as for the WR storms. Next, further corrections were added to reduce the errors in Table 4 to a value near zero. This required that 12 hours be added to the S-12 R result, reducing the error to -1; and, that 36 hours be added to the S-36 R and S-60 R results, reducing the average errors to +3 and -7, respectively. For a first guess, the S-12 R wind field was assumed to indicate winds 12 hours prior to recurvature. Since the correction for the S-36 R wind field was 36 hours more than that of the S-12 R wind field the hypothesis was formed that the wind distribution 12 hours prior to recurvature should resemble some average S-12 R--S-36 R wind field. The 36 hour correction for the S-60 R regime should render it indicative of winds 36 hours prior to recurvature.

The hypothesis was tested by deriving a wind field overlay composed of the average of the S-12 R and S-36 R wind fields. This wind field is shown in Figure 10 and will be referred to as R 36. Results indicated remarkable similarity between the R 36 wind field and that observed at recurvature. The R 24 and R 48 wind fields were representative of the maximum and minimum wind fields observed at recurvature, respectively. In addition, the S-60 R wind field closely resembled the observed wind field 24 hours prior to recurvature. Winds in the north-northwest demonstrated best results.

Since the need exists to forecast recurvature/non-recurvature and the time of recurvature up to 72 hours in advance and the recurvature wind fields were useful only to 24 hours, a relationship was sought between recurvature and the non-recurvature wind fields.

During the study no apparent relationship could be found between recurvature and the winds of the non-recurvature wind fields equatorward of the axis of the STR. Therefore, the original non-recurvature wind regimes were modified and renamed. Henceforth, the S-60 NR, S-36 NR, and

S-12 NR wind fields will be NR3, NR2, and NR1, respectively (Figures 11, 12, and 13).

It was observed that at a given time prior to recurvature, SR storms were always farther south of the mid-latitude westerlies than their WR counterparts. On the other hand, recurvers characterized by a WR usually had a smaller northward component of movement prior to recurvature than their SR counterparts. Additionally, TC's in a WR conforming to the NR1 (S-12 NR) wind field did not recurve for at least 84 hours. In the SR, however, TC's were observed to recurve as quickly as 18 hours after adhering to the NR1 wind field. The westerly wind intensities of the NR1, NR2, and NR3 wind fields are quite similar. They do, however, indicate deeper westerly flow with decreasing time. This is best depicted as a small shift of the axis of the STR toward the TC.

The NR3 overlay was applied to all SR storms. Whenever the axis of the STR on the overlay coincided with the axis of the STR of the observed 200 mb wind field, a reasonable match was assumed. The best correlation between the wind regimes and recurvature was observed when utilizing the position of the STR axis in the north-northwest sector of the TC. The time of the match was considered the onset of NR3. Similarly, the NR2 and NR1 overlays were applied to the observed 200 mb wind field, and the onset of NR2 and NR1 were determined, respectively. The onset of R 72 (S-60 R) was previously found when compiling Table 4. The time difference between the onset of NR3 and NR1 was considered the duration of the NR3-NR1 transition. Likewise, the time difference between the onset of NR1 and R 72 was considered the duration of the NR1-R 72 transition.

If the duration of the NR3-NR1 transition was 30 hours or less, the SR TC recurved; if the duration was 36 hours or more, the SR TC did not recurve. Thus, a scheme for determining recurvature or non-recurvature was found for SR TC's.

The difference between the time of the onset of NR3, NR1, and R 72, and the time of recurvature were ascertained. Correlations were computed between the various durations and the time differences between the onsets of NR3, NR1, and R 72, and recurvature. The correlation coefficients and significances determined by the 1% criterion for linear correlation coefficients are listed in Table 5.

The northward component of movement (NCM) between the JTWC first warning position and each onset (NR3, NR1, R 72), and between each onset and recurvature was determined. The NCM between the JTWC first warning and recurvature was computed and was found to have a minimum value of approximately 5.5 knots (2.9 m/s). Therefore, all NCM's, between the JTWC first warning and each onset, less than 5.5 knots (2.9 m/s) were increased to this value. Correlations were made between the various NCM's. Regression equations were computed for those correlations determined as significant by the 1% criterion for linear correlation coefficients (Table 5). Similarly, the NCM from each onset to recurvature was correlated with the NCM between each onset minus 12 hours and each onset minus 24 hours (Table 5).

The above operation was performed replacing the NCM with the actual speed of movement. Results are listed in Table 5.

Finally, the direction of movement from NR1 to recurvature was correlated with the direction of movement from the JTWC first warning to NR1. Again, results are shown in Table 5.

A synoptic study of the Summer Regime (SR) was accomplished to identify relationships between upper tropospheric (200 mb) flow and the movement of tropical cyclones. Results of such a study should be useful to the forecaster in identifying a storm's potential for recurvature, non-recurvature, northward movement, acceleration, or deceleration. The effects of upper tropospheric flow on erratic movement will be discussed in a forthcoming paper by the author.

Figure 14 is indicative of a non-recurvature situation. When the Asian upper level anticyclone remains extended over the western Pacific to a position north and east of a TC, the TC will exhibit a greater westward than northward component of movement, and recurvature will not occur. Such TC's commonly affect the southern Ryukyu Islands, Taiwan, and the Peoples Republic of China. The westward movement of the TC appears to be related to the strength of the 200 mb winds at the eastern or southeastern periphery of the STR. If these winds are 10 to 20 knots (5.1 to 10.3 m/s) the TC will move toward the northwest into the ridge; if the winds are 20 to 40 knots (10.3 ot 20.6 m/s) the TC will move toward the west-northwest; if the winds are 40 to 60 knots (20.6 to 30.9 m/s) the TC will move toward the west; and if the winds are greater than 60 knots (30.9 m/s) the TC will move south of west.

Figure 15 is characteristic of TC's with a greater northward than westward component of movement. Although intense cyclonic cells within the EAT are projected down to the middle troposphere, they frequently elude the sparse data at this level and the resulting analysis is not definitive. This is disastrous if one depends on the use of mid-tropospheric flow in steering TC's. If the EAT is relatively stationary, a TC moving toward it will eventually be subjected to northward steering currents. The northward displacement exhibited by the TC increases with the intensity of the EAT and decreases with distance from the EAT. This synoptic pattern is conducive to recurvature.

Figure 16 illustrates another synoptic pattern which is conducive to recurvature. An anticyclone northeast of a tropical cyclone can produce strong southeasterly flow. In such cases, tropical cyclones are observed to acquire a large northward component and move toward recurvature. If, however, the anticyclone to the northeast builds westward, the storm would acquire a more westward component (Figure 17). The overall speed of movement could remain the same, or even increase, but the storm will move toward stronger mid-latitude westerlies more slowly.

It was observed that during the transition seasons a TC might initially be in an SR, but change to a WR. This most commonly occurred with TC's between 135E and 140E, and the Asian land mass. In this region (during transition seasons) the TUTT is weak and short wave troughs moving eastward from Asia can be quite strong. East of 135E to 140E, the TUTT is stronger and the short wave troughs are weaker. It was found that if during transition seasons, a TC acquired a direct link between its outflow circulation and the mid-latitude westerlies, best results were obtained by treating it as a WR TC west of 135E to 140E, and as an SR TC east of 135E to 140E.

Figure 18 is an example of a synoptic pattern which may retard a TC's northward component of movement. An anticyclone to the west or northwest of a tropical cyclone can produce flow with a southward component which will reduce the TC's northward component. Any southward flow toward the storm, regardless of the synoptic pattern producing it, may retard a TC's northward movement.

After assessing all of the data concerning the SR TC's, some qualitative rules could be derived. These rules are integrated into Table 6 with the sequence to be used in determining recurvature/non-recurvature and the timing of recurvature.

## IV. SUMMARY

The original 200 mb wind fields derived by George provided the basis for an operationally applicable, TC recurvature/non-recurvature, forecast technique. When applied to a data set, independent of that utilized by George, the original wind regimes for recurving TC's correlated well with recurvature of some TC's and poorly with recurvature of others. A synoptic analysis of the upper tropospheric environment of all the storms revealed that recurving storms were characterized by one of two regimes:

1. A Winter Regime (WR) in which there is a direct link between the upper level TC circulation and the mid-latitude westerlies at least 72 hours prior to recurvature; and,

2. A Summer Regime (SR) in which the upper level TC circulation and the mid-latitude westerlies are separated by the TUTT and subtropical ridge, until approximately 24 hours before recurvature.

The WR characterized TC's which correlated well with the original 200 mb wind fields for recurving TC's, while the SR characterized those TC's which, in general, correlated poorly.

Through a series of small, but significant, modifications the original 200 mb wind fields for recurving TC's provided an operationally applicable technique for forecasting recurvature meeting the WR criterion. The technique establishes the timing of recurvature at intervals 24, 48, and 72 hours ahead of time. A set of rules for applying the technique, and for determining recurvature versus non-recurvature was derived (Table 3).

A straight forward forecast technique based on the 200 mb wind fields of George could not be derived for SR TC's. The recurvature wind fields were somewhat applicable, but only within 24 hours of recurvature. Although the non-recurvature wind fields indicated no recurvature within 84 hours for WR TC's, this was not the case with SR ones. In the SR, TC's were observed to recurve within 18 hours after meeting the non-recurvature criteria at S-12 NR (NR1).

It was observed that TC's undergoing the transition from S-60 NR (NR3) to S-12 NR (NR1) in 30 hours or less would recurve, while those making this transition in 36 hours or more would not recurve.

The timing of recurvature beyond 24 hours could not be determined utilizing the actual wind fields. Several of the wind fields, however, were utilized as reference points from which a conditional climatology of recurving, SR TC's was produced.

In addition to the wind field study, a synoptic study was performed to determine how various synoptic features at the 200 mb level affected the movement of SR TC's.

Results of the wind field study, the conditional climatology with regression equations, and the synoptic study were compiled into a forecast technique to determine recurvature/non-recurvature and the timing of recurvature for SR TC's (Table 6).

## V. CONCLUSIONS

The value of this forecast study can only be determined after applying it on an operational basis. It will require two years to acquire a sufficient data base for the evaluation. This evaluation will be conducted during the 1977 and 1978 typhoon seasons by JTWC.

The most undesirable feature of the forecast technique is its subjectivity. It is foreseeable that different forecasters will arrive at somewhat varied conclusions as to the timing of recurvature. However, this variance should only amount to approximately 12 hours with the WR technique if the forecast rules are correctly applied. If recurvature can be forecast within 12 hours of its occurrence at the 24-, 48-, and 72-hour forecast intervals, a significant improvement in the forecasting of recurvature will be realized. It is unlikely that such accuracy in forecasting the timing of recurvature for SR storms will be realized with the SR technique. This is expected from the poorer correlation between the available original wind fields and the recurvature of SR TC's. The ability to determine recurvature vice non-recurvature, however, should contribute significantly to reducing the overall 24-, 48-, and 72-hour forecast errors for both WR and SR TC's.

A portion of the subjectivity is inherent from the data base of the original study. It would be both desirable and valuable if the original composited data base were stratified by synoptic regimes. Such stratification is essential for improving the SR technique.

The SR study illustrates the potential for utilizing conditional climatology tables in tropical cyclone forecasting. Although many such tables are available, they have, for the most part, been prepared without regard to synoptic regimes.

The study has shed additional light on the importance of the TUTT as a significant synoptic feature. It is imperative that future dynamic models be able to adequately forecast both the movement and intensity of the TUTT and of the cyclonic cells within it. Additionally, daily upper tropospheric analyses need to be included in the various climatological analysis publications.

## VI. SUGGESTED RESEARCH

Further studies concerning the environment of tropical cyclones should consider stratifications similar to the WR and SR. It would be useful to apply this stratification to George's original data base, and then utilize the results to improve this forecast study. The WR wind field at recurvature would be useful for application to 200 mb prognostic charts. A completely new set of composited wind fields should be developed for SR TC's and probably for those TC's occurring during transition seasons.

In the George study, geopotential height fields, meridional and zonal wind fields, and temperature fields were also derived. Additional operationally useful forecast tools for recurvature and non-recurvature might be developed from these fields. The author feels that such studies should utilize data from the stratifications suggested above. This is essential for SR systems.

Finally, a strong effort should be extended toward producing an accurate dynamic model of the TUTT which can be incorporated into existing PE models or future global models.

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TABLE 1. Tropical Storms and Typhoons Utilized in the Modified Recurvature/Non-Recurvature Study

| STORM | MONTH | YEAR | TYPE | DATE AND TIME OF RECURVATURE (Z) | USED IN DERIVING WIND FIELDS | USED IN DERIVING SYNOPTIC RULES |
|---|---|---|---|---|---|---|
| | | 1976 | | | | |
| KATHY | JAN-FEB | | TY | 30/18 | X | |
| LORNA | FEB-MAR | | TS | | | X |
| MARIE | APR | | TY | 10/18 | X | |
| NANCY | APR-MAY | | TS | | | X |
| OLGA | MAY | | TY | 25/12 | X | |
| PAMELA | MAY | | TY | 23/12 | X | |
| RUBY | JUN-JUL | | TY | 26/18 | X | |
| SALLY | JUN-JUL | | TY | 28/00 | X | |
| THERESE | JUL | | TY | 18/06 | X | |
| WILDA | JUL | | TS | 24/06 | X | X |
| VIOLET | JUL | | TS | | | X |
| ANITA | JUL | | TY | 25/06 | X | X |
| BILLIE | AUG | | TY | | | X |
| CLARA | AUG | | TS | | | X |
| DOT | AUG | | TS | 21/18 | X | X |
| ELLEN | AUG | | TS | | | X |
| FRAN | SEP | | TY | 09/12 | X | X |
| GEORGIA* | SEP | | TS | | | |
| HOPE | SEP | | TY | 16/15 | X | X |
| IRIS | SEP | | TY | | | X |
| JOAN | SEP | | TY | 21/00 | X | X |
| LOUISE | OCT-NOV | | TY | 04/00 | X | |
| MARGE | NOV | | TS | 09/18 | X | |
| NORA | DEC | | TS | 06/09 | X | |
| OPAL** | DEC | | TS | 07/18**** | | |
| | | 1975 | | | | |
| LOLA | JAN | | TY | | | X |
| MAMIE | JUL | | TS | | | X |
| NINA | JUL-AUG | | TY | | | X |
| ORA | AUG | | TY | | | X |
| PHYLLIS | AUG | | TY | 18/00 | X | X |
| RITA*** | AUG | | TY | 23/00**** | | X |
| SUSAN | AUG-SEP | | TS | 28/00 | X | X |
| TESS | SEP | | TY | 06/06 | X | X |
| VIOLA* | SEP | | TS | | | |
| WINNIE | SEP | | TY | 10/18 | X | X |
| ALICE | SEP | | TY | | | X |
| BETTY | SEP | | TY | | | X |
| CORA | OCT | | TY | 03/15 | X | X |
| DORIS | OCT | | TS | 06/00 | X | X |
| ELSIE | OCT | | TY | | | X |
| FLOSSIE | OCT | | TY | | | X |
| GRACE | OCT-NOV | | TS | 30/12 | X | |
| HELEN | NOV | | TS | | | X |
| IDA | NOV | | TY | 09/15 | X | |
| JUNE | NOV | | TY | 22/00 | X | |
| | | 1974 | | | | |
| AMY | MAR | | TY | 16/18 | X | |
| BABE | APR | | TS | 30/00 | X | |
| IRMA | NOV | | TY | | | X |
| KIT | DEC | | TY | | | X |

*Considered, but not utilized; moved toward the northeast under deep southwesterly monsoon flow and dissipated.

**Considered, but not utilized; Opal developed after recurvature.

***Rita moved toward the north-northeast throughout most of its life; point of recurvature could not accurately be determined.

****Estimated

TABLE 2. Winter Regime Storms and the Error Determined as the Difference Between the Time of the Earliest Reasonable Match of Observed and Overlay Winds, and the Time the Match Would Have Occurred Based on the Original Wind Regimes

| YEAR / STORM | S-12 R | S-36 R | S-60 R |
|---|---|---|---|
| 1976 | | | |
| KATHY | -12 | -18 | -18 |
| MARIE | 0 | 0 | -24 |
| OLGA | --* | -12 | -12 |
| PAMELA | -21 | -39 | -12 |
| LOUISE | -30 | 0 | -12 |
| MARGE | -27 | +6 | -6 |
| NORA | -6 | -18 | -18 |
| 1975 | | | |
| DORIS | -12 | -12 | -12 |
| GRACE | -6 | -24 | -18 |
| IDA | -18 | -12 | -18 |
| JUNE | -18 | -18 | -18 |
| 1974 | | | |
| AMY | -21 | -21 | -9 |
| BABE | -12 | 0 | 0 |
| AVERAGE ERROR (HR) | -15 | -12 | -15 |
| AVERAGE ERROR PLUS 12 HR | -3 | 0 | -3 |

*Data not available

TABLE 3. Sequence and Rules for Applying the Winter Regime Recurvature/Non-Recurvature Forecast Technique

| RULE | APPLICABLE FIGURES |
|---|---|
| 1. Apply the NR 1* wind field; if observed westerly winds do not exceed this profile, the storm will not recurve within 84 hours. | FIG. 13 |
| 2. Apply R 72 wind field; when the profile matches the profile of winds observed in the nearest sector east of the axis of the upper level trough, forecast recurvature in 72 hours. | FIG. 6 |
| 3. Apply the R 48 wind field; when this criteria is met as in 2 above, forecast recurvature in 48 hours. | FIG. 7 |
| 4. Apply the R 24 wind field; when criteria is met as in 2 above, forecast recurvature in 24 hours. | FIG. 8 |
| 5. Apply the R 72, R 48 and R 24 wind fields to the 200 mb 36 hour prog in order to forecast when the criteria in 2, 3, and 4 above will be met. | FIG. 6, 7, 8 |
| 6. If a trough is quasi-stationary over or near India, recurvature will not occur even if the criteria in 4 above is met. These storms will go ashore over southeastern Asia. | FIG. 4 |
| 7. Winds must increase outward continuously for $10^{o}$ to $11^{o}$ latitude. If they increase then decrease then increase again the wind fields should be assumed not to fit. | FIG. 3 |

*Derived from the "summer regime" storms (Figure 13)

TABLE 4. Summer Regime Storms and the Error Determined as the Difference Between the Time of the Earliest Reasonable Match of Observed and Overlay Winds, and the Time the Match Would Have Occurred Based on the Original Wind Regimes

| YEAR<br>STORM | S-12 | S-36 | S-60 |
|---|---|---|---|
| 1976 | | | |
| RUBY | -15 | -36 | -48 |
| SALLY | -15 | -36 | -48 |
| THERESE | -18 | -30 | -42 |
| WILDA | -36 | -60 | -66 |
| ANITA | -24 | -54 | -66 |
| DOT | -30 | -42 | -60 |
| FRAN | -12 | 0 | -24 |
| HOPE | -36 | -36 | -60 |
| JOAN | -36 | -60 | -66 |
| 1975 | | | |
| PHYLLIS | -30 | -48 | -60 |
| TESS | -18 | -36 | -42 |
| WINNIE | -36 | -48 | -24 |
| CORA | -36 | -60 | -72 |
| AVERAGE ERROR (A) | -25 | -45 | -55 |
| TIME ADDED TO AVERAGE ERROR (B) | (24) | (48) | (48) |
| A + B | -1 | +3 | -7 |

TABLE 5. Correlation of selected variables; y is the dependent variable; x is the independent variable; r is the correlation coefficient; $\sigma_r$ is the standard deviation, $1/\sqrt{N-2}$ where N is the sample size; m is the slope; b is the intercept; ON is the onset; REC is recurvature; DU is duration; NCM is the northward component of movement; FW is the JTWC first warning; H is hours; SOM is the speed of movement; and, DOM is the direction of movement.

| y | x | r | 2.6$\sigma_r$ | y=mx+b |
|---|---|---|---|---|
| ON NR3-REC | DU NR3-NR1 | +.52 | +.75 | |
| ON NR1-REC | DU NR1-R 72 | +.67 | +.75 | |
| ON R 72-REC | DU NR1-R 72 | -.11 | +.75 | |
| NCM FW-REC | NCM FW-NR3 | +.94 | +.78 | y=.95(x)+.99 |
| NCM FW-REC | NCM NR3-12H | +.71 | +.82 | |
| NCM FW-REC | NCM NR3-24H | +.78 | +.87 | |
| NCM FW-REC | NCM FW-NR1 | +.97 | +.75 | y=.96(x)+.43 |
| NCM FW-REC | NCM NR1-12H | +.83 | +.78 | y=.93(x)+2.91 |
| NCM FW-REC | NCM NR1-24H | +.80 | +.82 | |
| NCM FW-REC | NCM FW-R72 | +.97 | +.75 | y=.96(x)+.25 |
| NCM FW-REC | NCM R 72-12H | +.97 | +.75 | y=.95(x)+.09 |
| NCM FW-REC | NCM R 72-24H | +.90 | +.75 | y=.91(x)+.03 |
| NCM NR3-REC | NCM FW-NR3 | +.94 | +.78 | y=.95(x)+.99 |
| NCM NR1-REC | NCM FW-NR1 | +.88 | +.75 | y=.84(x)+1.71 |
| NCM R 72-REC | NCM FW-R 72 | +.75 | +.75 | y=.69(x)+2.63 |
| SOM NR3-REC | SOM FW-NR3 | +.85 | +.78 | y=.93(x)+2.37 |
| SOM NR1-REC | SOM FW-NR1 | +.83 | +.75 | y=.81(x)+2.23 |
| SOM R 72-REC | SOM FW-R 72 | +.67 | +.75 | |
| SOM NR1-REC | SOM FW-NR3 | +.77 | +.78 | |
| SOM R 72-REC | SOM FW-NR3 | +.66 | +.78 | |
| SOM R 72-REC | SOM FW-NR1 | +.64 | +.75 | |
| DOM NR1-REC | DOM FW-NR1 | +.90 | +.78 | y=.60(x)+128.86 |

TABLE 6. Sequence and Rules for Applying the Summer Regime Recurvature/Non-Recurvature Forecast Technique

| RULE | APPLICABLE FIGURES |
|---|---|
| A. To determine recurvature or non-recurvature: | |
| 1. Apply the NR3 wind field; when the axis of the STR matches that of the 200 mb analysis NNW of the TC | FIG. 11 |
| 2. Apply the NR2 wind field; when the axis of the STR matches that of the 200 mb analysis NNW of the TC | FIG. 12 |
| 3. Apply the NR1 wind field; when the axis of the STR matches that of the 200 mb analysis NNW of the TC | FIG. 13 |
| 4. Determine the duration of the NR3-NR1 transition. | |
| a. If the duration is $\leq$30 hr the TC will recurve or go ashore near recurvature. | |
| b. If the duration is >36 hr the TC will not recurve. | |
| 5. If the DOM from the 1st warning to NR1 is <300°; recurvature will not occur. | |
| B. To determine the time of recurvature: | |
| 1. The direction of the future track can be obtained from: | |
| The DOM from NR1 to recurvature = .60 (DOM from the 1st warning to NR1) + 128.86. | |
| 2. To obtain the point of recurvature: | |
| a. Apply the R 36 wind field to the 200 mb 36 hr prog (placing the TC center on the track obtained in B.1.) until winds "reasonably" match NNW of the TC. This will be the average point of recurvature. Update with each 36 hr prog. | FIG. 10 |
| b. Similarly, apply the R 24 and R 48 wind fields to determine the maximum and minimum points of recurvature, respectively. | FIG. 7 and 8 |
| 1) 40% will recurve between R 48 and R 36. | |
| 2) 60% will recurve between R 24 and R 36. | |
| 3. Further refinement to the point of recurvature can be obtained by applying the following rules: | |
| a. The NCM from NR1 to recurvature = .84 (NCM from the 1st warning to NR1)* + 1.71. | |
| b. The SOM from NR1 to recurvature = .81 (SOM from 1st warning to NR1) + 2.23. | |
| c. At NR1: | |

TABLE 6. Sequence and Rules for Applying the Summer Regime Recurvature/Non-Recurvature Forecast Technique (Continued)

| RULE | APPLICABLE FIGURES |
|---|---|
| 1) If the NCM >15 kt, recurvature will occur in 18 to 30 hr (90 percentile). | |
| 2) If the NCM <15 kt, recurvature will occur in 36 to 78 hr (90 percentile). | |
| d. The NCM from the 1st warning to recurvature = .96 (NCM from the 1st warning to R 72)* + .25. | |
| e. At R 72: | |
| 1) If the NCM >15 kt, recurvature will occur in 6 to 24 hr (90 percentile). | |
| 2) If the NCM <15 kt, recurvature will occur in 12 to 48 hr (90 percentile). | |

C. During transition seasons TC's west of 140E will adhere to the winter regime and TC's east of 140E will adhere to a summer regime.

*If the NCM <5.5 kt, increase it to 5.5 kt.

DOM = direction of movement
SOM = speed of movement
NCM = northward component of movement

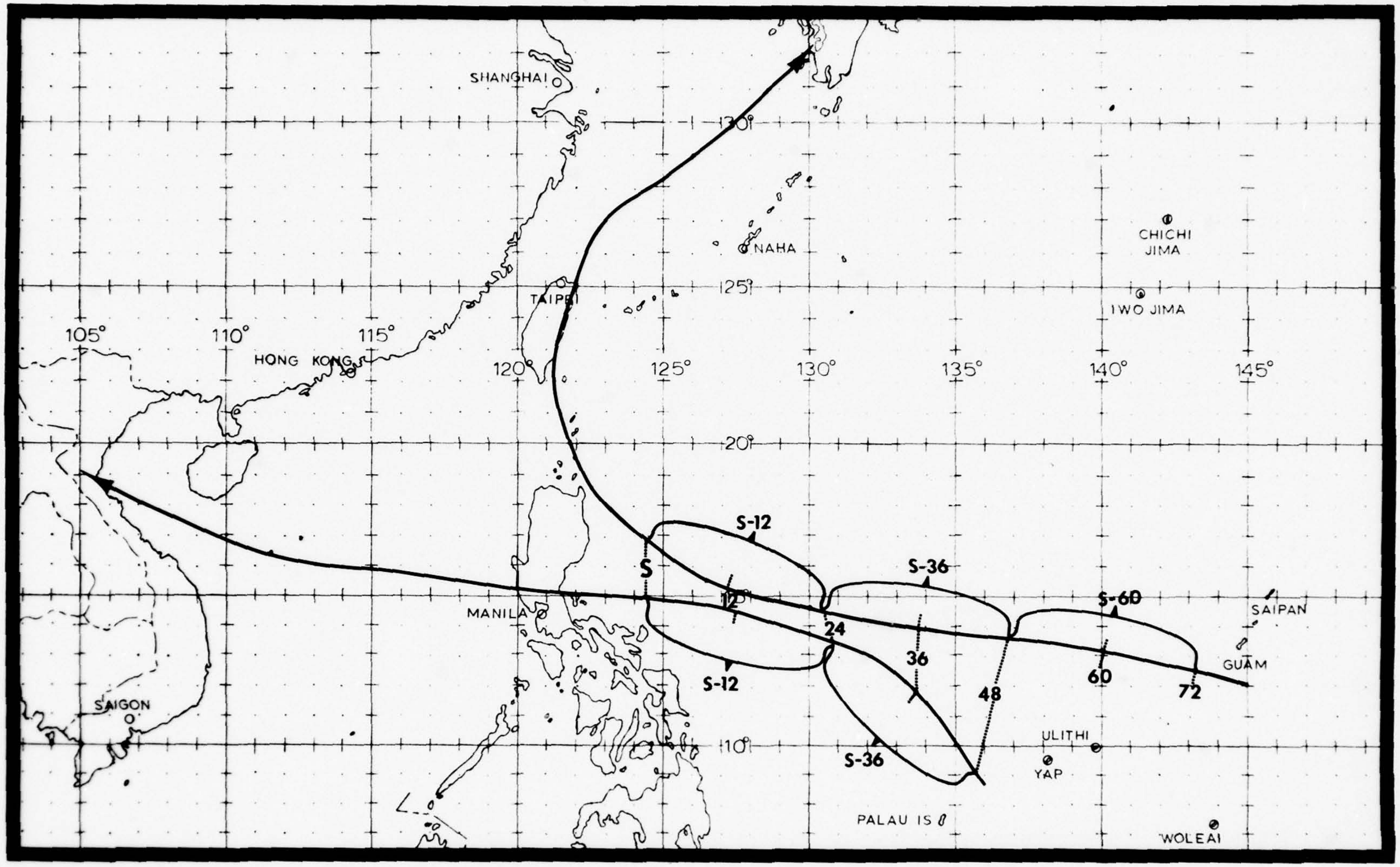


FIGURE 1. Example of paired, recurving and non-recurving storm tracks used in George's study. Numbers between tracks indicate synoptic periods, prior to the S-point time, which were composited to derive George's S-12, S-36, and S-60 wind, height, and temperature fields. Brackets denote synoptic periods used in the compositing schemes. The S-point is discussed in the text. (Modified from George 1975)

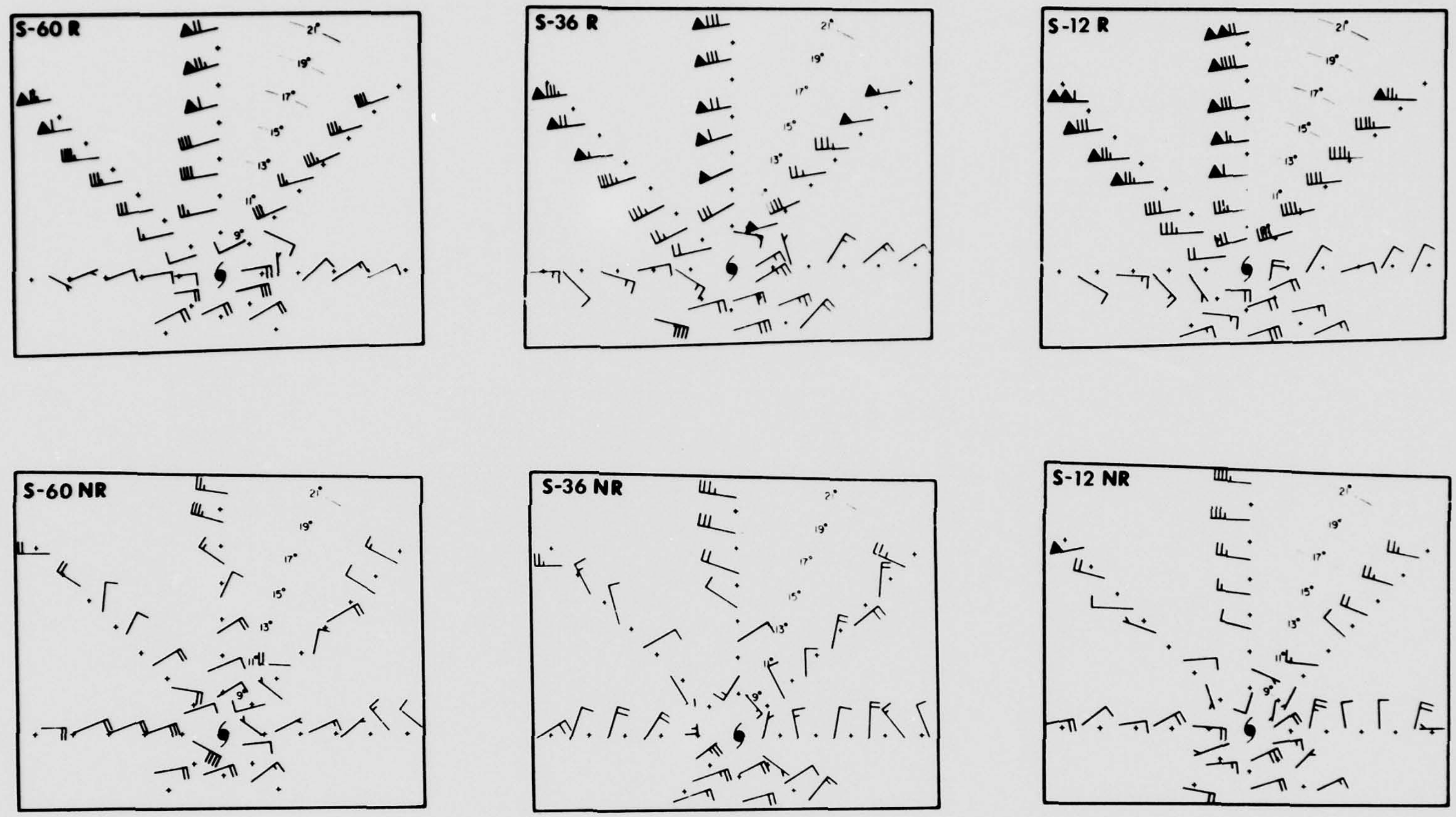


FIGURE 2. 200 mb recurvature (R) and non-recurvature (NR) wind fields derived by George. Note that the distance from storm center to 9 degree latitude radial is not to scale. (From George 1975)

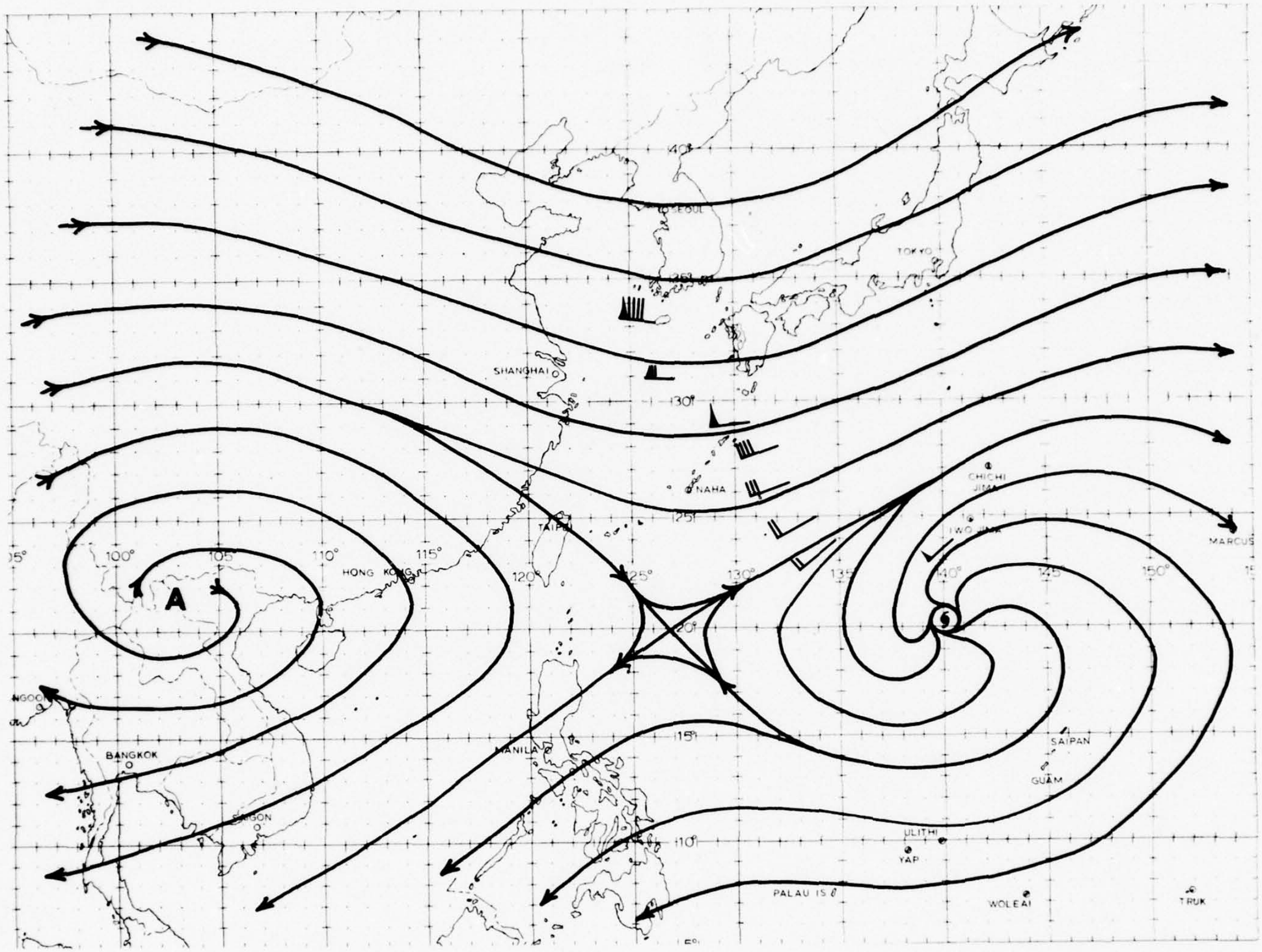


FIGURE 3. 200 mb streamline analysis depicting a Winter Regime (WR) situation. Wind barbs are in knots and illustrate the direct link between the tropical cyclone upper level outflow circulation and the mid-latitude westerlies.

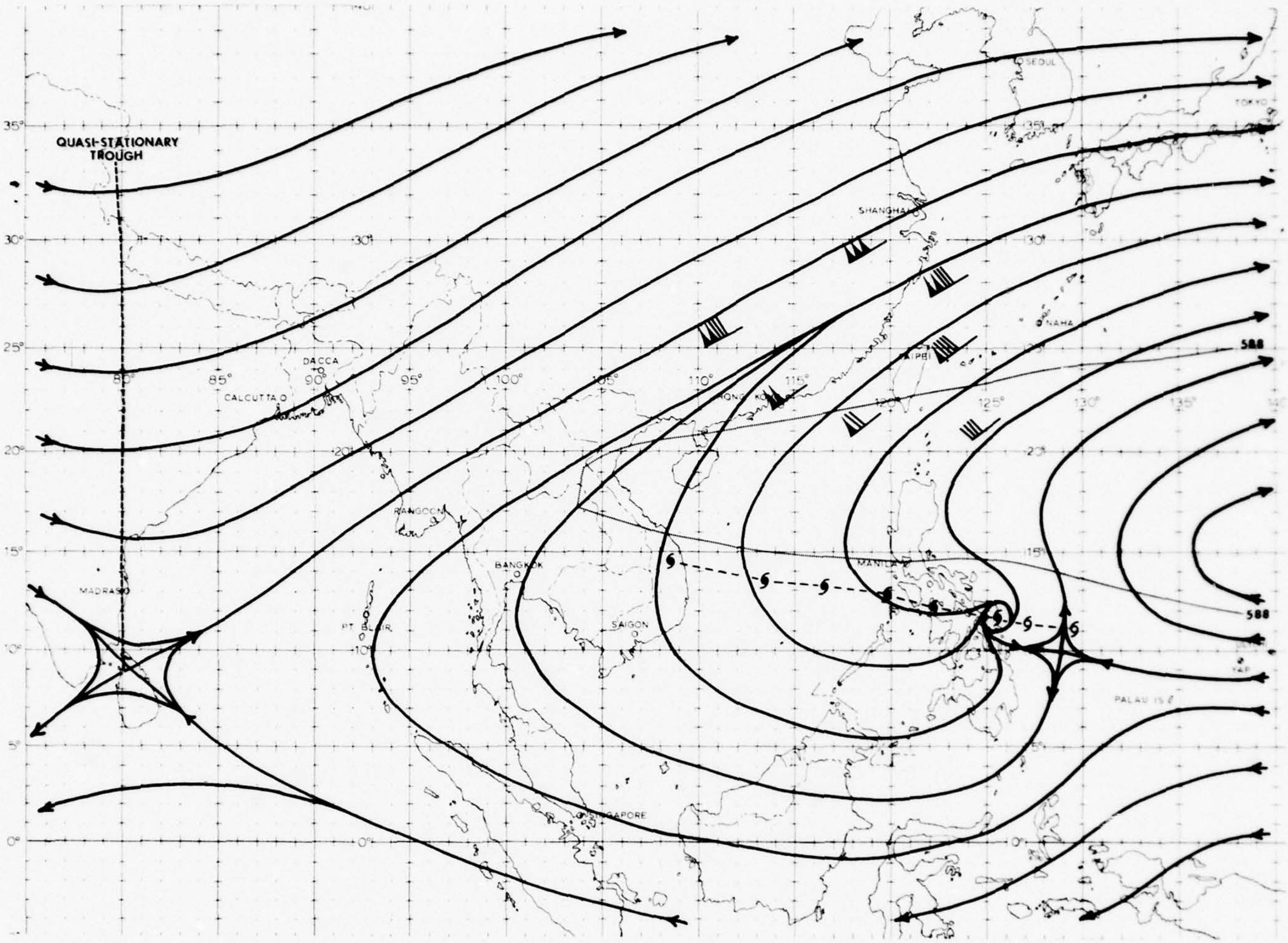


FIGURE 4. 200 mb streamline analysis illustrating the primary WR non-recurvature situation. Fine dashed line represents the 500 mb 588 decameter contour. Thick dashed line shows the tropical cyclone past (tropical storm symbol) and future (typhoon symbol) cyclone track.

Figure 5a. Visual image of a vertically stacked Tropical Storm Nancy entering a region of upper level westerlies. The dashed line shows the equatorward 588 decameter contour of the 500 mb subtropical ridge near picture time and the dotted line shows the same feature 24 hours earlier. Wind barbs show 200 mb flow in knots. (29 April 1976, 2043Z) (DMSP imagery)

FIGURE 5b. Tropical Storm Nancy 24 hours after 5a, and after its low level circulation has been sheared from its associated convective cloud mass. Solid wind barbs show upper level flow in knots, the dashed wind barb indicates the mean low level flow in knots, and the dashed line shows the position of the 588 decameter contour. (30 April 1976, 2030Z) (DMSP imagery)

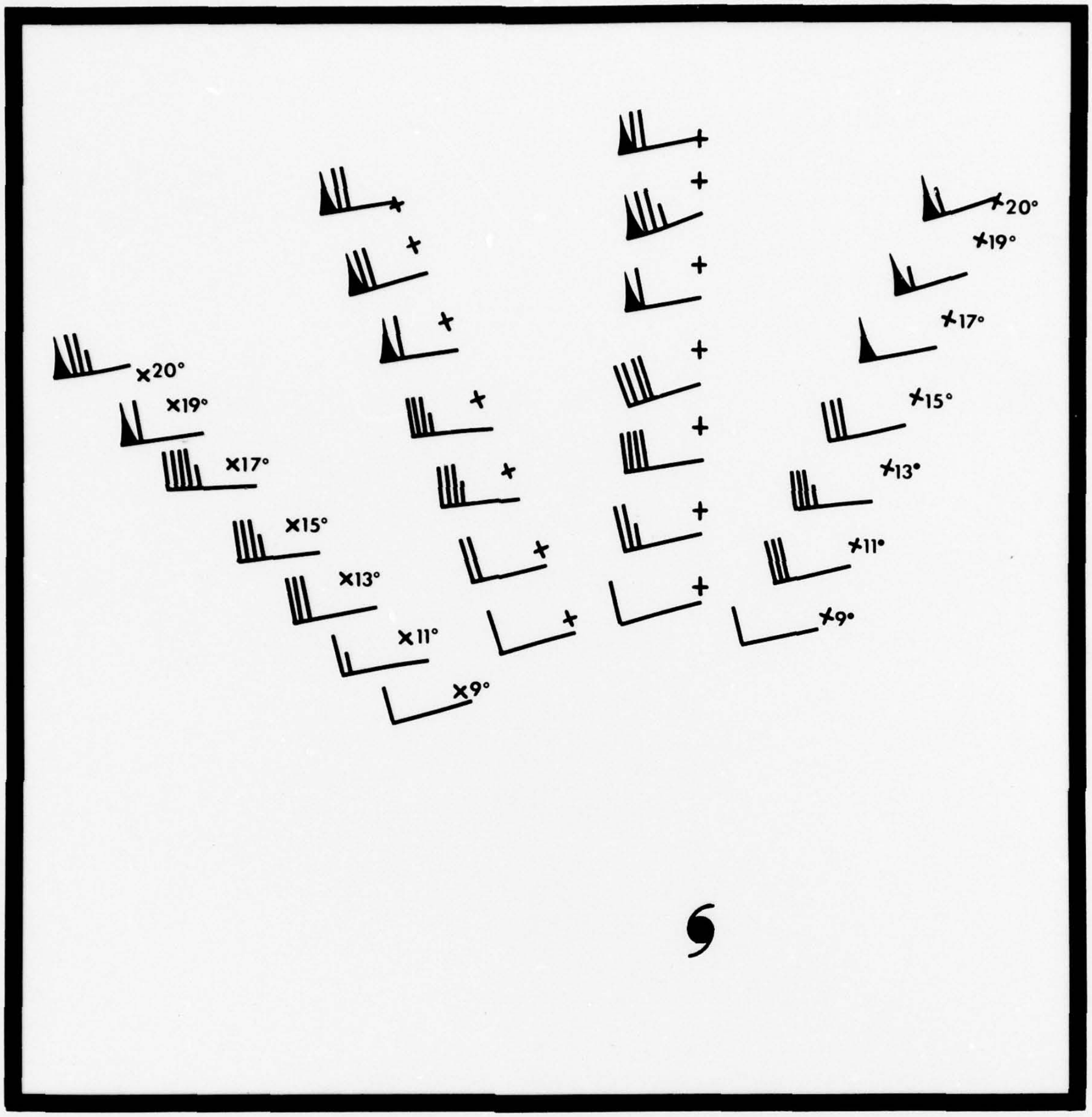


FIGURE 6. R 72 wind field; wind barbs are in knots.

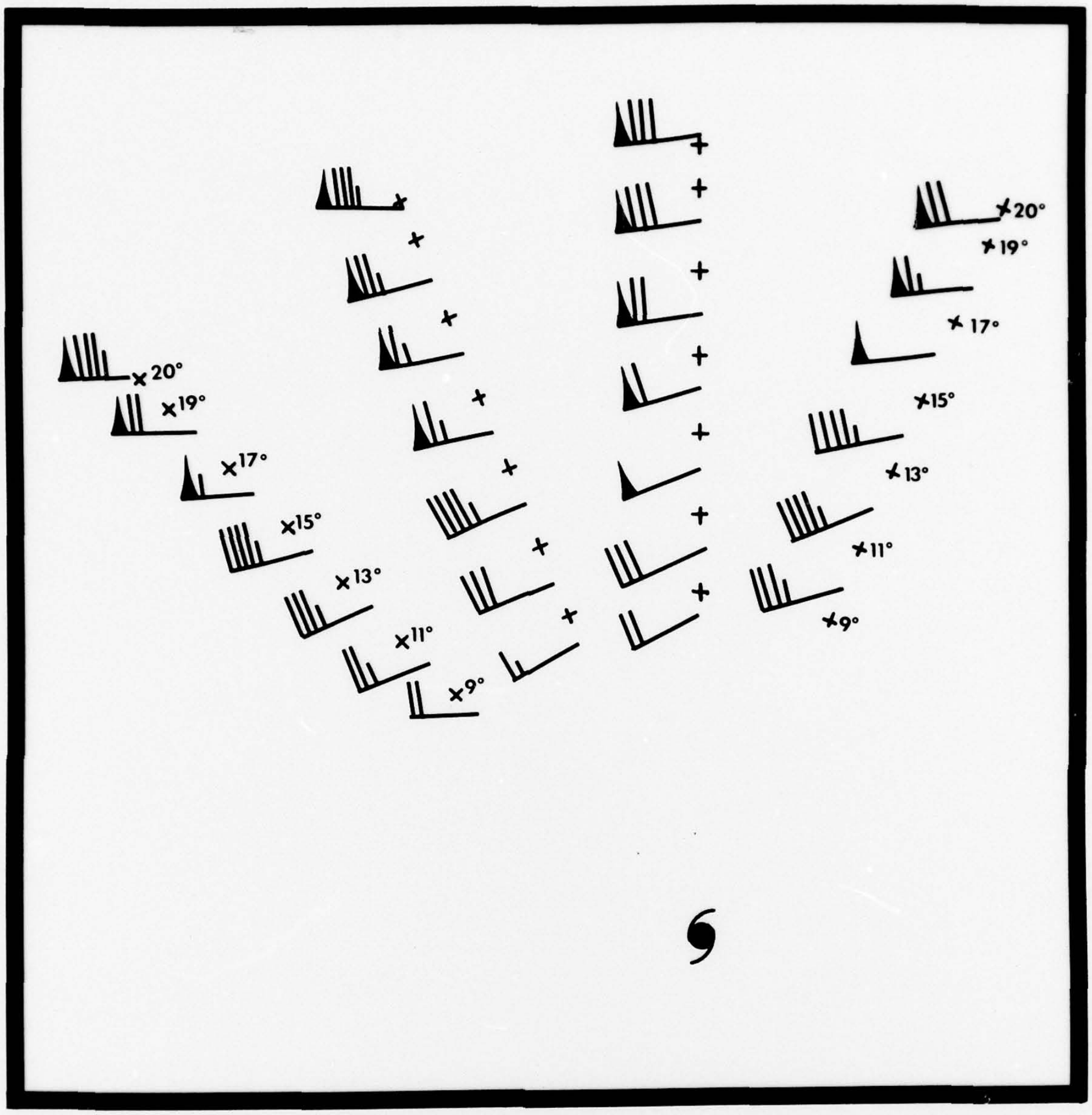


FIGURE 7. R 48 wind field; wind barbs are in knots.

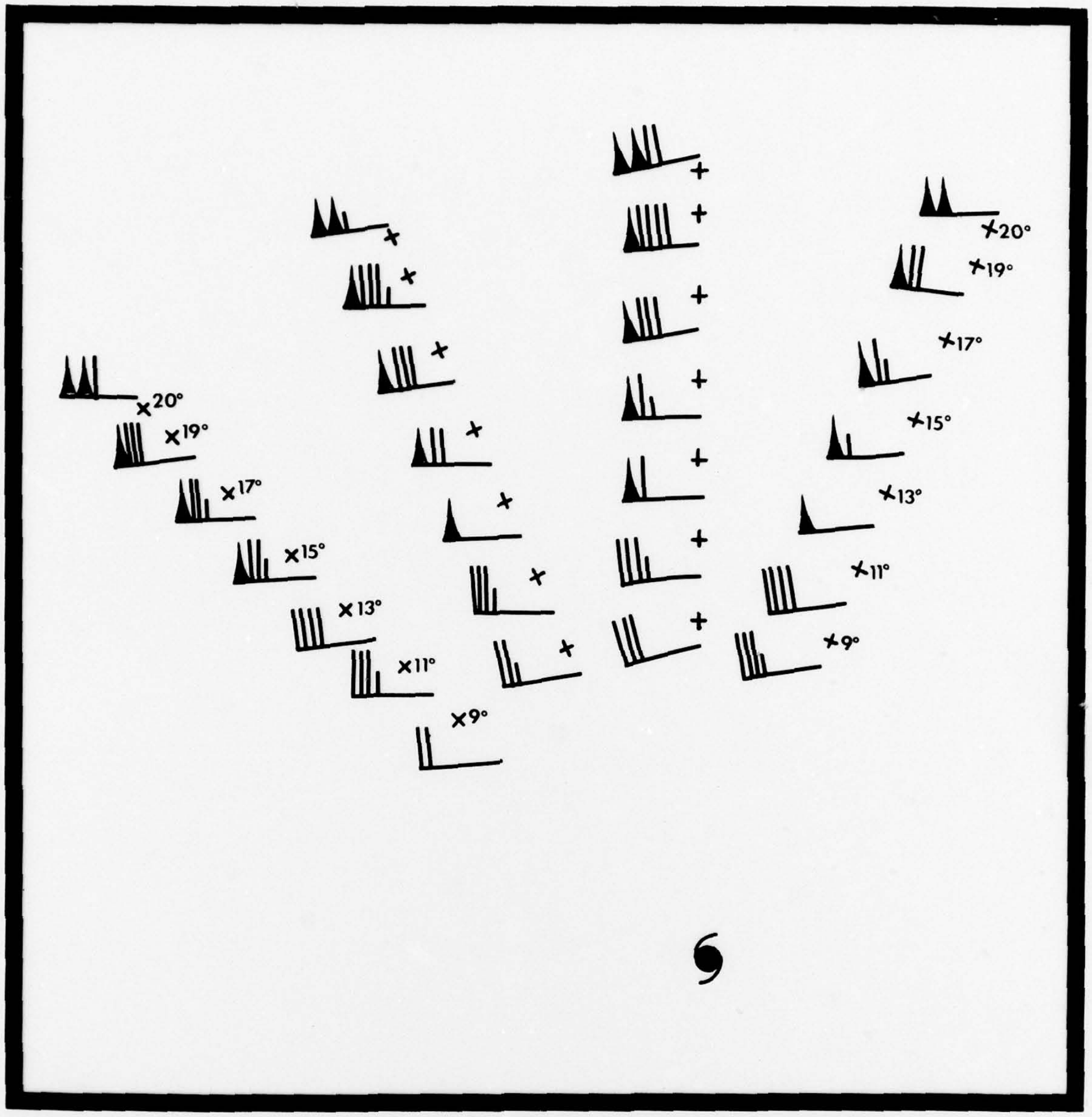


FIGURE 8. R 24 wind field; wind barbs are in knots.

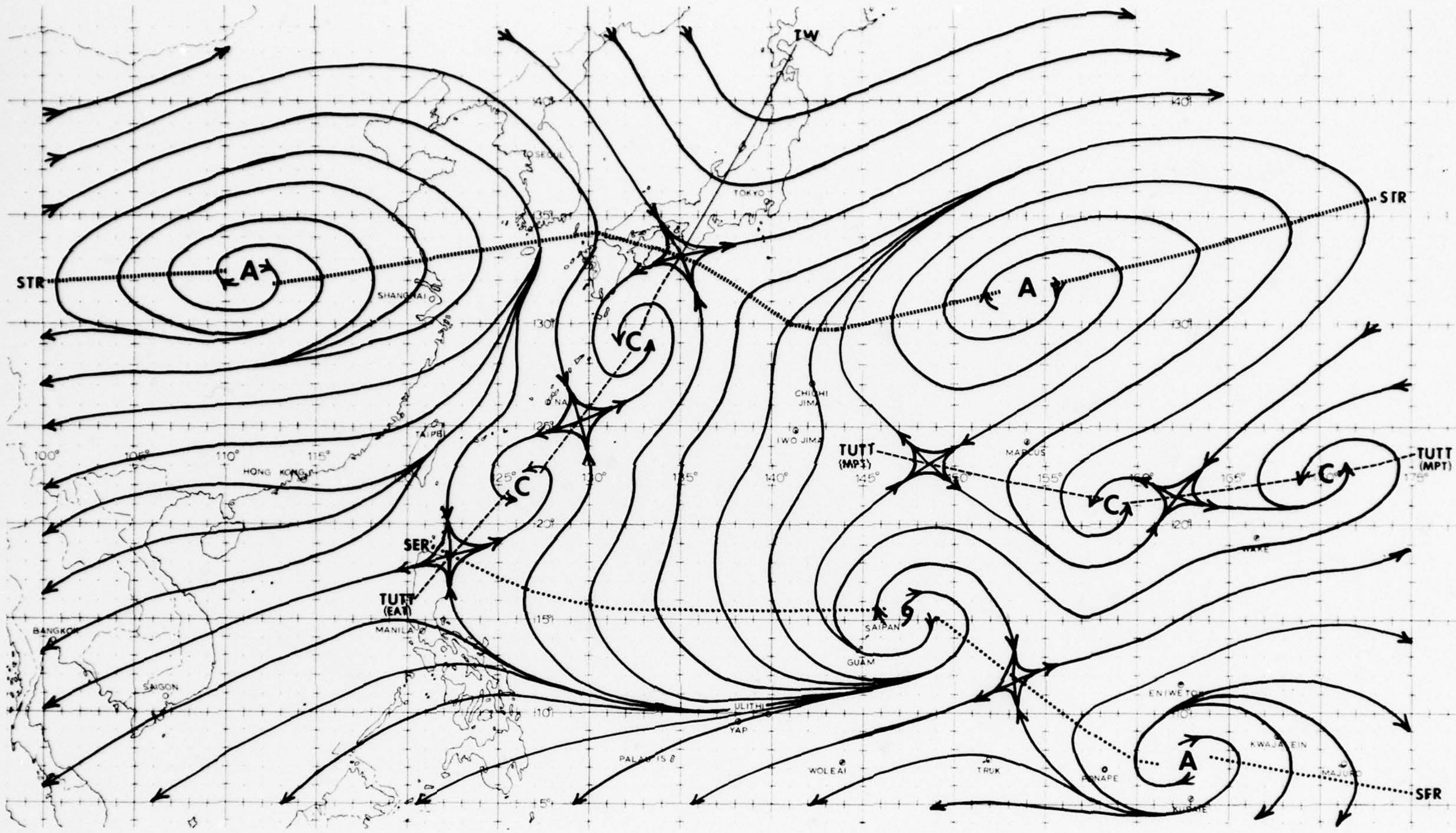


FIGURE 9. 200 mb streamline analysis depicting the Summer Regime (SR). TW is a trough in the westerlies (short dashed), STR is the subtropical ridge (heavy short dashed), SER is the subequatorial ridge (dotted), TUTT is the tropical upper tropospheric trough (long dashed), MPT is the Mid-Pacific Trough, and EAT is the East Asian Trough.

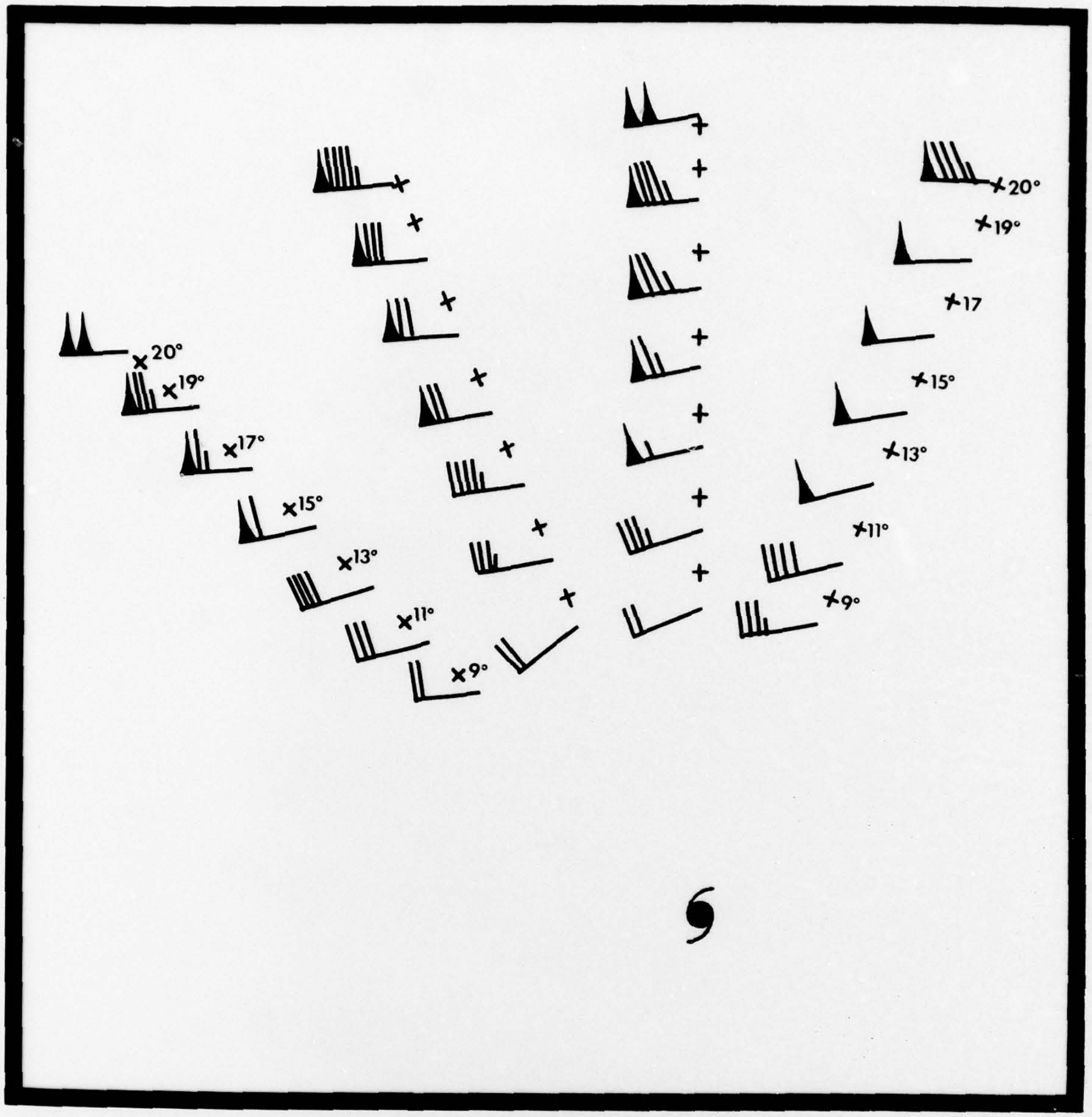


FIGURE 10. R 36 wind field; wind barbs are in knots.

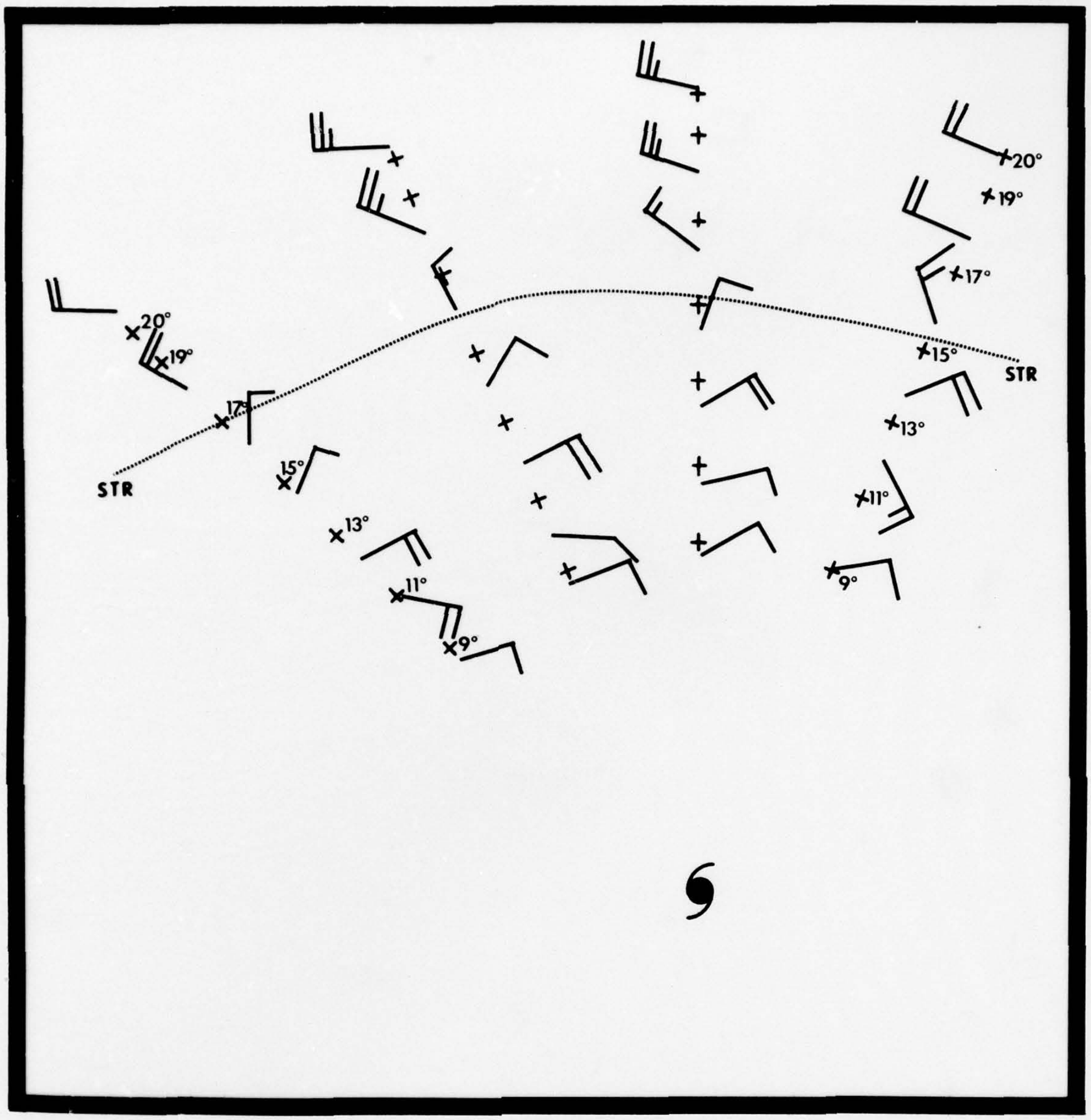


FIGURE 11. NR3 wind field; STR is the axis of the sub-tropical ridge; wind barbs are in knots.

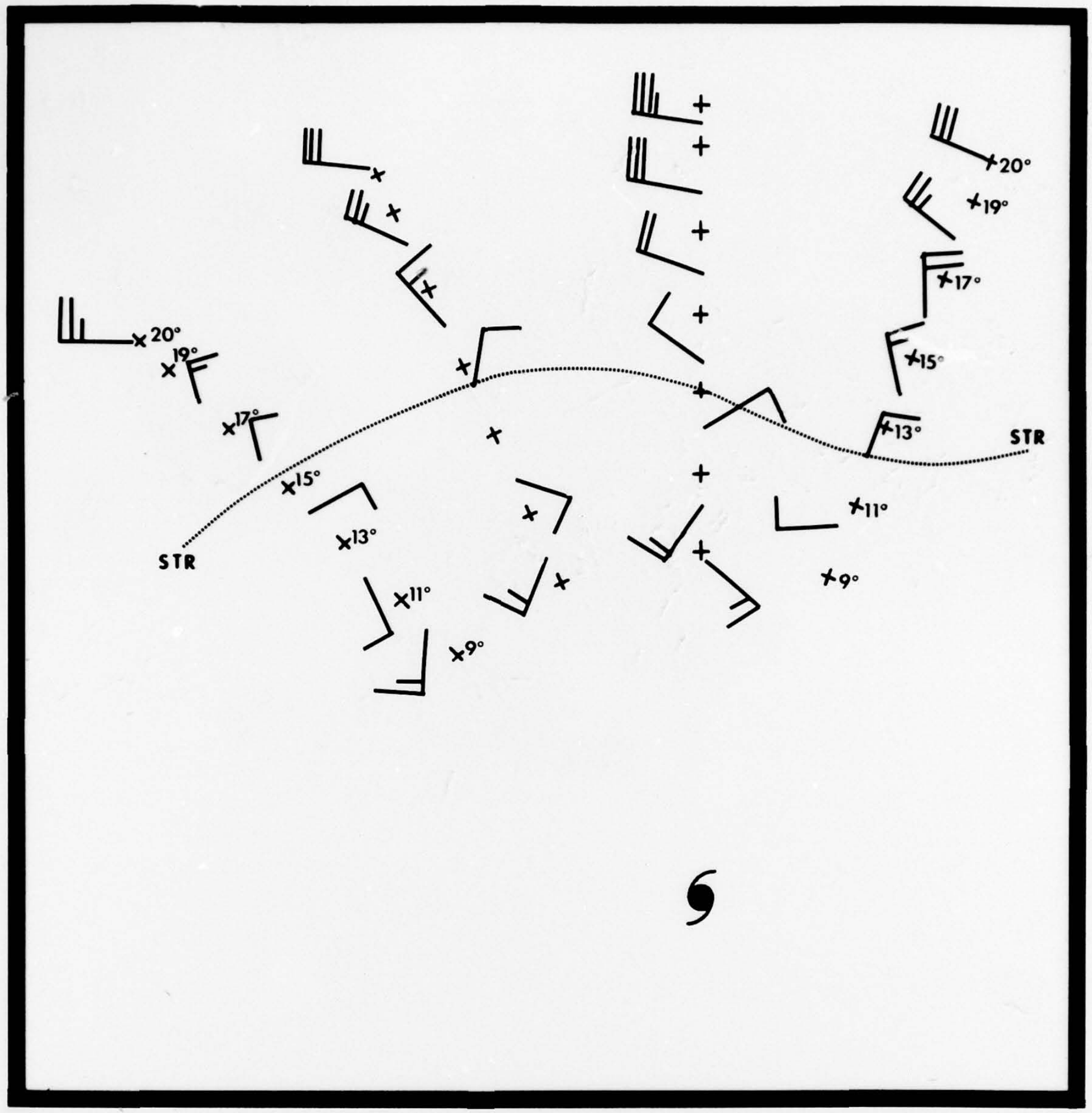


FIGURE 12. NR2 wind field; STR is the axis of the sub-tropical ridge; wind barbs are in knots.

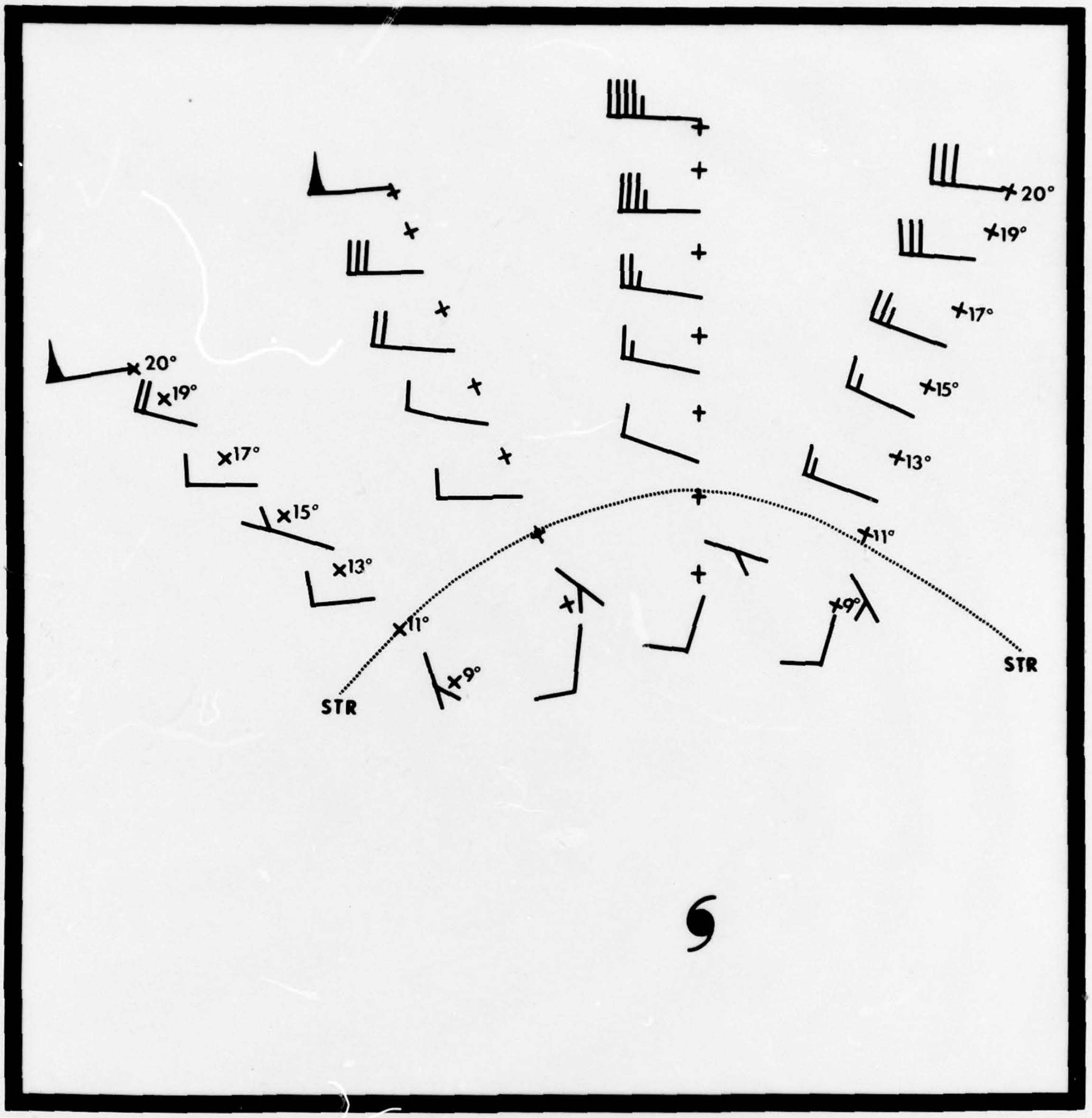


FIGURE 13. NR1 wind field; STR is the axis of the subtropical ridge; wind barbs are in knots.

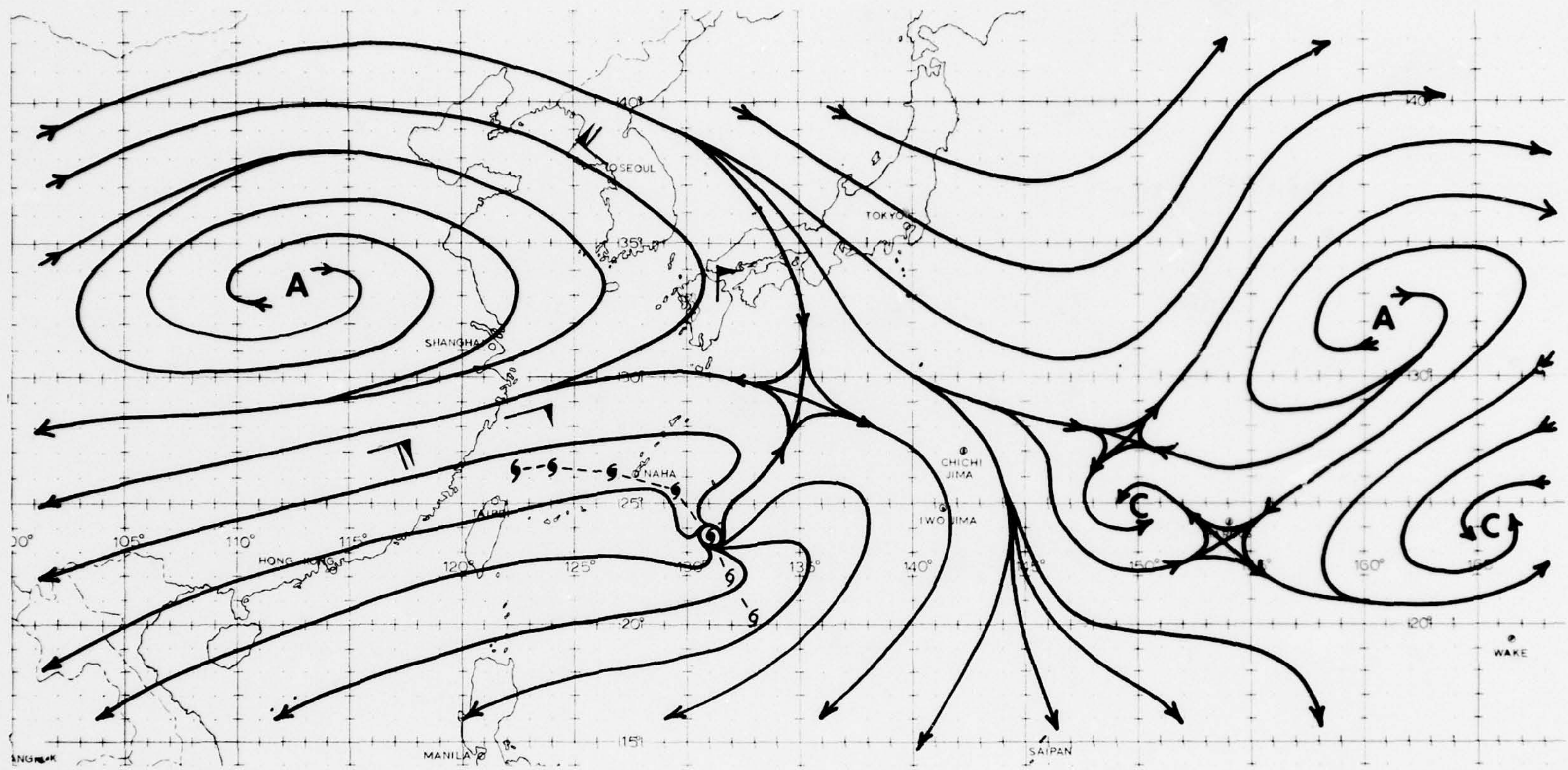


FIGURE 14. 200 mb streamline analysis illustrating a non-recurvature situation during an SR. Dashed line shows past (tropical storm symbol) and future (typhoon symbol) movement of tropical cyclone. Wind barbs are in knots.

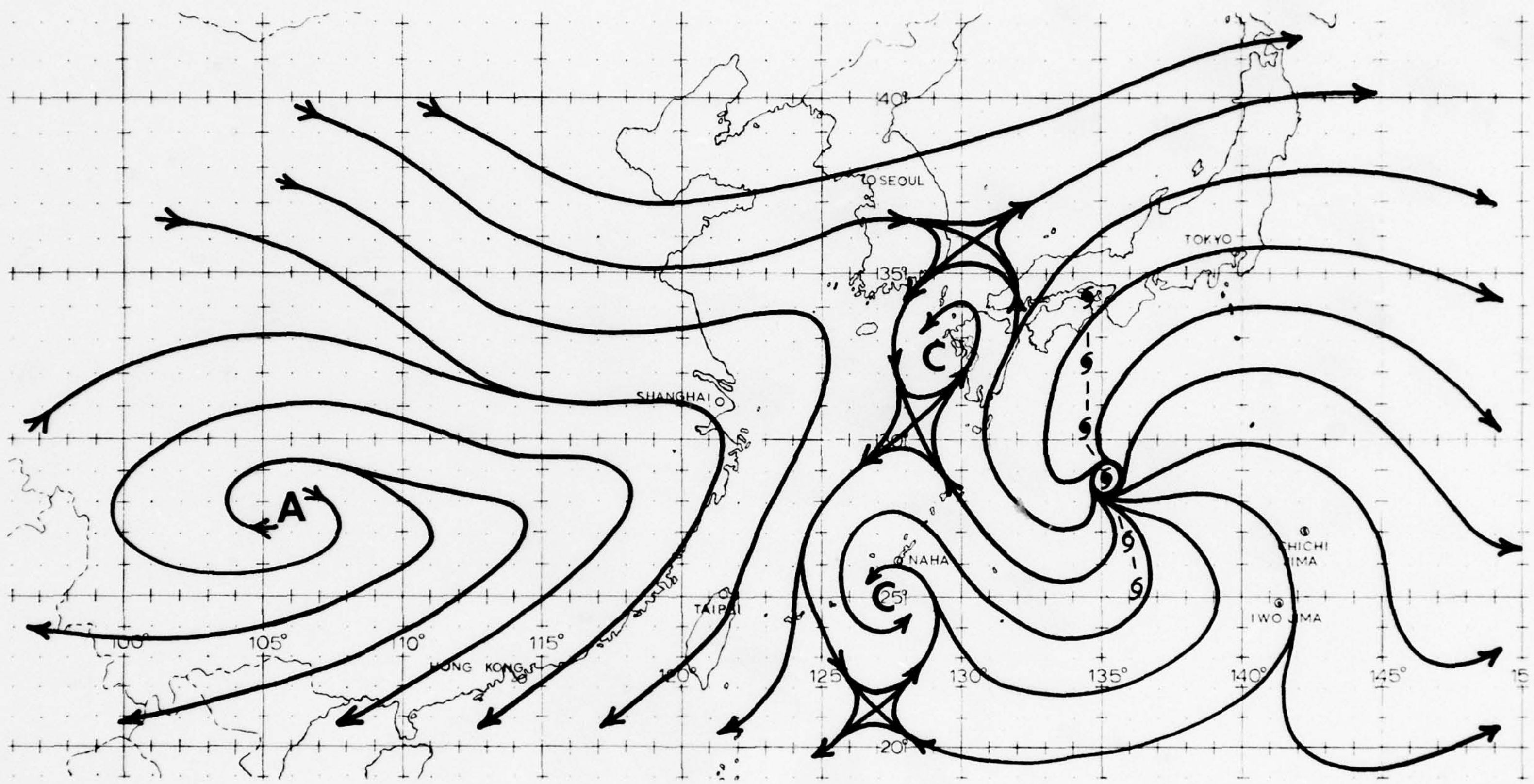


FIGURE 15. 200 mb streamline analysis of synoptic situation dictating northward movement of SR tropical cyclones. Dashed line shows past (tropical storm symbols) and future (typhoon symbols) cyclone movement.

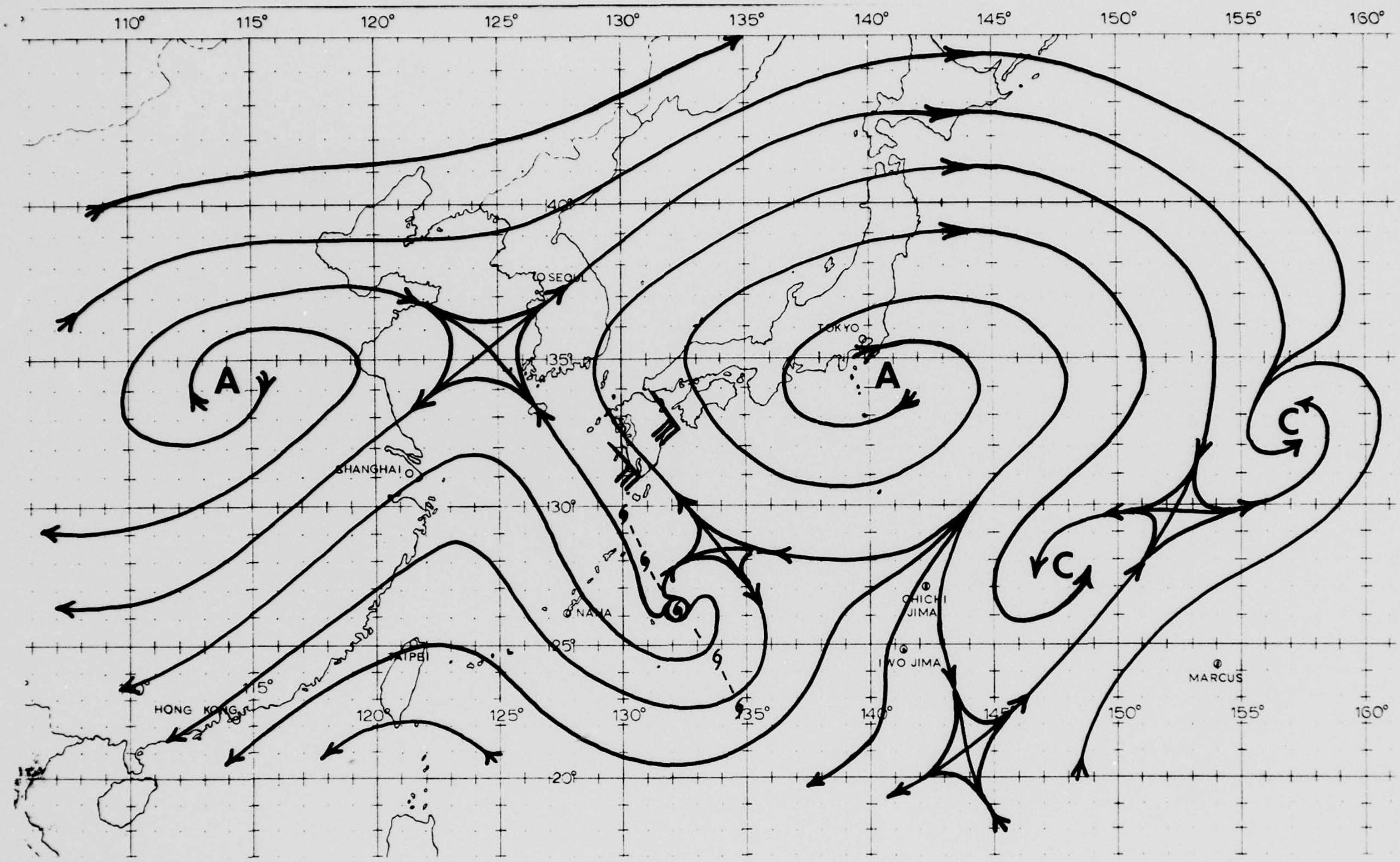


Figure 16. 200 mb streamline analysis depicting a synoptic condition under which an SR tropical cyclone would move toward recurvature. Dashed line shows past (tropical storm symbols) and future (typhoon symbols) cyclone movement. Wind barbs are in knots.

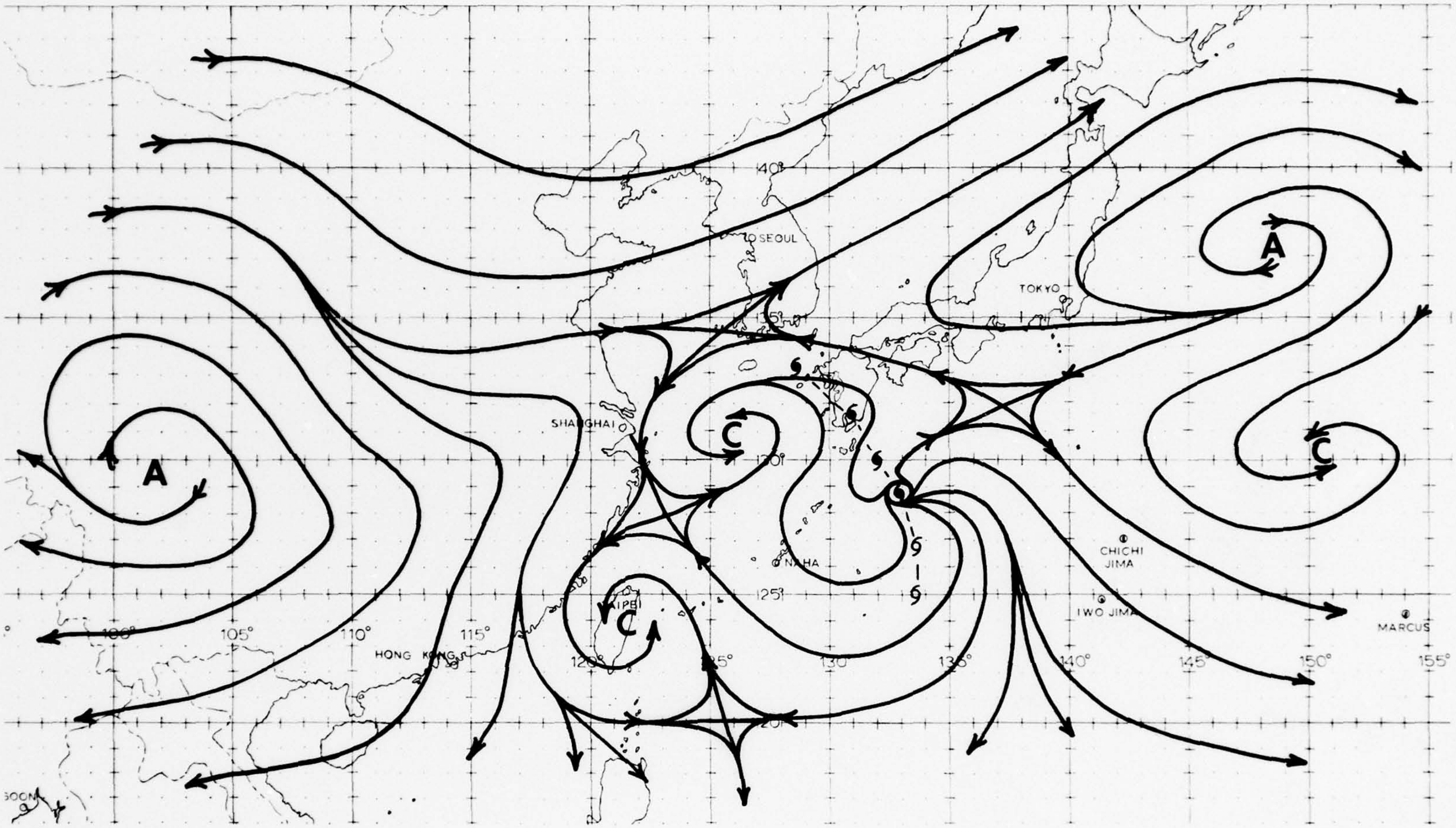


Figure 17. 200 mb streamline analysis depicting a synoptic situation under which a northward moving SR tropical cyclone would acquire a more westward component of movement. Dashed lines show the past (tropical storm symbols) and future (typhoon symbols) movement of the tropical cyclone.

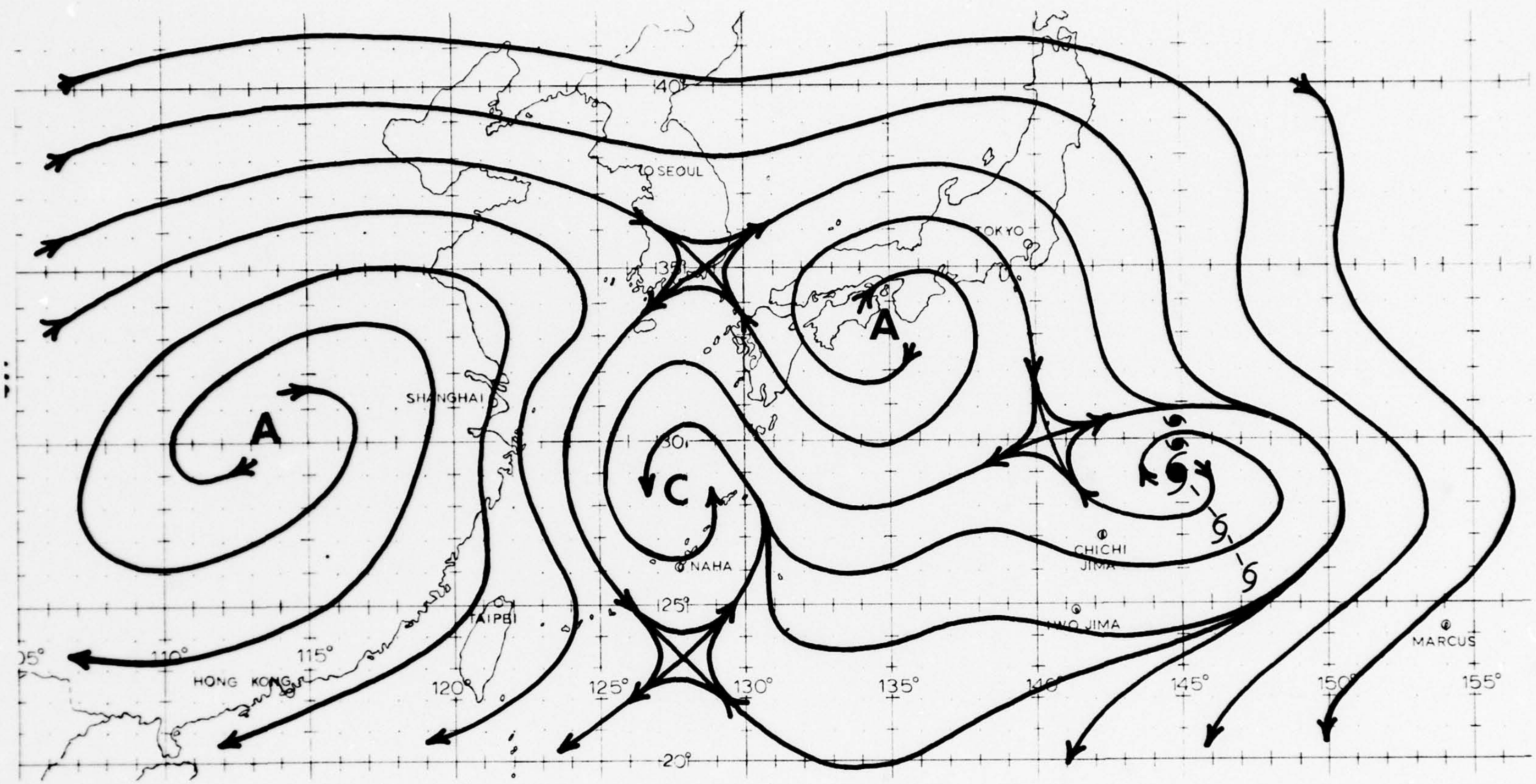


Figure 18. 200 mb streamline analysis illustrating a synoptic situation conducive to reducing an SR tropical cyclone's northward component of motion. Tropical storm symbols indicate past cyclone movement and typhoon symbols indicate future cyclone movement.

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## REPORT DOCUMENTATION PAGE

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5. TYPE OF REPORT & PERIOD COVERED: TECH NOTE (1974-1976)
6. PERFORMING ORG. REPORT NUMBER:
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8. CONTRACT OR GRANT NUMBER(s):
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TROPICAL UPPER TROPOSPHERIC TROUGH (TUTT)
TYPHOON MOVEMENT (cont'd)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

In his paper, Tropical Cyclone Motion and Surrounding Parameter Relationships, John E. George demonstrates the relationship between various 200 mb wind fields and recurvature/non-recurvature. Evaluation of the wind fields with data independent of George's study indicated that significant modification of his study was required to produce an operationally applicable recurvature/non-recurvature study. Synoptic analysis revealed two distinct environments affecting tropical cyclones, a Winter Regime and a Summer Regime. All tropical cyclones were stratified accordingly. By integrating the results ~~(cont'd)~~ CONT

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BLOCK 19. (cont'd)

SUBTROPICAL RIDGE

BLOCK 20. (cont'd)

CONT'

of the evaluation with results from rigorous synoptic and statistical analyses, operationally applicable recurvature/non-recurvature techniques were developed for, both, Winter Regime and the Summer Regime tropical cyclones.