Naval Research Laboratory
Monterey, CA 93943-5502

NRL/PU/7541--95-0010

Tropical Cyclone Forecasters Reference Guide
4. Tropical Cyclone Motion

C. R. Sampson, Editor
LT R. A. Jeffries, USN

Forecast Support Branch
Marine Meteorology Division

C. J. Neumann

Science Applications International Corp.
Monterey, CA 93940

October 1995

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. Agency Use Only *(Leave blank).*

2. Report Date.
October 1995

3. Report Type and Dates Covered.
Final

4. Title and Subtitle.
Tropical Cyclone Forecasters Reference Guide
4. Tropical Cyclone Motion

5. Funding Numbers.
PE 0603207N
PN X1596
AN DN153235

6. Author(s).
C.R. Sampson (NRL), editor
LT R.A. Jeffries, USN
C.J. Neumann (SAIC)

7. Performing Organization Name(s) and Address(es).
Naval Research Laboratory, Marine Meteorology Division
Monterey, CA 93943-5502
Science Applications International Corp., Monterey CA 93940

8. Performing Organization Report Number.
NRL/PU/7541--95-0010

9. Sponsoring/Monitoring Agency Name(s) and Address(es).
Space and Naval Warfare Systems Command (PMW-175)
Washington, DC 20363-5100

10. Sponsoring/Monitoring Agency Report Number.

11. Supplementary Notes.
LT Jeffries was assigned to NRL MMD as a research officer.

12a. Distribution/Availability Statement.
Approved for public release; distribution unlimited.

12b. Distribution Code.

13. Abstract *(Maximum 200 words).*
One of the keys to safe and successful naval operations in the tropics is an understanding of tropical meteorology. The Tropical Cyclone Forecasters Reference Guide is designed primarily as a ready reference for weather forecasters required to provide tropical meteorology support to staff commanders. This report provides an overview of tropical cyclone motion forecasting and is Chapter 4 of the reference guide. Subjects discussed include operational forecasting procedures, synoptic pattern recognition, and tropical cyclone track climatology.

14. Subject Terms.
Tropical cyclone motion
Tropical cyclone forecast aids
Tropical cyclone track climatology

15. Number of Pages.
121

16. Price Code.

17. Security Classification of Report.	18. Security Classification of This Page.	19. Security Classification of Abstract.	20. Limitation of Abstract.
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	Same as report

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

TABLE OF CONTENTS

ACKNOWLEDGEMENTS

This project is sponsored by the Oceanographer of the Navy through the Space and Naval Warfare Systems Command Program Office, Program Element 0603207N. The authors wish to thank Dr. Jan-Hwa Chu, Mr. Stephen Bishop and Ms. Winona Carlisle of the Naval Research Laboratory, Rich Courtney of Fleet Numerical Meteorology and Oceanography Center and Ronald Englebretson and Eleanor Estes of SAIC for their contributions.

TROPICAL CYCLONE FORECASTERS REFERENCE GUIDE

4. TROPICAL CYCLONE MOTION

Introduction

One of the most challenging problems of tropical cyclone forecasting 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 200 nm at 24 hours, 400 nm at 48 hours, and 800 nm at 72 hours. Large errors can be costly, both in lives and dollars, and also expand the range of errors, causing the average error to be higher than the most frequently occurring (modal) error and less meaningful to 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 (Guard, 1977).

1. INFLUENCES ON TROPICAL CYCLONE MOTION

Tropical cyclone motion is the result of a complex interaction between a number of internal and external influences. Environmental steering is typically the most prominent external influence on a tropical cyclone, accounting for as much as 70 to 90 percent of the motion (Neumann, 1992). Theoretical studies have shown that in the absence of environmental steering, tropical cyclones move poleward and westward due to internal influences (Elsberry et al, 1987).

1.1 Environmental Steering

The dominant influence on tropical cyclone movement is the environmental steering. Determination of the environmental steering for a given tropical cyclone is not easy. Many different levels and layers have been proposed for use and there is some difficulty in deciding which level or layer is best for a given storm.

Environmental steering is usually computed by separating the tropical cyclone winds from the environmental winds. The separation of flow is anywhere from 1-7° radially from the tropical cyclone center (Fig. 4.1). The winds on the outside of the separation are used for determining environmental steering and are commonly named the steering flow. In this section, several useful

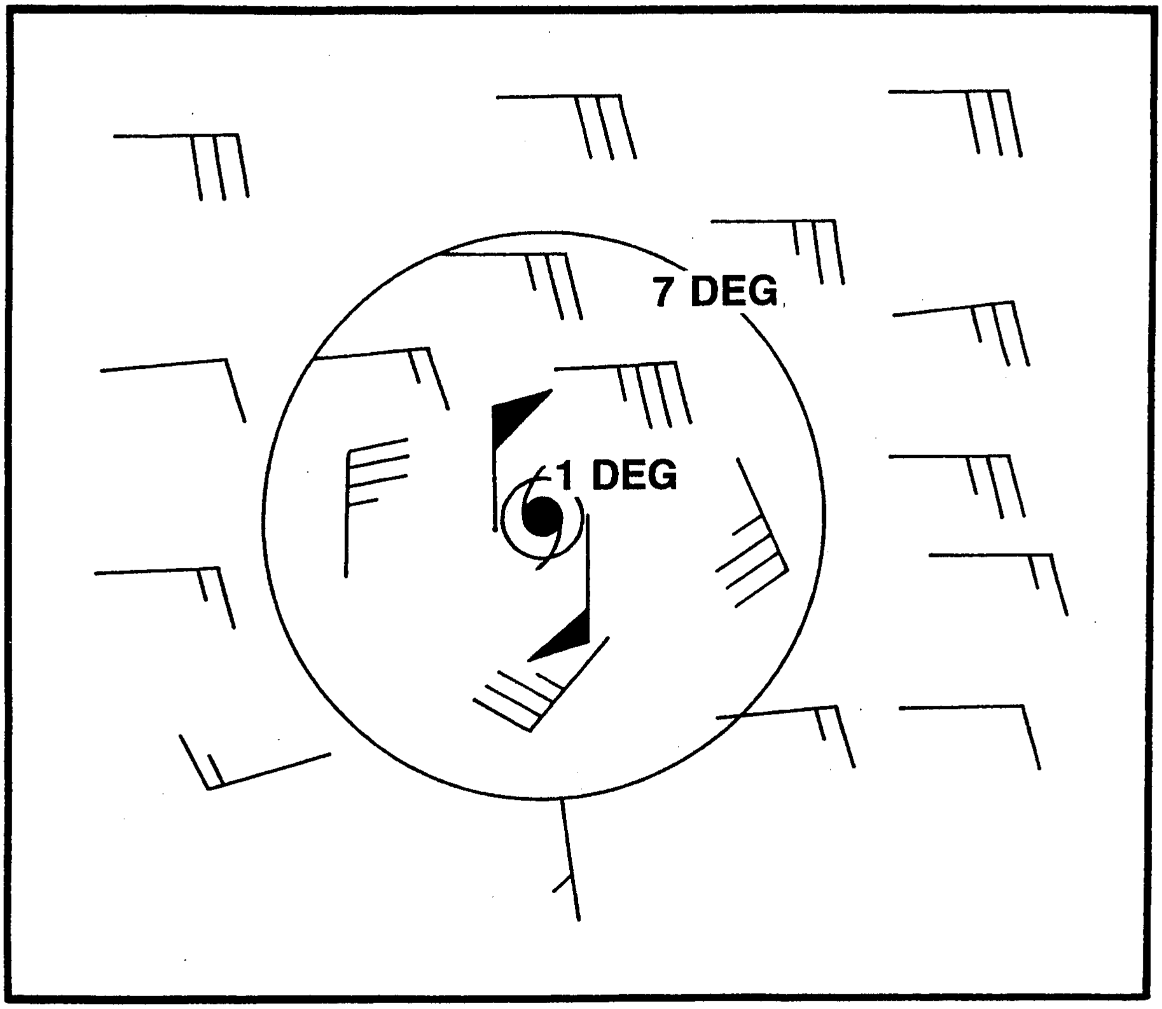


Figure 4.1. Schematic showing tropical cyclone imbedded in steering flow. Separation of tropical cyclone and environment is usually anywhere from 1-7 degrees radially from tropical cyclone center.

concepts for determining steering are discussed. One of the complicating factors in determining steering is analysis uncertainty near a tropical cyclone vortex. Because of this, some models such as JTWC92 (Neumann, 1992) make use of what is referred to as implied steering. Here, more conservative predictors (geopotential heights at rather large distances from the storm center (up to 15 degrees of latitude) are used to infer geostrophic steering flow. For example, for tropical cyclones located in the deep tropics, the intensity of the poleward subtropical ridge line, which is typically located about 600 nm poleward of the tropical cyclone, is used by these models to estimate the steering flow near the storm itself. This procedure might be considered to be a satisfactory operational trade-off between the desire to measure actual steering and the uncertainty of the analysis near the tropical cyclone.

1.1.1 Steering Level Determination

The first step in computing environmental steering is determining a level to use. Generally, more intense storms extend higher in the troposphere and have higher steering levels (Dong and Neumann, 1986). Figure 4.2 demonstrates how the steering level can change through intensification.

a. **Deep Layer Mean** - Although early studies concentrated on different pressure levels for determining environmental steering (George and Gray, 1976; Brand et al., 1981), recent studies show that layer averages appear to be better suited to the task (Sanders et al., 1980; Chan and Gray, 1982; Dong and Neumann, 1986). Neumann (1979) tested a number of functions as to their ability to explain the variance of Atlantic tropical cyclone motion. He found that the Sanders and Burpee (1968) pressure weighted wind function also provided for the maximum variance reduction when applied to the height fields. The deep layer mean specified by Neumann,

$$D = (75*D1 + 150*D2 + 175*D3 + 150*D4 + 100*D5 +75*D6 + 50*D7 + 50*D8 + 50*D9 + 25*D10)/900$$

where D1 through D10 are the heights (or winds) at the 1000, 850, 700, 500, 300, 250, 200, 150, and 100 mb level, respectively, is used by Fleet Numerical Meteorological Oceanography Center (FNMOC), Monterey, CA.

b. **Shallow Layer or Single Level Steering Flow** - There are times when shallow layer or single level steering flow is superior to the DLM steering. The following is general guidance for which layer or levels to use for steering.

1) When in doubt, use the 10-level deep-layer-mean. Not having a DLM or other information on the storm, the 500 mb level is the best single level from which to estimate future motion.

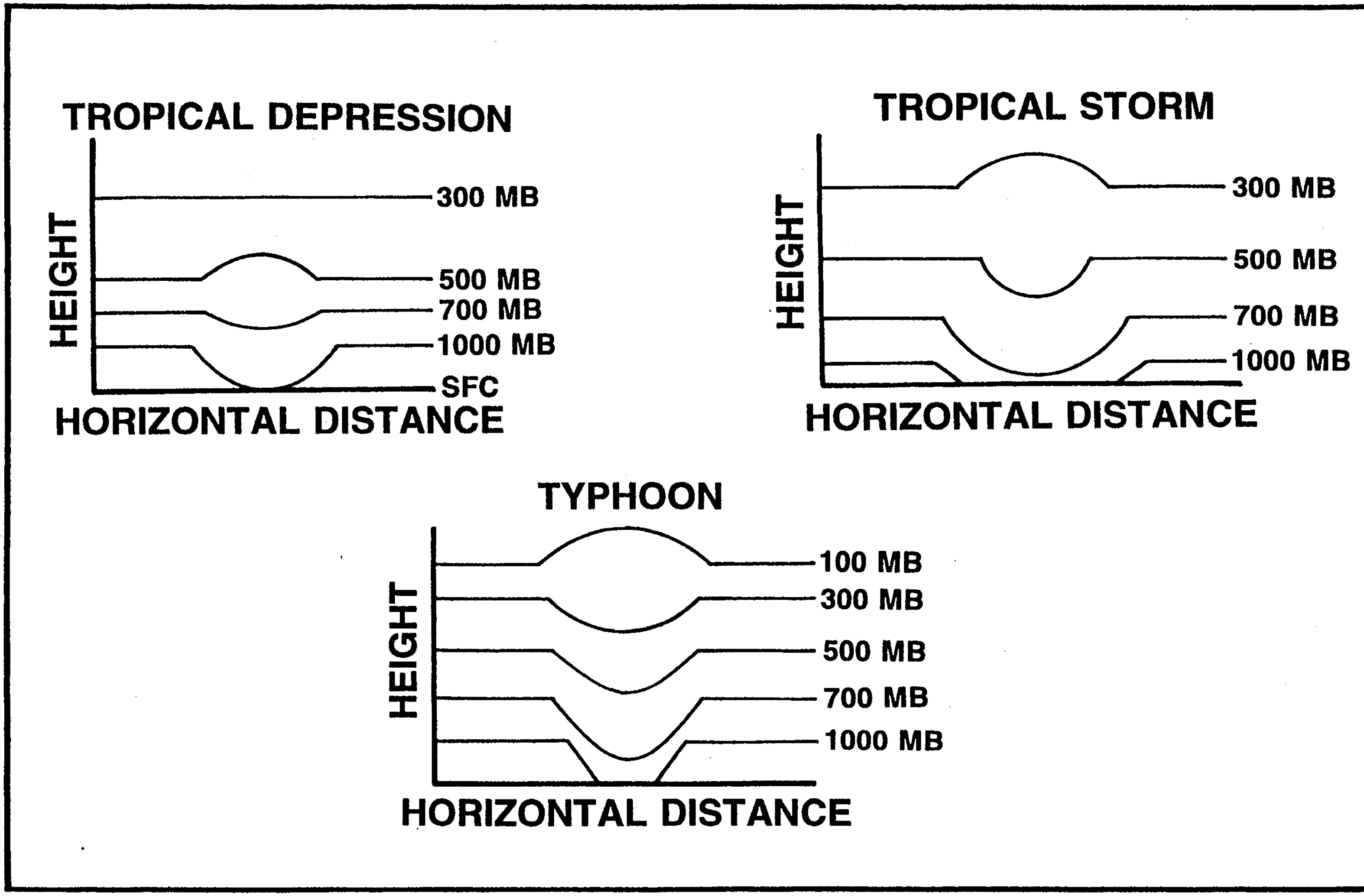


Figure 4.2. Idealized vertical cross sections of a tropical cyclone as it develops. As the cyclone intensifies, the vertical depth increases and the tropical cyclone steering level increases.

2) Be aware, particularly for large storms, that inflow at 1000 mb and outflow at 100 mb might distort the steering flow. However, these layers are not weighted very heavily in the DLM computation.

3) Weak storms are steered by a shallow layer which can be estimated by using the 700 mb alone.

4) For storms embedded in a sheared environment, the lower portion of the storm tends to follow the low-level flow and the upper portion of the storm tends to follow the upper circulation and storm weakening is typical. Thus, since the "eye" is associated with the lower level circulation, it is better to use 850 or 700 mb.

5) For very large storms, interactions between the storm and the environment make it difficult to define a steering flow even with the availability of a DLM.

1.2 Internal Influences

Large scale environmental forcing (steering) typically explains most of the tropical cyclone motion variance and smaller scale internal influences are sometimes masked by the larger scale pattern. However, when the steering flow is small, these internal influences might be the dominant factor(s) moving the storm.

1.2.1 <u>The Beta Effect</u>

The beta effect ($B-\frac{\partial f}{\partial y}$) reflects the variation of the Coriolis force with latitude. The effect (which acts in a westward and poleward direction) causes tropical cyclone motion to deviate from a path determined by environmental steering alone. The effect for Northern Hemisphere tropical cyclones is that storms embedded in the easterlies south of the subtropical ridge move faster and slightly to the right of the steering flow, storms moving northwest tend to move faster and to the left of the steering flow, storms moving northeastward tend to move slower and to the left of the steering flow (Elsberry et al., 1987).

The beta effect is a function of the size, but not necessarily the intensity of a storm (DeMaria, 1985). When the storm size is small and the steering flow is moderate to strong (e.g., 15 knots or 7.7m/s), the direction of motion reflects the direction of the steering flow. When the storm size is large, the beta effect may have a major impact on the motion.

1.2.2 <u>Storm Winds Affecting Steering</u>

Large storms have strong winds out to 5-7° radially that could affect steering flow computations. Super Typhoon Abby (1983) was large enough (a 30 knot wind radius of over 350 nm or 650 km) that storm winds were included in steering flow computations (Chan, 1986). There is evidence that the steering flow concept may not be as applicable in large storms (such as Abby) as it is for smaller storms.

1.2.3 <u>Eye Wobble</u>

Since the advent of looped geostationary satellite imagery it has been noted that the eye of a tropical cyclone sometimes moves relative to the apparent center of mass of the tropical cyclone. This wobble is usually less than the eye diameter, but can result in erroneous determinations of the current storm motion if the tropical cyclone is tracked from center fix to center fix.

Sheets (1985) suggests tracking the mass field envelope of the tropical cyclone rather than the eye. The mass field envelope is defined as an area of high winds surrounding the center of the tropical cyclone and is best determined by reconnaissance aircraft flying through the storm. Tracking the mass field envelope eliminates the effect of eye wobble on the track.

Another technique is the best track method (Fig. 4.3). This method uses subjective weighting of various types of fixes to determine motion trends over a 24 hour period.

Forecast agencies (e.g., Joint Typhoon Warning Center and National Hurricane Center) typically try to eliminate eye wobble and suspected fix errors from official tracks. This is why the official track position is typically in conflict with fix positions.

2. TROPICAL CYCLONE MOTION TERMINOLOGY

Many terms are used to describe a tropical cyclone's motion and its synoptic environment. The following list of definitions, although not exhaustive, provides a baseline of tropical cyclone motion terminology.

2.1 Straight Moving Tropical Cyclones

As shown in Figure 4.4, non-recurving or straight moving tropical cyclones track approximately 260-320 degrees throughout their lifetimes (Hodanish, 1991). These tropical cyclones are typically embedded in the deep easterly flow equatorward of a well established subtropical anticyclone.

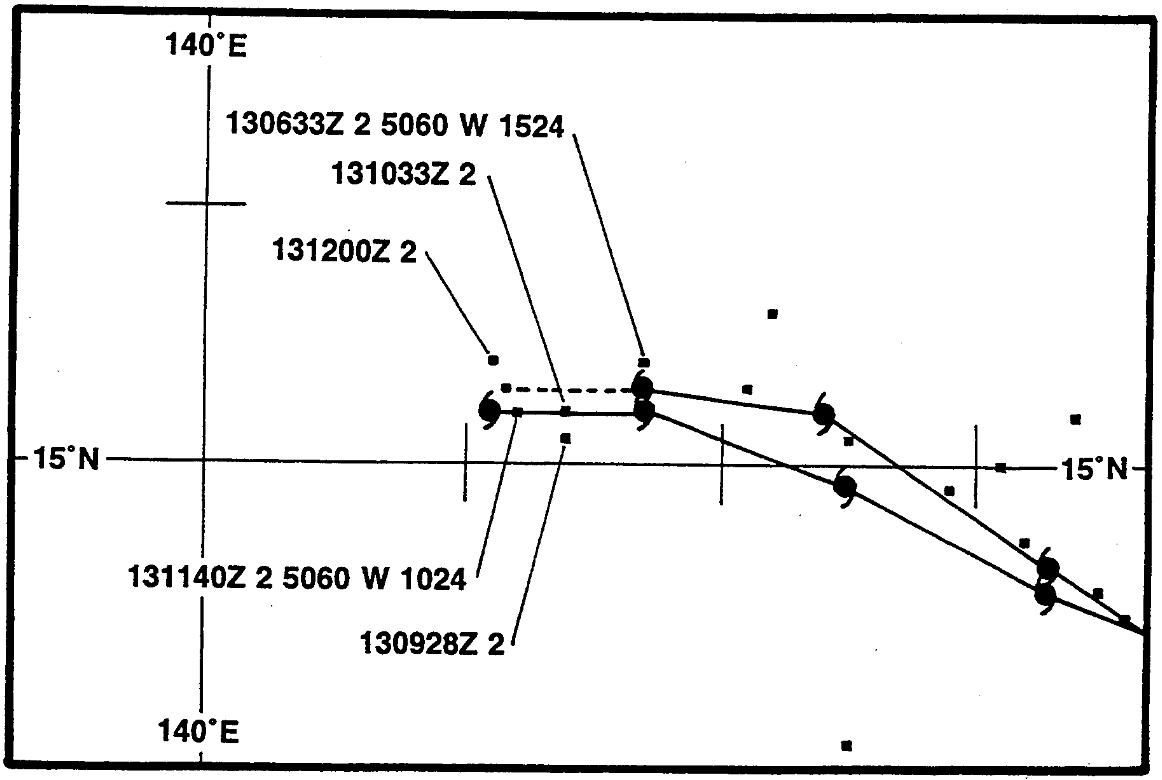


Figure 4.3. Example of a tropical cyclone best track in the South China Sea. The line of the connected circles illustrates an objective best track generated by the Automated Tropical Cyclone Forecast System (ATCF). The diamond symbols with highlighted date/time groups denote the fixes used for constructing a best track.

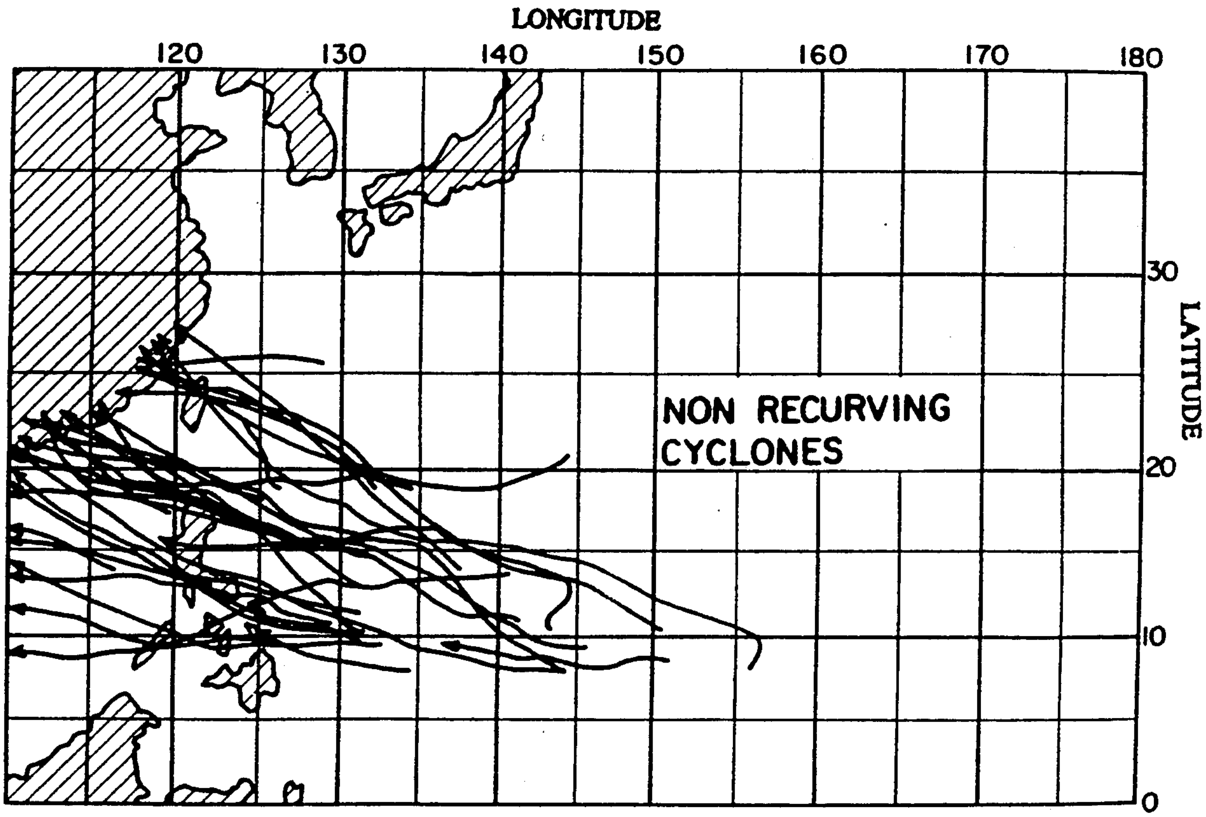


Figure 4.4. The tracks of approximately 28 nonrecurving tropical cyclones (Hodanish, 1991).

2.2 Recurving Tropical Cyclones

Recurvature is defined as poleward movement of a tropical cyclone from the deep easterlies of the tropics into the strong upper level westerlies of the mid-latitudes. This motion is generally associated with tropical cyclones that move westward and poleward around the western portion of the subtropical ridge and then turn poleward and eastward under the influence of the mid-latitude westerlies. Recurving tropical cyclones can be further classified with respect to how rapidly they recurve.

a. **Sharply Recurving Cyclones** - Sharply recurving cyclones are those which change rapidly from a westerly or northwesterly course to a northeasterly or easterly one (Fig. 4.5).

b. **Slowly Recurving Cyclones** - Slowly recurving cyclones are those which change slowly from a westerly or northwesterly course to a northeasterly or easterly one (Fig. 4.5). The term broad recurvature is also used for these tracks.

2.3 Left (NH)/Right (SH) Turning Tropical Cyclones

A left (northern hemisphere)/right (southern hemisphere) turning tropical cyclone is one which is on a poleward course but instead of continuing to recurve poleward and eastward, it turns back to the left/right and resumes a poleward and westward course (Fig. 4.5).

A **stair-step** occurs when a tropical cyclone embedded in the mean flow associated with the subtropical ridge moves poleward for a short period of time then resumes a westward track. Stair-steps have been observed to occur as weak shortwave troughs transit along the poleward side of the subtropical ridge.

2.4 Erratic Moving Tropical Cyclones

Erratic moving or looping tropical cyclones are storms that move at speeds less than three knots and have significant changes in direction over short periods of time. These significant changes in storm direction are at times characterized by looping or circular direction changes (Fig. 4.5).

2.5 Equatorward of the Ridge

Tropical cyclones moving in this environment are embedded in the deep easterlies equatorward of the latitude of the subtropical ridge line (Fig. 4.6). These storms typically track west-northwestward (NH)/west-southwestward (SH).

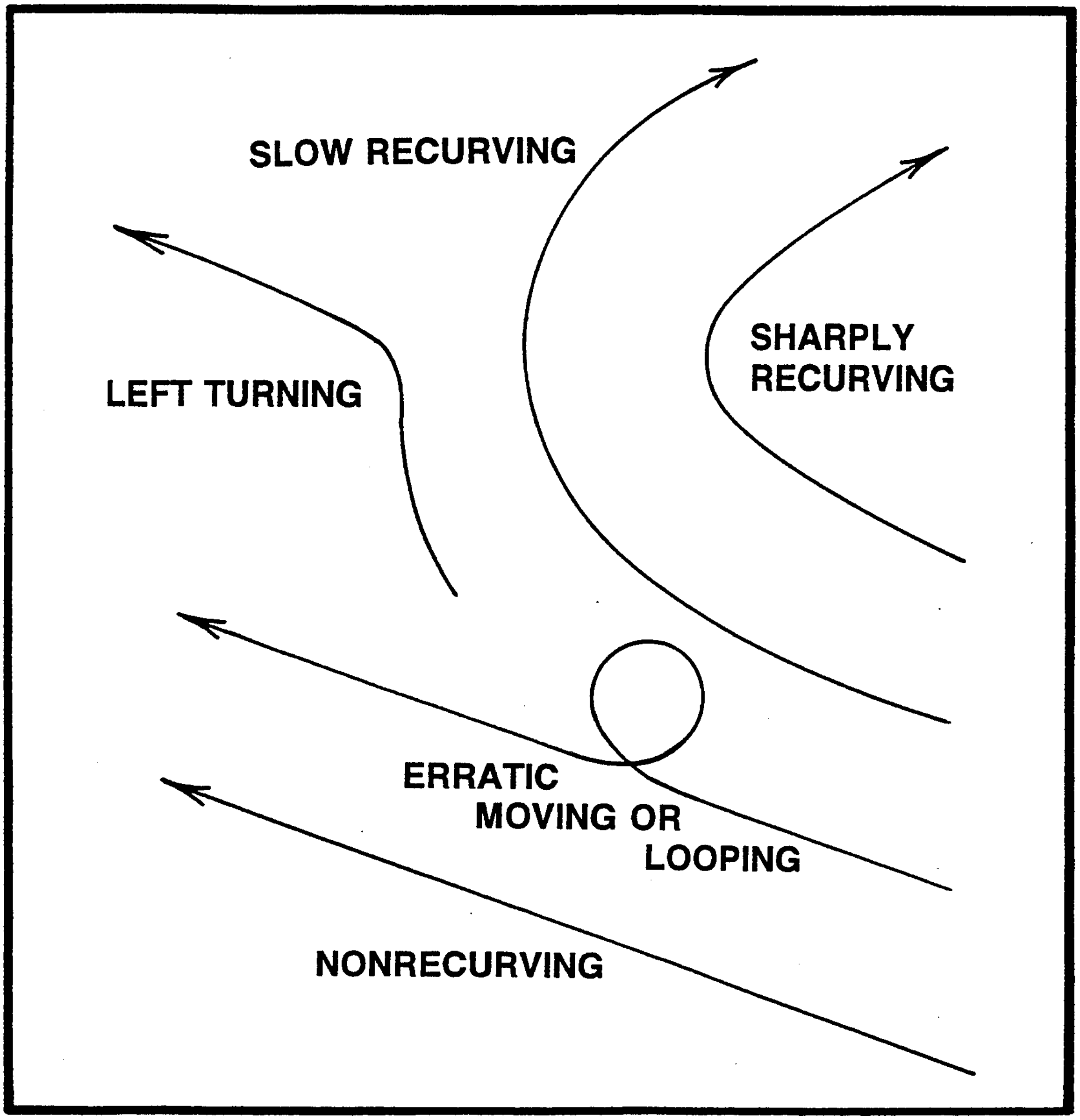


Figure 4.5. Five types of tropical cyclone tracks.

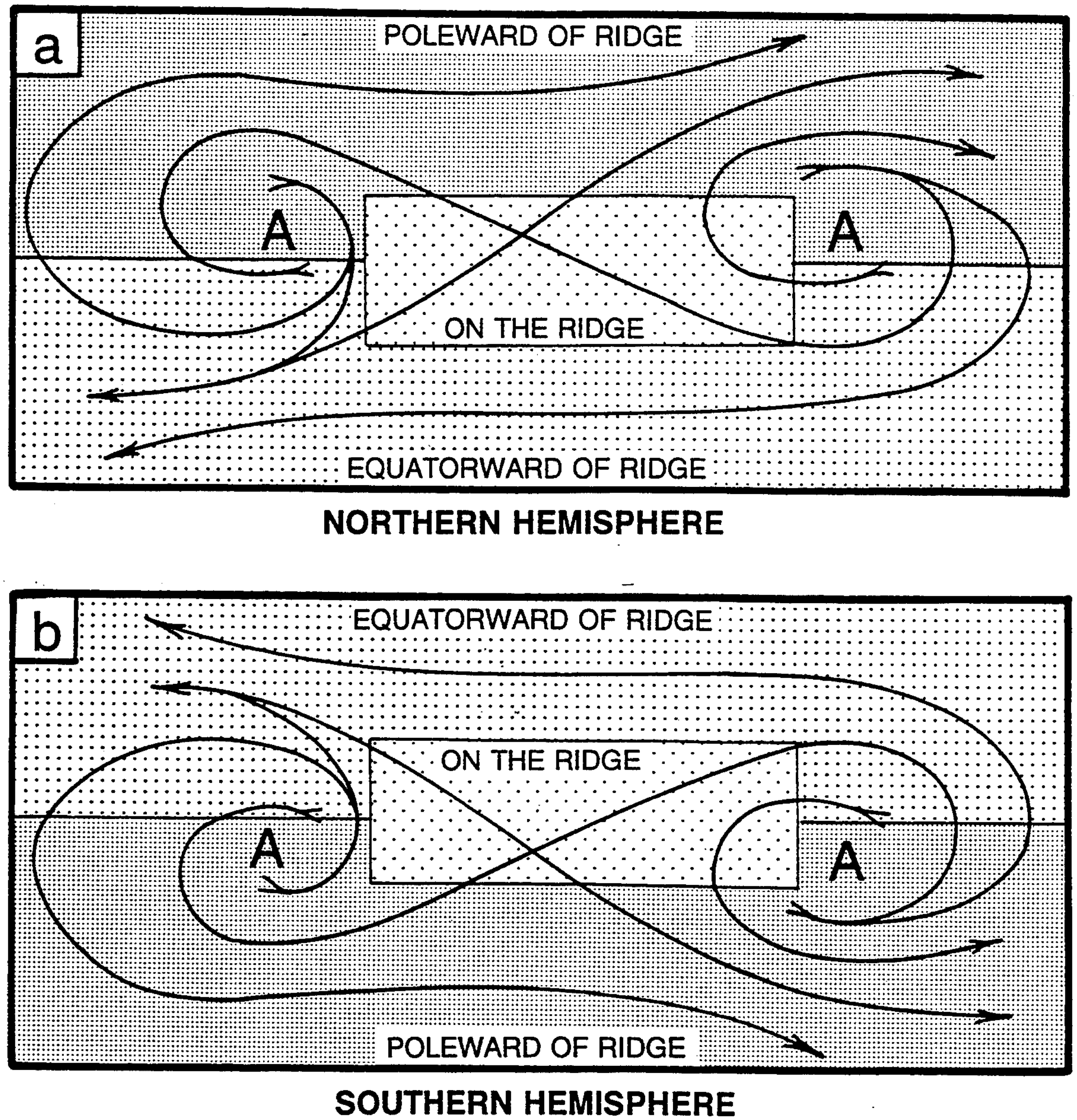


Figure 4.6. Schematic diagram depicting synoptic regions. Hatched boxes define the areas usually associated with the terms poleward of the ridge, on the ridge, and equatorward of the ridge.

2.6 On the Ridge

Tropical cyclones moving in this environment are embedded in the weak steering flow associated with breaks in the subtropical ridge (Fig. 4.6). These storms are typically located near the mean latitude of the subtropical ridge and move slowly in response to the weaker winds associated with the ridge line and breaks in the ridge. Erratic or looping motion is common in this environment.

2.7 Poleward of the Ridge

Tropical cyclones moving in this environment are embedded in the mid-latitude westerlies poleward of the mean latitude of the subtropical ridge (Fig. 4.6). These storms are typically accelerating under the influence of the westerlies.

2.8 Binary Interaction

Occasionally two tropical cyclones will come in close proximity (within about 10 degrees latitude) to one another and rotate about their geometric center. This type of interaction is often referred to as the Fujiwhara Effect.

3. MOTION FORECASTING TECHNIQUES

A significant amount of effort has been expended to develop pattern recognition techniques for motion forecasting. Many of these methods were developed for specific regions of the world and may not be applicable to other regions. These methods are subjective in nature and hence it is difficult to evaluate their utility. In spite of this, a few of these methods are described in this section.

3.1 Slow or Looping Versus Fast Moving Tropical Cyclones

Key features of idealized 500 mb and corresponding surface patterns for slow or looping versus fast moving tropical cyclones have been compiled for the western North Pacific and Atlantic oceans (Xu and Gray, 1982). The idealized 500 mb and corresponding surface patterns are shown, in schematic format, in Figures 4.7 and 4.8. Rules determined from the key features schematics are:

a. **Looping or Slow Motion** - Looping or slow tropical cyclone movement is associated with a large amplitude 500 mb trough to the northeast (about 20-30 degrees of longitude) of the tropical cyclone. The higher the latitude, the further east the trough is relative to the looping storm.

b. **Fast Motion** - A trough west (10-20 degrees of longitude) of a recurving tropical cyclone is associated with fast tropical cyclone movement. Tropical cyclones which are equatorward of a well-defined subtropical ridge experience fast westward movement.

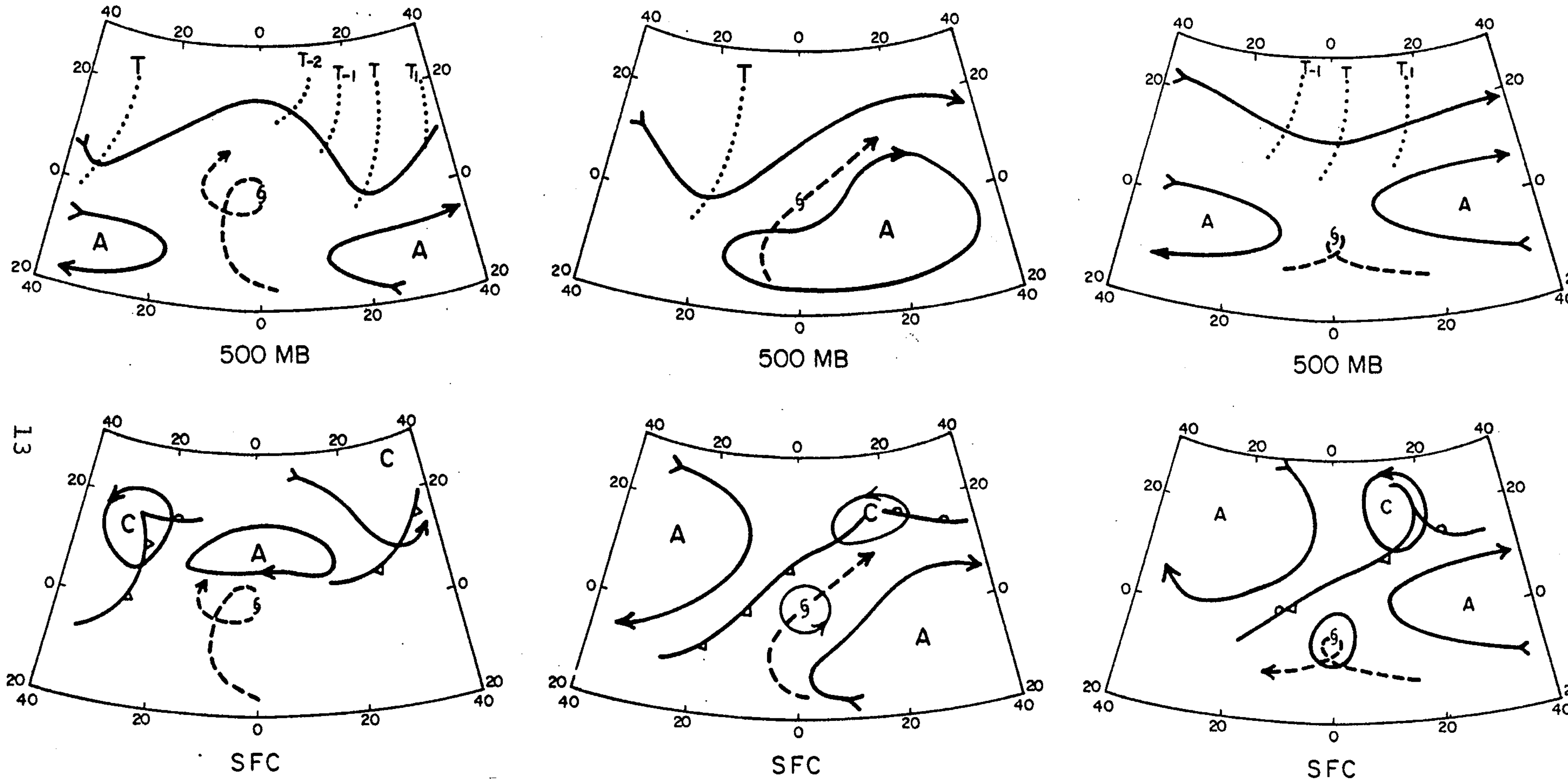


Figure 4.7. Idealized 500 mb pattern (above) and corresponding surface pattern (below) depicting the type of motion predicted. (After Xu and Gray, 1982).

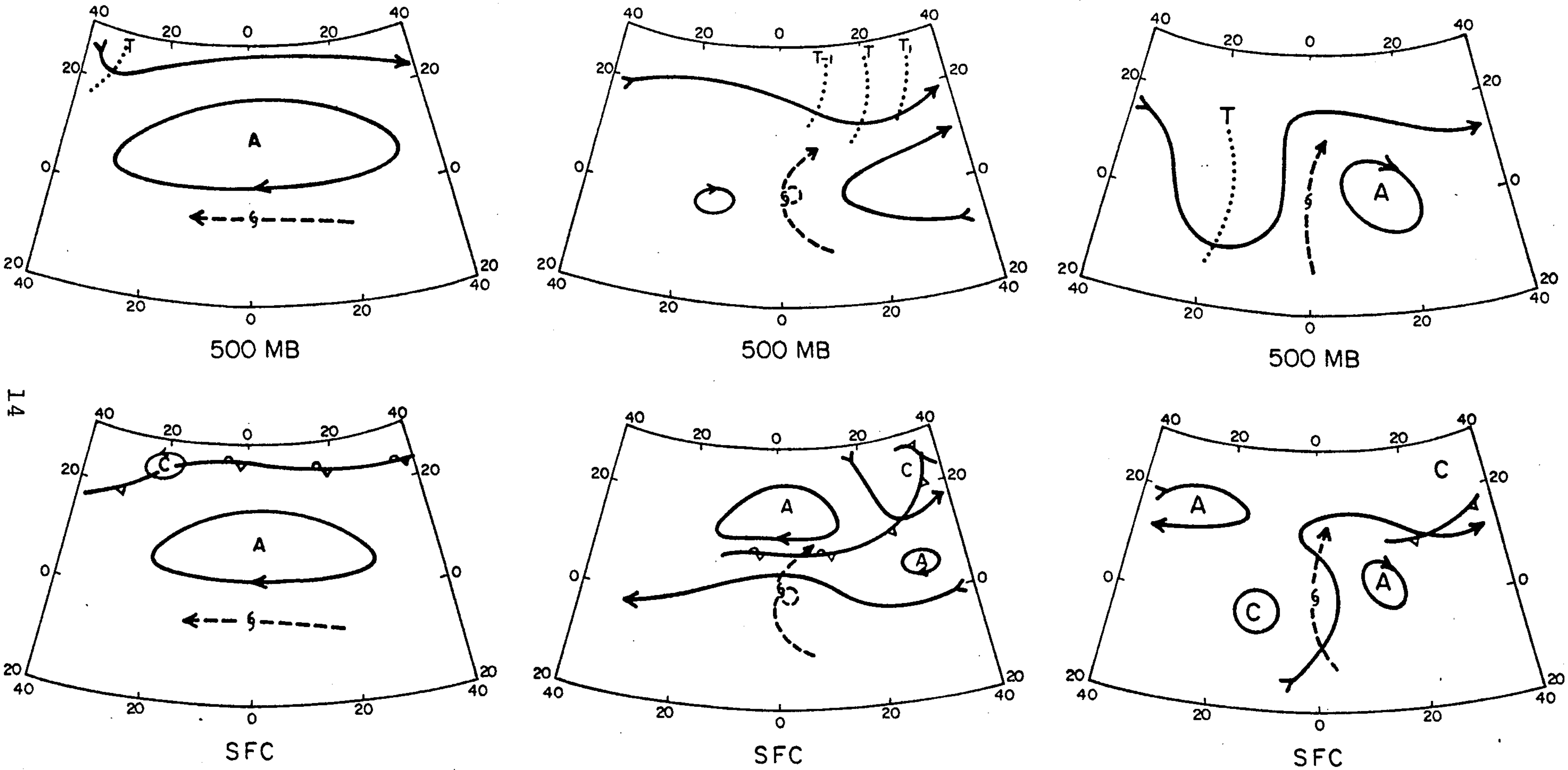


Figure 4.8. Idealized 500 mb pattern (above) and corresponding surface pattern (below) depicting the type of motion predicted. (After Xu and Gray, 1982)

3.2 Recurvature Decisions Based on 200 mb Charts

Composites for recurving and non-recurving tropical cyclones were developed for the western North Pacific using 200 mb synoptic wind patterns by George and Gray (1976). Generally, when strong westerly winds (greater than 50 knots or 25 m/s) are seen within 20 degrees of latitude north of the storm, the storm is forecast to recurve. If the winds are weak or easterly, recurvature will not occur. A modification of these rules has been done in which storms are stratified by season and region (Guard, 1977). The modifications were done based on evaluation against an independent set of tropical cyclone data. Appendix A is an abridged version of this technique. One advantage to using the 200 mb level is that data are more plentiful than at the mid-levels. One disadvantage is that storm motion is better correlated with deep layer mean or mid-level steering flow.

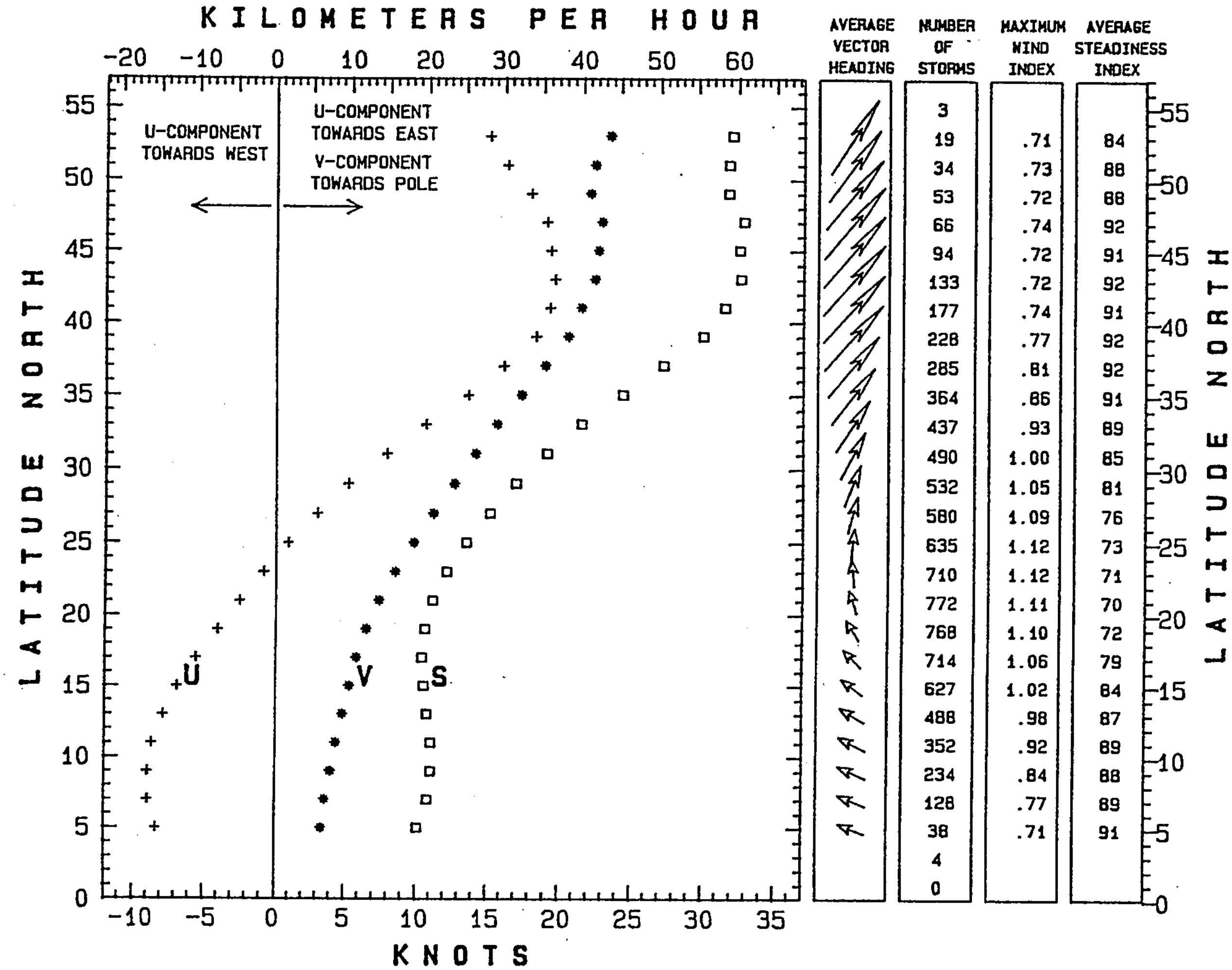
3.3 Acceleration Prediction

Tropical cyclone forecast errors are based on the distance between a forecast storm position and the later observed position. Therefore, for a given directional error, storms with higher translational speeds can expect higher forecast error. This is reflected in forecast error statistics.

Failure to anticipate the acceleration will yield even higher forecast errors and this has been a long-standing problem associated with recurving storms. In the fear of observing large forecast errors, forecasters are reluctant to accelerate storm motion.

In Figure 4.9, it can be noted that equatorward of about 24N, the average motion of tropical cyclones is rather constant. Although short-period accelerations do occur in connection with synoptic-scale surges in the trade-wind circulation, these are fairly short lived. Unanticipated accelerations at these latitudes are typically not associated with large forecast error. It can also be noted in the figure that most tropical cyclones are within these latitudes. Accordingly, forecasters become conditioned to the lower translational speeds associated with low-latitude storms.

Poleward of 25N, however, the acceleration of tropical cyclones is quite marked. Even with a reasonably good direction forecast, large along-track errors can result. For example, Table 4.1 gives the 48h forecast errors for the Western Pacific CLIPER model used at JTWC (WPCLPR). To illustrate the effect of increasing storm latitude (translational speed), this simple model, in a non-operational mode, was activated on all storms over the period 1946 through 1993. Although best-track input data were used, errors were normalized to operational WPCLIPR errors (247 nm) over the five-year period 1988-1992.



NUMBER OF STORMS	MAXIMUM WIND INDEX	AVERAGE STEADINESS INDEX
3		
19	.71	84
34	.73	88
53	.72	88
66	.74	92
94	.72	91
133	.72	92
177	.74	91
228	.77	92
285	.81	92
364	.86	91
437	.93	89
490	1.00	85
532	1.05	81
580	1.09	76
635	1.12	73
710	1.12	71
772	1.11	70
768	1.10	72
714	1.06	79
627	1.02	84
488	.98	87
352	.92	89
234	.84	88
128	.77	89
38	.71	91
4		
0		

Figure 4.9. Meridional profiles of zonal (u), scalar (s) storm speeds and of other specified parameters for the Western North Pacific basin, 1946 through 1993. For each tropical storm or typhoon, a single average value was calculated for each 2-degree latitudinal zone. Arrows give average vector storm direction with lengths proportional to storm speed. Maximum wind index is defined relative to an average overall wind index of 1.0. Steadiness index is a measure of motion change over successive 12h intervals where highest/lowest values are indicative of very steady/very unsteady motion. Latitudinal averages were not computed if number of tropical cyclones passing through band was less than 10. (Neumann, 1993)

In Table 4.1, it can be noted that WPCLPR forecast errors continually increase in going from south to north. Errors at 40N are about double those at 15N, with the largest rate of increase being near 40N. These large errors are caused by the rapidly increasing translational speeds as depicted in Figure 4.9. Thus, even a model such as WPCLPR, where the accelerations are known to the model, is subject to larger forecast errors due mainly to the higher translational speeds.

Table 4.1 Estimated Western Pacific CLIPER (WPCLPR) operational 48h forecast errors (nautical miles) over the 48-year period 1946 through 1993. Best-track error for the all-zones category was 223 nautical miles.

Latitude band	Number of cases	Error	% error increase from that of lower latitude band
10N (<12.5N)	1490	195	
15N (12.5 to 17.4N)	3437	204	4.6
20N (17.5 to 22.4N)	4429	215	5.4
25N (22.5 to 27.4N)	3278	238	9.7
30N (27.5 to 32.4N)	2345	273	14.7
35N (32.5 to 37.4N)	1371	316	15.8
40N (37.5 to 42.4N)	697	410	29.7
45N (42.5 to 47.4N)	323	504	22.9
50N (> 47.5N)	146	583	15.7
All zones	17546	247	

It can be shown that the errors of any motion prediction model or of the official operational forecast, although typically averaging less than CLIPER errors, exhibit a similar poleward error gradient. Thus, higher forecast errors associated with poleward moving storms are typical of any model. However, as mentioned earlier in this section, failure to anticipate these accelerations can result in even larger errors.

In an effort to minimize large forecast errors associated with tropical cyclones entering the westerlies, the TAPT forecast technique was developed. This 200 mb pattern-typing technique, developed for the western North Pacific tropical cyclones, gives an assessment of the magnitude and duration of accelerations associated with northward moving tropical cyclones that enter the mid-latitudes. An abridged version of this technique is provided in Appendix B.

3.4 **Satellite Image Interpretation**

Interpretation of storm related cloud features can infer short 12- to 24-hour motion of tropical cyclones. Changes in the direction of movement of the tropical cyclone have been correlated with rotational changes in the storm's gross features (Fett and Brand, 1975). The angular rotation of the gross features during the past 24 hours is added to a 24-hour persistence forecast to yield the new 24-hour forecast. Examples of gross features and rotated gross features are shown in Figure 4.10. This method was developed and tested for western North Pacific tropical cyclones, but similar methods were developed for other regions.

Lajoie and Nicholls (1974) developed a method which uses a cloud model (Fig. 4.11) and the following rules to help discern 12-hour direction of motion in the Australian region:

o A storm will not continue to move, nor curve in a direction towards a cumulonimbus-free sector; if it is moving towards such a sector, it will curve rapidly away from that direction.

o A storm having a single outer cloud band will move or curve within twelve hours of picture time towards a line joining the present position of the vortex center to the present position of the most developed cumulonimbus cluster at or near the downstream end of the outer cloud band,

o When a storm has two outer cloud bands and at or just prior to picture time is moving generally towards the most developed cumulonimbus cluster near the downstream end of one outer cloud band, it will curve within twelve hours of picture time towards a line joining the present position of the vortex center to the present position of the most developed cumulonimbus cluster near the downstream end of the other outer cloud band.

Note: The Lajoie and Nicholls method apparently gives good results in the Australian region, but requires satellite image interpretation skills and a tropical cyclone in which features shown in Figure 4.11 are visible.

3.5 A Systematic Approach to Tropical Cyclone Forecasting

A brief overview of a recently developed systematic approach to tropical cyclone forecasting in the western North Pacific region is presented in Appendix C. This systematic approach provides the forecaster with a track forecast methodology that combines traditional concepts with the latest dynamical insights into how tropical cyclones interact with their environment and thus affect their track. This approach was tested by JTWC forecasters during the latter half of the 1994 typhoon season.

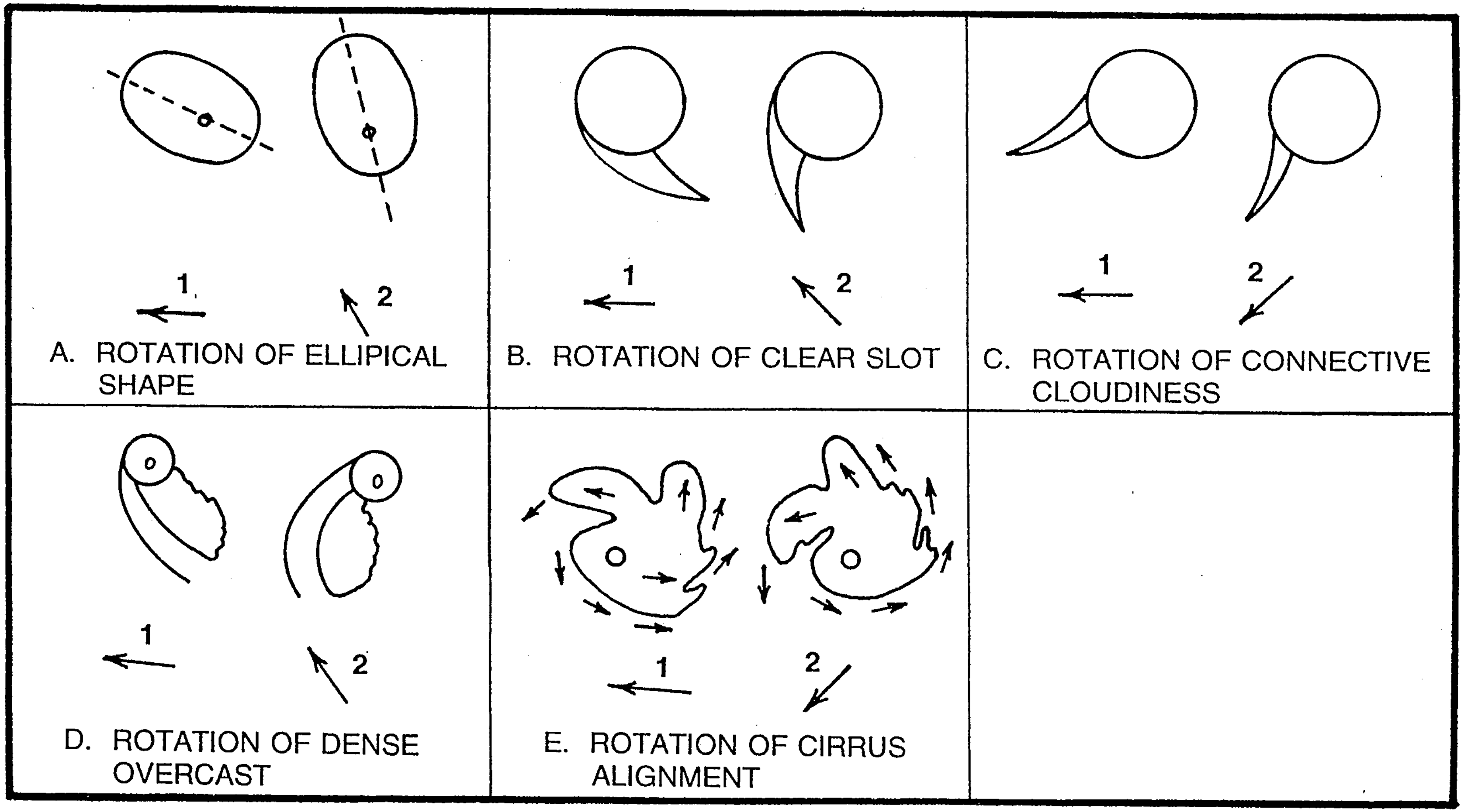


Figure 4.10. Characteristic changes in cloud patterns associated with directional changes of motion of tropical cyclones. Arrow 1 gives the mean 24 hour direction between the two pictures while arrow 2 gives the mean direction over the next 24 hours. (After Fett and Brand, 1975)

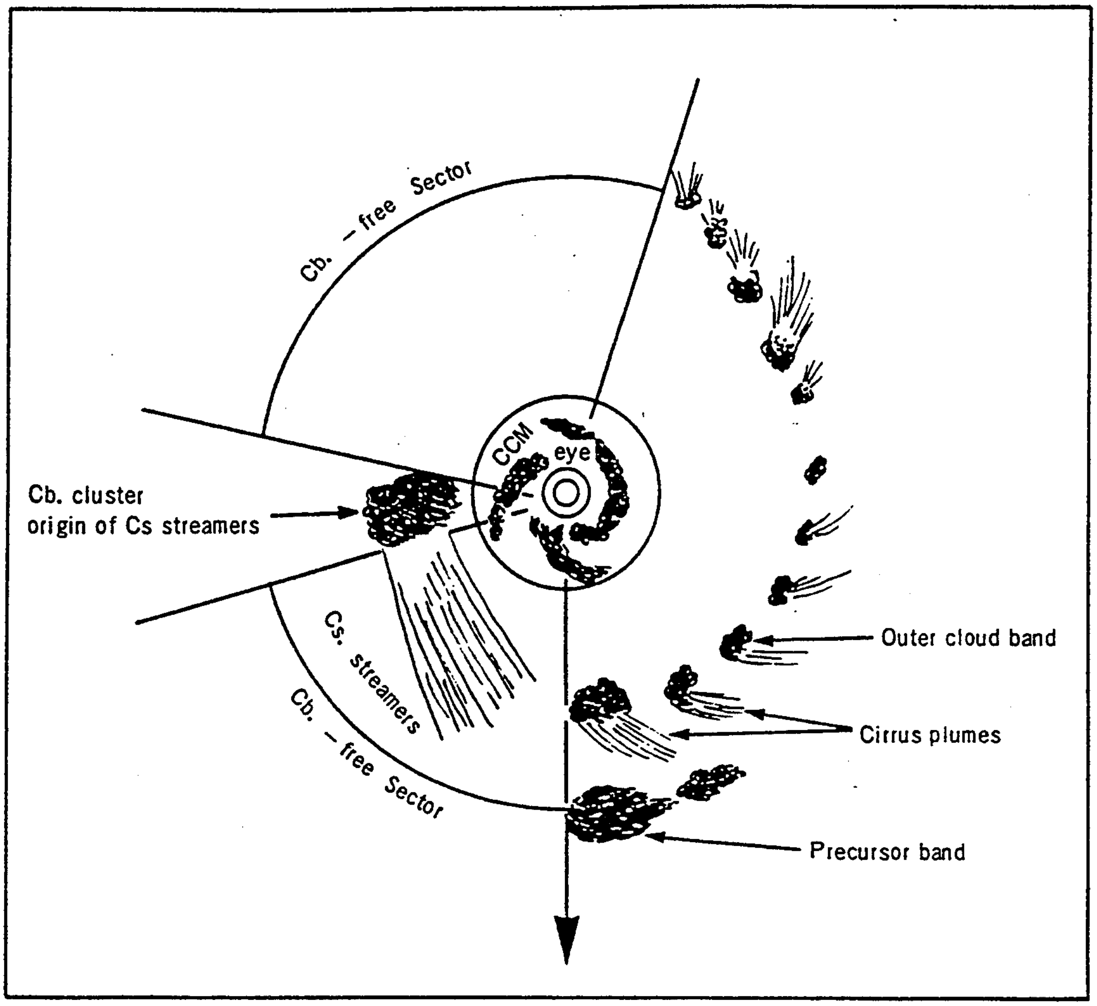


Figure 4.11. Lajoie and Nicholls' (1974) model of the cloud structure of a tropical cyclone. The principal features are: a) the central cloud mass (CCM), diameter 100 to 200 km, which changes configuration with time and from one picture to the next; b) one or two outer cloud-bands, separate from the CCM, with cumulonimbi more developed at the downstream end (pattern remains unchanged for several hours); c) pre-cursor bank (downstream end occurs along the same outward radius as that of the outer cloudbank); d) one or more cirrostratus streamers; e) a cumulonimbus free sector.

4. OPERATIONAL TROPICAL CYCLONE MOTION FORECASTING

Operational tropical cyclone motion forecasting is a complex forecast problem. However, if a procedural approach is applied to the forecast problem, it becomes a manageable task. The following material provides outlines of current (1993-94) forecast procedures at two operational centers and suggested guidelines for use by single stations and ships at sea.

4.1 JTWC Motion Forecasting Procedures

The Joint Typhoon Warning Center (JTWC) develops a tropical cyclone motion forecast in three phases: Field analysis, objective techniques analysis, and forecasting (Guard, et al., 1992).

4.1.1 **Field Analysis Phase**

The Navy Operational Global Atmospheric Prediction System (NOGAPS) analyses and prognoses at various levels are evaluated for position, development, and movement of not only the tropical cyclone, but also relevant synoptic features such as: 1) subtropical ridge, 2) mid-latitude troughs and associated weaknesses in the subtropical ridge, 3) monsoon surges, 4) influences of cyclonic cells in the Tropical Upper Tropospheric Trough (TUTT), and 5) other tropical cyclones. This process permits the Typhoon Duty Officer (TDO) to develop an initial impression of the environmental steering influences to which the tropical cyclone is and will be subjected as depicted by NOGAPS. The NOGAPS analyses are then compared to the hand-plotted and analyzed charts prepared by the TDO and to the latest satellite imagery in order to evaluate NOGAPS initialization. Finally, the TDO compares both the analysis and forecast charts with climatological charts. Noting latitudinal and longitudinal displacements of the subtropical ridge and long-wave mid-latitude features, the TDO tries to determine the degree to which the current situation reflects the climatological one.

4.1.2 Objective Techniques Analysis Phase

After displaying the latest set of forecasts given by JTWC's suite of objective techniques, the TDO evaluates the pattern produced by the set of forecasts according to the following principles. First, the degree to which the current situation is considered to be and will continue to be climatological is further refined by comparing the forecasts of the climatology-based objective techniques, dynamically-based techniques, and past motion of the present storm. This assessment partially determines the relative weighting given the different classes of objective techniques. Second, the spread of the pattern determined by the set of objective forecasts is used to provide a measure of the predictability of subsequent motion, and the advisability of including a low or moderate probability alternate forecast scenario in the prognostic reasoning message or warning. The spread of the objective techniques pattern is typically small well-before and/or well-after recurvature (providing high forecast confidence) and large near recurvature or during a quasi-stationary or erratic movement phase (increasing the likelihood of alternate scenarios).

4.1.3 Construct Forecast Phase

The TDO then constructs the JTWC official forecast giving due consideration to the following: 1) extent to which the synoptic situation is and is expected to remain climatological, 2) past statistical performance of the various objective techniques on the current storm, and 3) known properties of individual objective techniques given the present synoptic situation. The following general guidelines are applied:

o Give strong weight to persistence in the first 12 to 24 hours of the forecast period.

o Give significant weight to the last JTWC forecast at all forecast times, unless there is significant evidence to warrant a departure. (Also utilize latest forecasts from other regional warning centers, if applicable.)

o Give more weight to techniques which have been performing well on the current tropical cyclone and/or are expected to perform well in the current and expected synoptic situations.

o Stay within the "envelope" determined by the spread of objective techniques forecasts unless there is a very good reason for not doing so (e.g., all objective forecasts start out at a significant angle relative to past motion of the tropical cyclone).

4.2 NHC Motion Forecasting Procedures

The tropical cyclone track and intensity forecast procedures used at the National Hurricane Center (NHC), reported by Sheets (1990), are not too dissimilar from those used at JTWC. Guidance is received from a number of numerical and statistical models activated mainly at the National Meteorological Center (NMC), NHC, the NOAA Hurricane Research Division and a few other supporting agencies. Also, there is a considerable amount of coordination with other NWS and military offices. The final forecast is based on a subjective and objective evaluation of all available information. As at JTWC, satellite data and products derived therefrom are an important source of data.

One of the main differences between procedures at the two forecast centers is that NHC conducts a large amount of discourse with civil defense and news agencies. Also, aircraft reconnaissance is utilized for storms threatening or potentially threatening populated land masses.

4.2.1 Environmental Analyses Phase

The primary current environmental guidance results from specialized analyses conducted at NHC. These include standard hemispheric synoptic and subsynoptic scale meteorological analyses at the surface and standard pressure levels and predictions of synoptic and subsynoptic scale features derived from global, hemispheric and regional models from the NMC and the European Centre for Medium-Range Weather Forecasts (ECMWF). More specialized analyses performed at NHC include the previously mentioned 200 mb analysis, the analysis of the tropical oceanic lower layer (ATOLL) streamline and isotach analyses over the tropical and subtropical belts of the North Atlantic and eastern North Pacific ocean regions. These analyses take advantage of low-level and upper-level cloud drift winds derived from geosynchronous satellites in combination with aircraft reports and standard upper-air soundings. Other analyses include low-level, upper-level and deep-layer mean flow as well as vertical shear analysis of the horizontal wind, and time cross sections from selected upper-air stations from the west African coast westward through the Caribbean and Central America.

In addition to the above analyses, current animated satellite imagery is analyzed for qualitative assessments of flow pattern changes. Special emphasis is placed upon animated water vapor imagery for regions of moist and dry flow. The primary guidance for predicted environmental conditions is obtained from the NMC package of global, hemispheric and regional models with secondary guidance from ECMWF and the United Kingdom Meteorological Office (UKMO) models.

4.2.2 Tropical Cyclone Analyses

The next step involves detailed analyses of the tropical cyclone itself. These analyses involve all available satellite, reconnaissance aircraft, buoy, radar, etc., data and ship observations to determine the present and past motion, wind and pressure-field distributions, etc. This information is used as inputs to the numerical forecast aids.

4.2.3 Objective Aids Analysis

A package of five to seven tropical cyclone track forecast models are routinely run for each forecast cycle for both the Atlantic and eastern Pacific basins. In addition, two intensity forecast models (SHIFOR and SPIKE) are run for each case. All this information is used by the NHC hurricane specialist to arrive at a tropical cyclone track and intensity forecast for a period of 72 hours including wind-field distribution.

4.2.4 <u>Construct Forecast Phase</u>

NMC forecasters arrive at an independent track forecast primarily based upon NMC model guidance. Also, forecasters at NWS offices in areas that may be affected by the tropical cyclone sometimes arrive at their independent forecasts based on large scale guidance and local conditions. In addition, if the tropical cyclone is threatening a coastal region of the United States, the NHC uses the SLOSH model output for the appropriate basins and the expected tropical cyclone track and intensity. This may actually be a family of storm situations to account for uncertainties in the forecast.

4.3 Other Operational Centers

Tropical cyclone motion forecasts at other operational tropical cyclone forecast centers are produced in much the same way as JTWC and NHC forecasts are produced. Areas of responsibility for each of these forecast centers are discussed in Chapter 1.

4.4 Single Station Motion Forecasting Procedures

One of the most important tasks assigned to forecasters is providing recommendations to area and task force commanders who set conditions of readiness. In order to generate the recommendations, forecasters must assimilate a tremendous amount of data in a short period of time. One solution is to develop procedures for monitoring weather events. The following are suggested steps to monitor tropical cyclone forecasts affecting naval operations.

Step 1. <u>Pre-Deployment Tropical Cyclone Forecasting/Preparations</u>

Prior to any deployment involving passage through tropical cyclone regions, review the tropical cyclone motion climatology (see Appendix D) and conduct a pre-deployment briefing to the staff or on-scene commander. As a minimum, this briefing should include a monthly description of the tropical cyclone track climatology, a brief description of the forecast procedures from the responsible forecast center, the available typhoon havens (U.S. Navy, 1976 and 1982) and the tropical cyclone avoidance procedure described in the governing fleet operating instructions.

Step 2. <u>Past/Current Motion Analysis</u>

When a tropical cyclone develops or moves into the forecast area, plot the warning positions on a chronological series of analyses (e.g., NOGAPS Deep Layer Mean Analyses) starting at least 24 hours ago and concluding with the most current analysis. Analyze the synoptic environment (troughs, ridges, etc.) within 30 degrees latitude of the storm on each of the analyses. Try to identify synoptic features that influence the storm motion through the chronological series. Note changes in these synoptic features and how those changes appear to affect the storm motion. Synoptic features identified in this analysis could also influence motion over the next 72 hours.

Step 3. <u>Motion Forecast Verification</u>

In this phase of forecast preparation, the tropical cyclone motion forecast message is verified for accuracy and significant departures from previous forecasts. As a first step, plot the current forecast positions on the verifying prognostic charts from the numerical model (e.g., the NOGAPS 500 mb 48 hour prog), then note the movement of synoptic features identified during the previous step. An initial assessment of forecast confidence can now be made using Table 4.2 as a guide. (See Appendix C for discussion and schematic diagrams of the synoptic regions used in this table.)

Table 4.2 Tropical Cyclone Motion Forecast Confidence.

Synoptic Regions	**Motion Type**	**Forecast Confidence**
Dominant Subtropical Ridge	West-Northwestward Motion	High Confidence
Weakened Subtropical Ridge	Slow West-Northwestward Motion	Decreasing Confidence
Accelerating Mid-latitude Westerlies	Fast North-Northeastward Motion	High Confidence, Forecasts are Typically Slow
North Oriented	Slow Northward or Erratic Motion	Low Forecast Confidence
Multiple-TC Southerly Flow	Steady Northward Motion	Low Forecast Confidence
Multiple-TC Northerly Flow	Steady Northwestward Motion	Low Forecast Confidence

If a low confidence situation is identified, make an effort to understand the track forecast reasoning. A review of the prognostic discussions issued by the forecast center may provide enlightenment. For example, a forecast center may be in the process of changing from one primary forecast track scenario to another. This is usually a gradual process, completed over a few warning periods to avoid the windshield wiper effect (the switching back and forth between straight running and recurving forecast tracks resulting in a windshield wiper of variability of the forecast track guidance).

Step 4. Forecast Recommendations

Brief the current forecast track to the customer, but be sure that the customer is also informed of the errors associated with track forecasts and your confidence in the current forecast. Track forecasts issued by JTWC/NHC have mean errors of approximately 120/100 nm at 24 hours, 240/200 nm at 48 hours, and 360/300 nm at 72 hours. Other major forecast centers have comparable mean forecast errors. Consider these errors when making forecast recommendations to on-scene commanders. The following two paragraphs describe scenarios in which the mean forecast errors are applied to the forecast.

Ships operating in the 7th Fleet area must remain outside the 30 knot wind radius at all times. To meet this requirement, the ship must always plan to remain outside the forecast 30 knot wind radius plus an additional 120 (+24 hrs), 240 (+48 hrs), and 360 nm (+72 hrs) exclusion area on either side of the forecast track.

If JTWC is considering two possible forecast track scenarios, ships must remain outside the danger area of both the primary and alternate forecast. This occasionally will make operations in the western Pacific very difficult, especially operations involving transits near the Philippines.

REFERENCES

Allard, R.A., 1984: A climatology of the characteristics of tropical cyclones in the Northeast Pacific during the period 1966-1980. Master of Science Thesis, Texas Tech University, 106 pp.

Arakawa, H., 1952: Mame Taifu or midget typhoon (small storms of typhoon intensity). Geophysical Magazine, 24, 463-474.

Brand, S., 1970: Interaction of binary tropical cyclones of the western North Pacific. J. Appl. Meteor., 9, 433-441.

Brand, S., C.A. Buenafe and H.D. Hamilton, 1981: Comparison of tropical cyclone movement and environmental steering. Mon. Wea. Rev., 109, 908-909.

Burroughs, L.D. and S. Brand, 1972: Speed of tropical storms and typhoons after recurvature in the western North Pacific Ocean. ENVPRESCHFAC Tech Paper 7-72, U.S. Naval Postgraduate School, Monterey, CA, 36 pp.

Carr, L.E., and R.L. Elsberry, 1994: Systematic and Integrated Approach to Tropical Cyclone Track Forecasting Part 1. Approach Overview and Description of Meteorological Basis. NPS-MR-94-002, Naval Postgraduate School, Monterey, CA 93943, 273 pp.

Carr, L.E., and R.L. Elsberry, 1995: Monsoonal interactions leading to sudden tropical cyclone track changes. Mon. Wea. Rev., 123, 265-289.

Chan, J.C.-L., 1986: Supertyphoon Abbey - An example of present track forecast innadequacies. Wea. And Forecasting, 1, 113-126.

Chan, J.C.-L. and W.M. Gray, 1982: Tropical cyclone movement and surrounding flow relationships. Mon. Wea. Rev., 110, 1354-1374.

Crutcher, H.L. and R.G. Quayle, 1974: Mariners Worldwide Climatic Guide to Tropical Storms at Sea. U.S. Department of Commerce, NOAA/EDS, National Climatic Center in cooperation with The Naval Weather Service Environmental Detachment, Asheville, NC, 114pp. + 312 charts.

DeMaria, M., 1985: Tropical cyclone motion in a nondivergent barotropic model. Mon. Wea. Rev, 113, 1199-1210.

Dong, K., and C.J. Neumann, 1983: On the relative motion of binary tropical cyclones. Mon. Wea. Rev., 111, 945-953.

Dong, K., and C.J. Neumann, 1986: The relationship between tropical cyclone motion and environmental geostrophic flows. Mon. Wea. Rev., 114, 115-122.

Elsberry, R.L., 1987: Tropical cyclone motion. Chapter 4, A Global View of Tropical Cyclones, Office of Naval Research, 91-131.

Fett, R.W., and S. Brand, 1975: Tropical cyclone movement forecats based on observations from satellites. J. Appl. Meteor., 452-456.

George, J.E., 1975: Tropical Cyclone Motion and Surrounding Parameter Relationships. Atmospheric Science Paper No. 241, Colorado State University, FT. Collins, CO., 105 pp.

George, J.E., and W.M. Gray, 1976: Tropical cyclone motion and surrounding parameter relationships. J. Appl. Meteor., 15, 1252-1264.

Guard, C.P., 1977: Operational application of a tropical cyclone recurvature/non-recurvature study based on 200 mb wind fields. FLEWEACEN Tech Note JTWC 77-1, 40 pp.

Guard, C.P., 1983: A study of North Pacific tropical storms and typhoons that intensify after recurvature. Tech Note First Weather Wing, 288 pp.

Guard, C.P., L.E. Carr, F.H. Wells, R.A. Jeffries, N.D. Gural, and D.K. Edson: Joint Typhoon Warning Center and the challenges of multibasin tropical cyclone forecasting. Wea. and Forecasting, 7, 328-352.

Hodanish, S.J., 1991: An observational analysis of tropical cyclone recurvatures. Colo. State Dept. of Atmos. Sci. Paper No. 480, Colo. State Univ., Fort Collins, CO 80523

Keenan, T.D., 1982: A diagnostic study of tropical cyclone forecasting in Australia. Aust. Met. Mag., 30,69-80.

Lajoie, F.A., and N. Nicholls, 1974: A relationship between the direction and movement of tropical cyclones and the structure of their cloud systems. Tech Rep. No. 11, Bureau of Meteorology, Melbourne, Australia, 22 pp.

Lander, M.A., 1994: Description of a monsoon 'gyre' circulation and its effects on the tropical cyclones in the western North Pacific during August 1991. Wea. and Forecasting. 9, 640-654.

Miller, R.J., T.L. Tsui and A.J. Schrader, 1988: Climatology of North Pacific Tropical Cyclone Tracks, NEPRF Technical Report TR 8810, Naval Environmental Prediction Research Facility, Monterey, CA 93943, 490 pp.

Neumann, C.J., 1979: On the use of deep-layer-mean geopotential height fields in statistical prediction of tropical cyclone motion. 6th Conference on Probability and Statistics in Atmospheric Sciences. Amer. Meteor. Soc., Boston, 32-38.

Neumann, C.J., 1992: The Joint Typhoon Warning Center (JTWC92) model. SAIC, Final Report, Contract No. N00014-90-C-6042, 85 pp.

Neumann, C.J., 1993: Global Guide to Tropical Cyclone Forecaster (Chapter 1) WMO Technical Document Number 560.

Pike, A.C., 1985: The variation of track forecast difficulty among tropical cyclone basins. Extended abstracts of 16th Conference on Hurricanes and Tropical Meteorology. Amer. Meteor. Soc., Boston. 76-77.

Sadler, J.C., 1975: The upper tropospheric circulation over the global tropics, Dept. of Meteorology, Atlas UHMET 75-05, University of Hawaii, Honolulu, Hawaii.

Sanders, F., A.L. Adams, N.J.B. Gordon, and W.D. Jensen, 1980: Further development of a barotropic operational model for predicting paths of tropical storms. Mon. Wea. Rev., 108, 642-654.

Sanders, F., and R.W. Burpee, 1968: Experiments in barotropic hurricane track forecasting. J. Appl. Meteor., 7, 313-323.

Sheets, R.C., 1990: The National Hurricane Center - Past, Present and Future. Wea. and Forecasting, 5, 185-232.

Sheets, R.C., 1985: Hurricane tracking using a Mass Field Envelope approach. Extended Abstracts, 16th Conference on Hurricanes and Tropical Meteorology, Amer. Meteor. Soc., Boston, pp. 38-39.

U.S. Navy, 1976: Typhoon havens handbook for the western Pacific and Indian Oceans, S. Brand and J. Bleloch, eds. NAVENPREDRSCHFAC TP 5-76. Naval Res. Lab., Marine Meteorology Division, Monterey, CA 93943-5502.

U.S. Navy (var. auth.), 1982: Hurricane havens handbook for the North Atlantic Ocean. Plus changes 1,2,3,4,5. NAVENVPREDRSCHRAC TR 82-03, Naval Research Laboratory, Marine Meteorology Division, Monterey, CA 93943-5502.

Weir, R.C., 1982: Predicting the acceleration of northward-moving tropical cyclones using upper-tropospheric winds. NAVOCEANCOMCEN/JTWC Technical Note 82-2, U.S. Naval Oceanography Command Center/Joint Typhoon Warning Center, FPO San Francisco, CA 96630, pp40.

Xu, J., and W.M. Gray, 1982: Environmental circulations associated with tropical cyclones experiencing fast, slow, and looping motion. Atmos. Sci. paper No. 346, Colorado State University, Fort Collins, CO, 27 pp.

APPENDIX A

OPERATIONAL APPLICATION OF A TROPICAL CYCLONE RECURVATURE/ NON-RECURVATURE STUDY BASED ON 200 MB WIND FIELDS (An abridged version from Guard, 1977)

As a follow on to the George (1975) technique, Guard (1977) developed an operational forecast technique that uses the 200 mb wind and 200 mb synoptic pattern analyses to determine the likelihood of recurvature. The following is an abridged version of the Guard (1977) technique which is primarily for use in the western North Pacific.

Select between one of the two seasonal synoptic regimes, winter (Fig. A.1) or summer (Fig. A.2). Then identify the recurvature or nonrecurvature pattern within the regime from the following four major categories.

1. Winter Regime Recurvature Pattern

For recurvature to occur in this synoptic pattern (Fig. A.3) an increasing belt of westerly winds must be located to the west-northwest of the tropical cyclone and have a direct link with the upper-levels of the tropical cyclone. If these criteria are not met, recurvature is unlikely.

2. Winter Regime Nonrecurvature Pattern

Figure A.4 depicts the typical winter regime nonrecurvature pattern. There are conditions where there appears to be a direct link between the westerlies and the tropical cyclone outflow, but recurvature does not occur. One such condition is illustrated in Figure A.4. If the axis of a mid-latitude trough is stationary, and is more than 2000 km west of the tropical cyclone, 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; tropical cyclones will move toward the west, south of the ridge, and dissipate over land.

The second condition occurs when a tropical cyclone, still well south of the axis of the mid-tropospheric subtropical ridge (STR), collides with upper level westerlies. When this occurs an upper tropospheric trough is induced near the intersection of the westerlies and the tropical cyclone's upper level outflow. Under such situations the mid-tropospheric STR is observed to build southward, west of the tropical cyclone. This southward shift of the STR produces strong vertical wind shear beneath the induced upper level trough. The tropical cyclone is then subjected to strong vertical wind shear and is reduced to a weak low-level circulation; it continues westward with the low level flow and the upper levels dissipate.

3. Summer Regime Recurvature Patterns

A synoptic study of the summer regime was conducted to identify relationships between upper tropospheric (200 mb) flow and the movement of tropical cyclones. Figures A.5, A.6, A.7, and A.8 show typical recurvature patterns.

Figures A.5 and A.6 are characteristic synoptic patterns that result in tropical cyclones with a greater northward than westward component of movement. Under the influence of the pattern in Figure A.5 the tropical cyclone would acquire a more eastward movement, and under Figure A.6 a more westward movement would be acquired. Although intense cyclonic cells within the East Asian Trough (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 tropical cyclones. If the EAT is relatively stationary, a tropical cyclone moving toward it will eventually be subjected to northward steering currents. The northward displacement exhibited by the tropical cyclone increases with the intensity of the EAT and decreases with distance from the EAT. This synoptic pattern is conducive to recurvature.

Figure A.7 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 (Fig. A.7). The overall speed of movement could remain the same, or even increase, but the storm will move more slowly toward stronger mid-latitude westerlies.

It was observed that during the transition seasons (spring and fall) tropical cyclones might initially be in a summer regime, but change to a winter regime. This most commonly occurred with tropical cyclones between 135E and 140E, and the Asian land mass. In this region (during transition seasons) the Tropical Upper Tropospheric Trough (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. When a tropical cyclone acquires a direct link between its outflow circulation and the mid-latitude westerlies during a transition season, the tropical cyclone should be treated as a winter tropical cyclone west of 135E to 140E and as a summer tropical cyclone east of 135E to 140E.

Figure A.8 is an example of a synoptic pattern which may retard a tropical cyclone'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 tropical cyclone's northward component. Any southward flow toward the storm, regardless of the synoptic pattern producing it, may retard a tropical cyclones northward movement.

4. Summer Regime Nonrecurvature Pattern

Figure A.9 is indicative of a nonrecurvature situation. When the Asian upper level anticyclone remains east of a tropical cyclone, the tropical cyclone will exhibit a greater westward than northward component of movement, and recurvature will not occur. Such tropical cyclones commonly affect the southern Ryukyu Islands, Taiwan, and the People's Republic of China. The westward movement of the tropical cyclone 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 tropical cyclone will move toward the northwest into the ridge; if the winds are 20 to 40 knots (10.3 to 20.6 m/s) the tropical cyclone will move toward the west-northwest; if the winds are 40 to 60 knots (20.6 to 30.9 m/s) the tropical cyclone will move toward the west; and if the winds are greater than 60 knots (30.9 m/s) the tropical cyclone will move south of west.

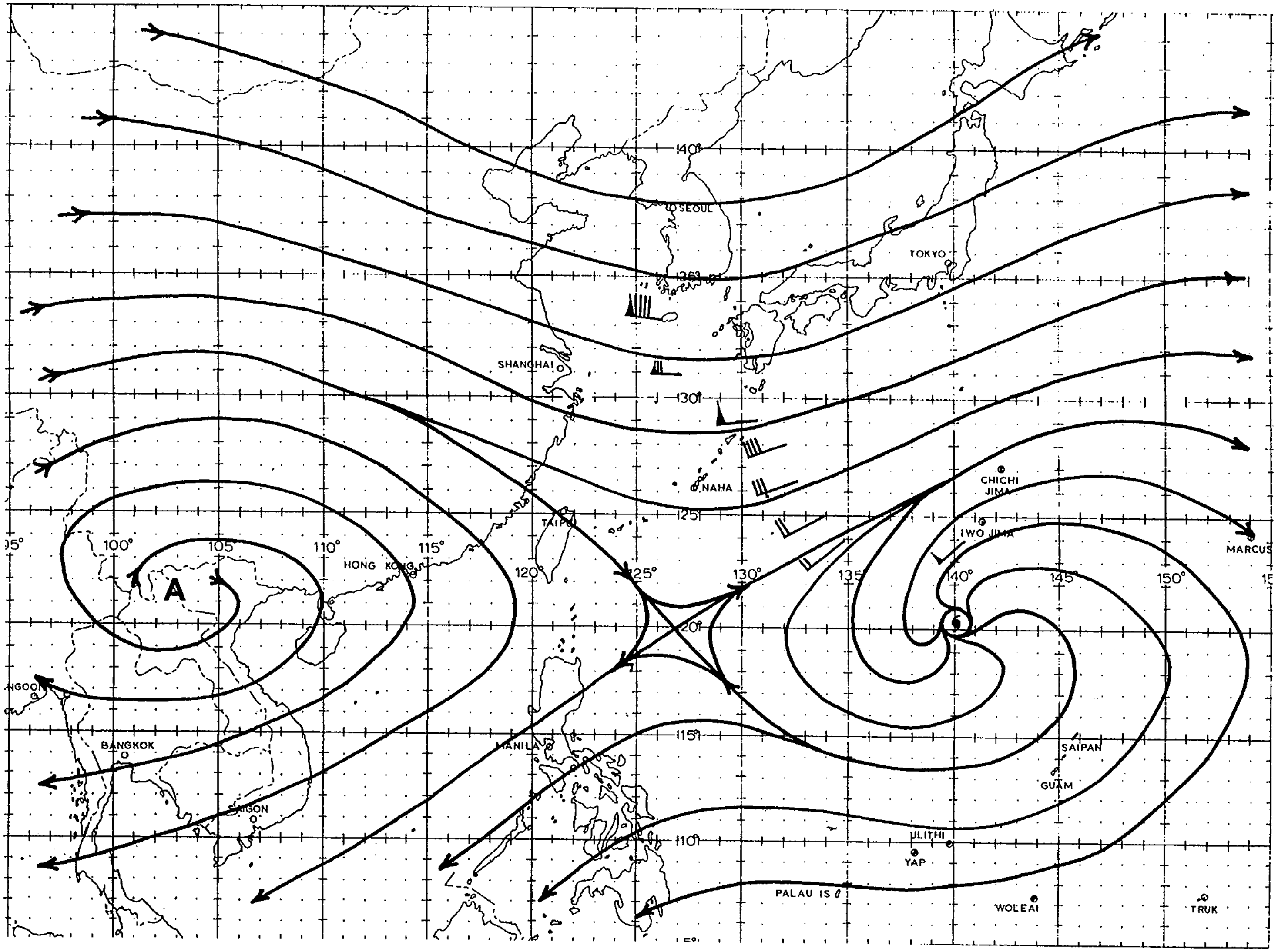


Figure A.1. A 200 mb streamline analysis depicting a winter regime situation. Wind barbs are in knots. Major longwave axis may vary longitudinally. (After Guard, 1977)

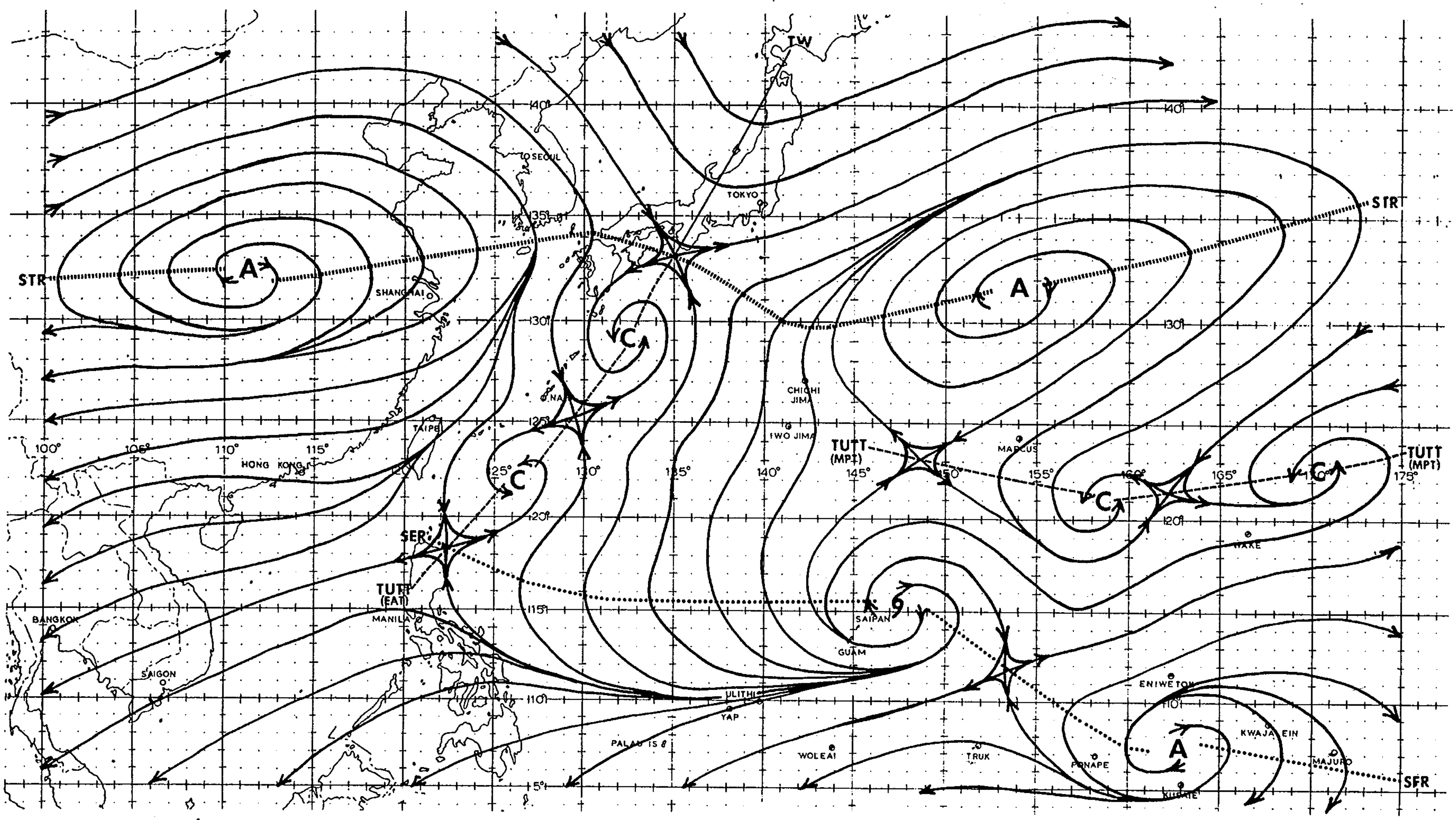


Figure A.2. A 200 mb streamline analysis depicting summer regime. TW is a trough in the westerlies (short dashed), STR is the subtropical ridge (heavy short dashed), SER is the subequatorial ridge (dotted), TUTT is the tropical upper tropospheric trough (long dashed), MPT is the Mid-Pacific Trough, and EAT is the East Asian Trough. (After Guard, 1977)

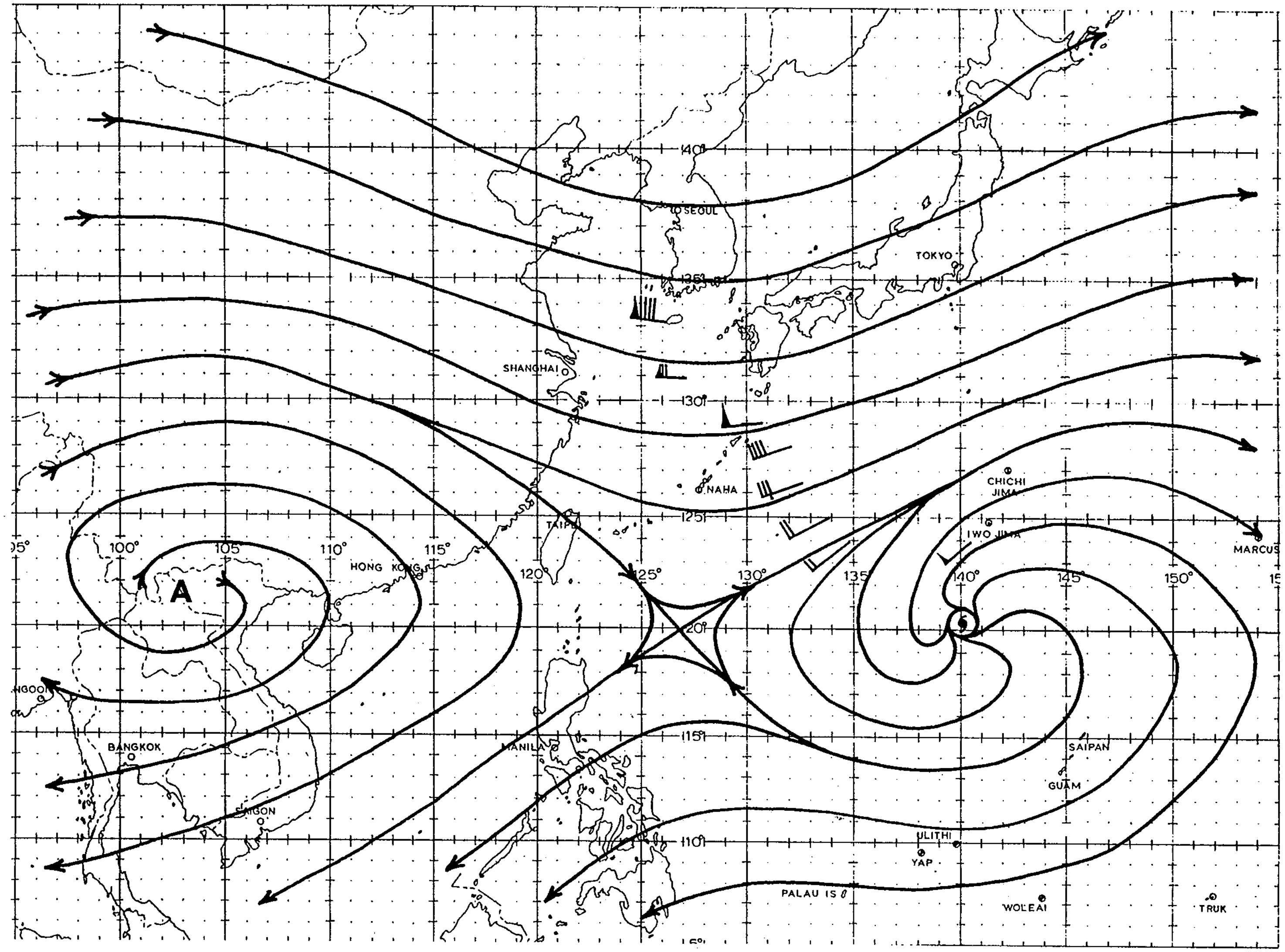


Figure A.3. A 200 mb streamline analysis depicting a winter regime situation. Wind barbs are in knots and illustrate the direct link between the tropical cyclone upper level outflow circulation and the mid-latitude westerlies. (After Guard, 1977)

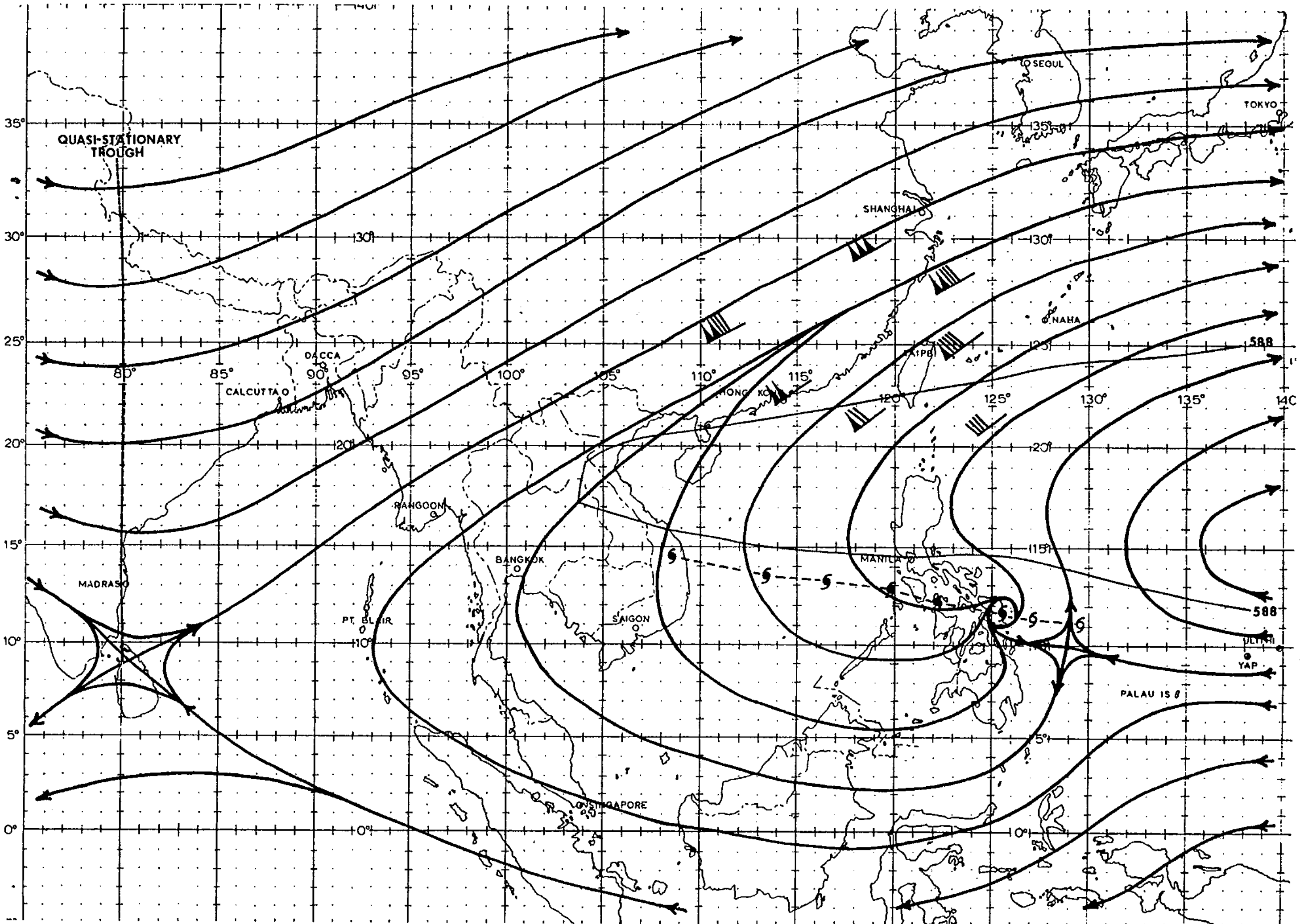


Figure A.4. A 200 mb streamline analysis illustrating the primary winter regime non-recurvature situation. Fine dashed line represents the 500 mb 588 decameter contour. Thick dashed line shows the tropical cyclone past (tropical storm symbol) and future (typhoon symbol) cyclone track. (After Guard, 1977)

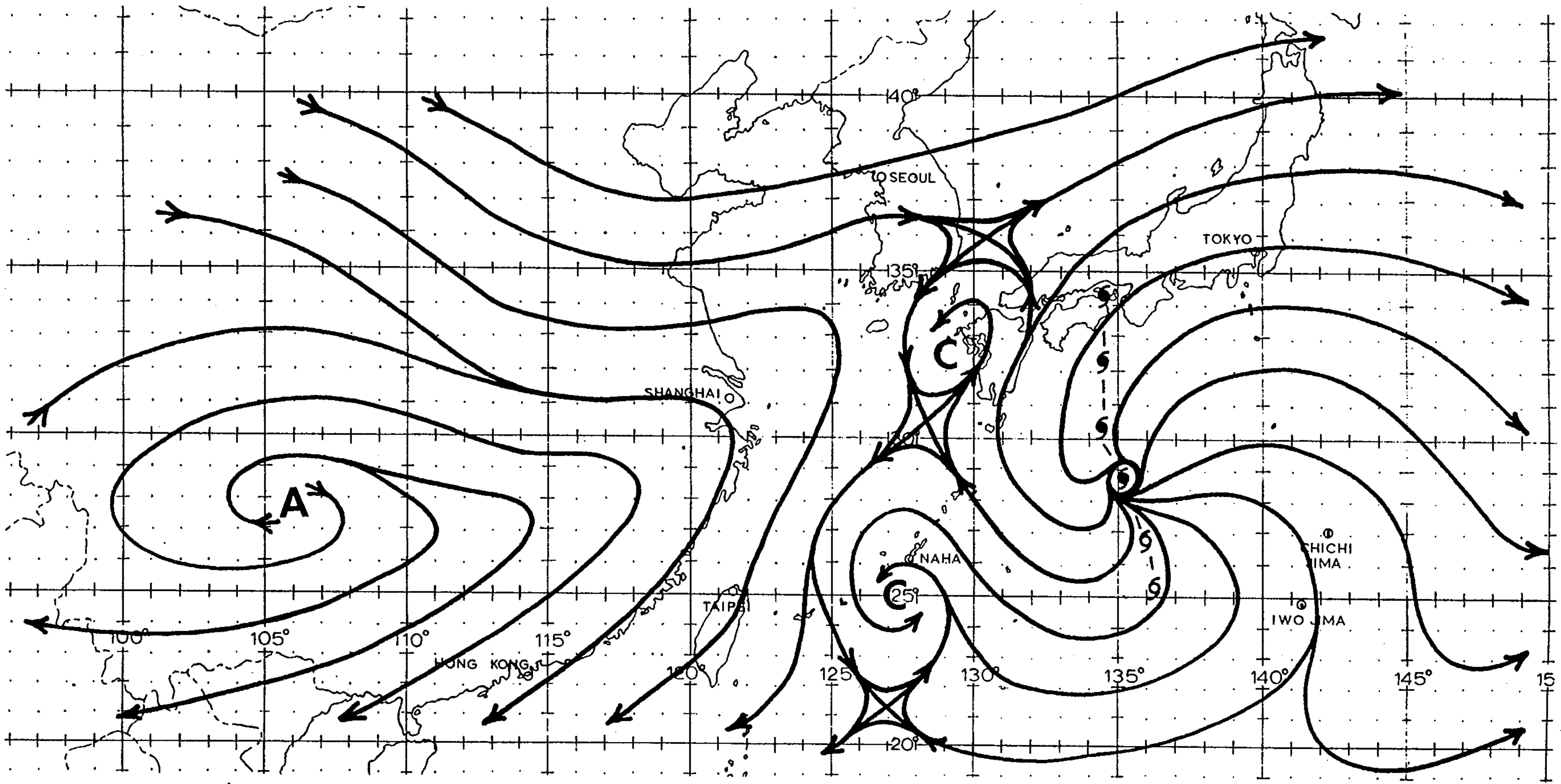


Figure A.5. A 200 mb streamline analysis of synoptic situation dictating north-ward movement of summer regime tropical cyclones. Dashed line shows past (tropical storm symbols) and future (typhoon symbols) cyclone movement. (After Guard, 1977)

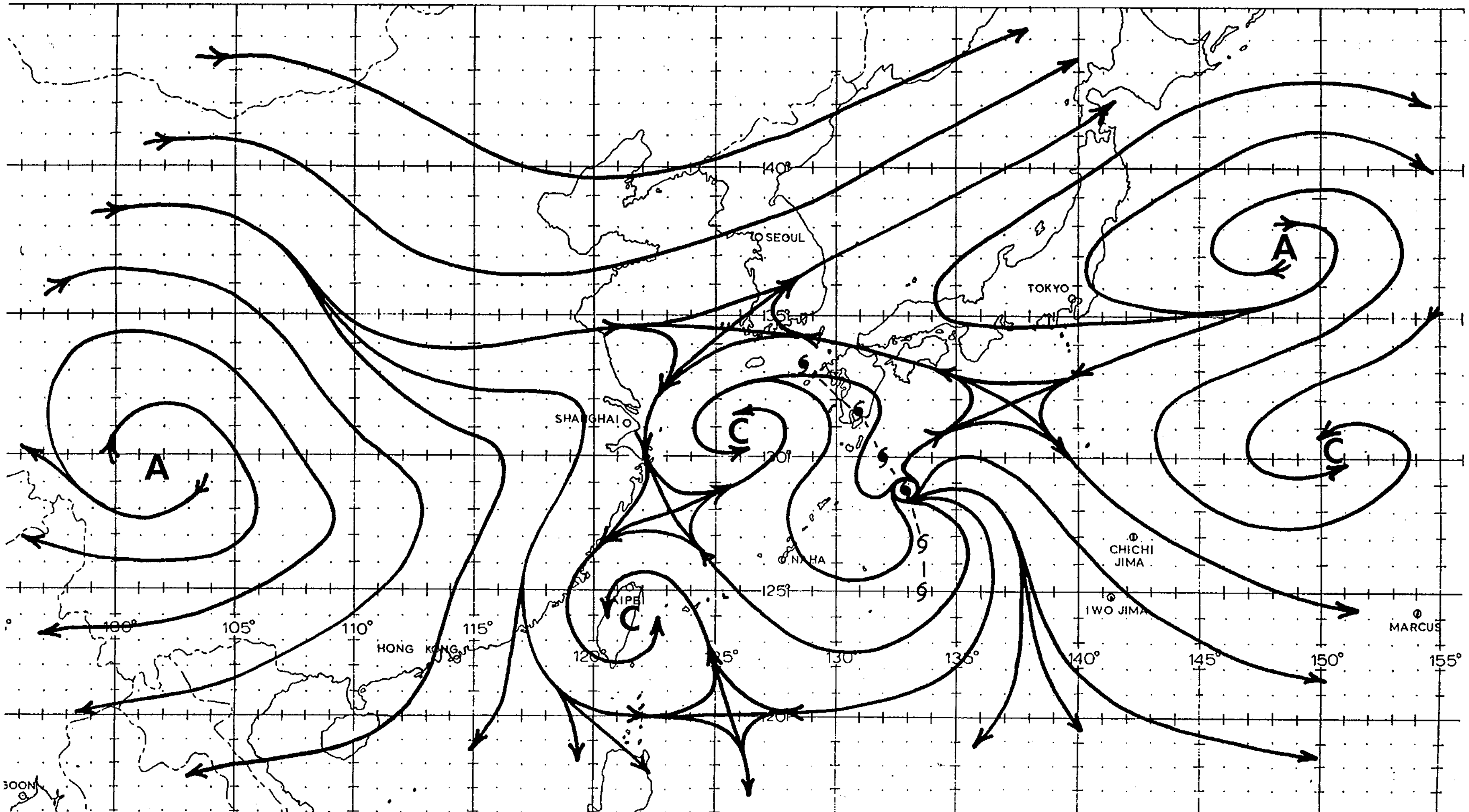


Figure A.6. A 200 mb streamline analysis depicting a synoptic situation under which a northward moving summer regime tropical cyclone would acquire a more westward component of movement. Dashed lines show the past (tropical storm symbols) and future (typhoon symbols) movement of the tropical cyclone. (After Guard, 1977)

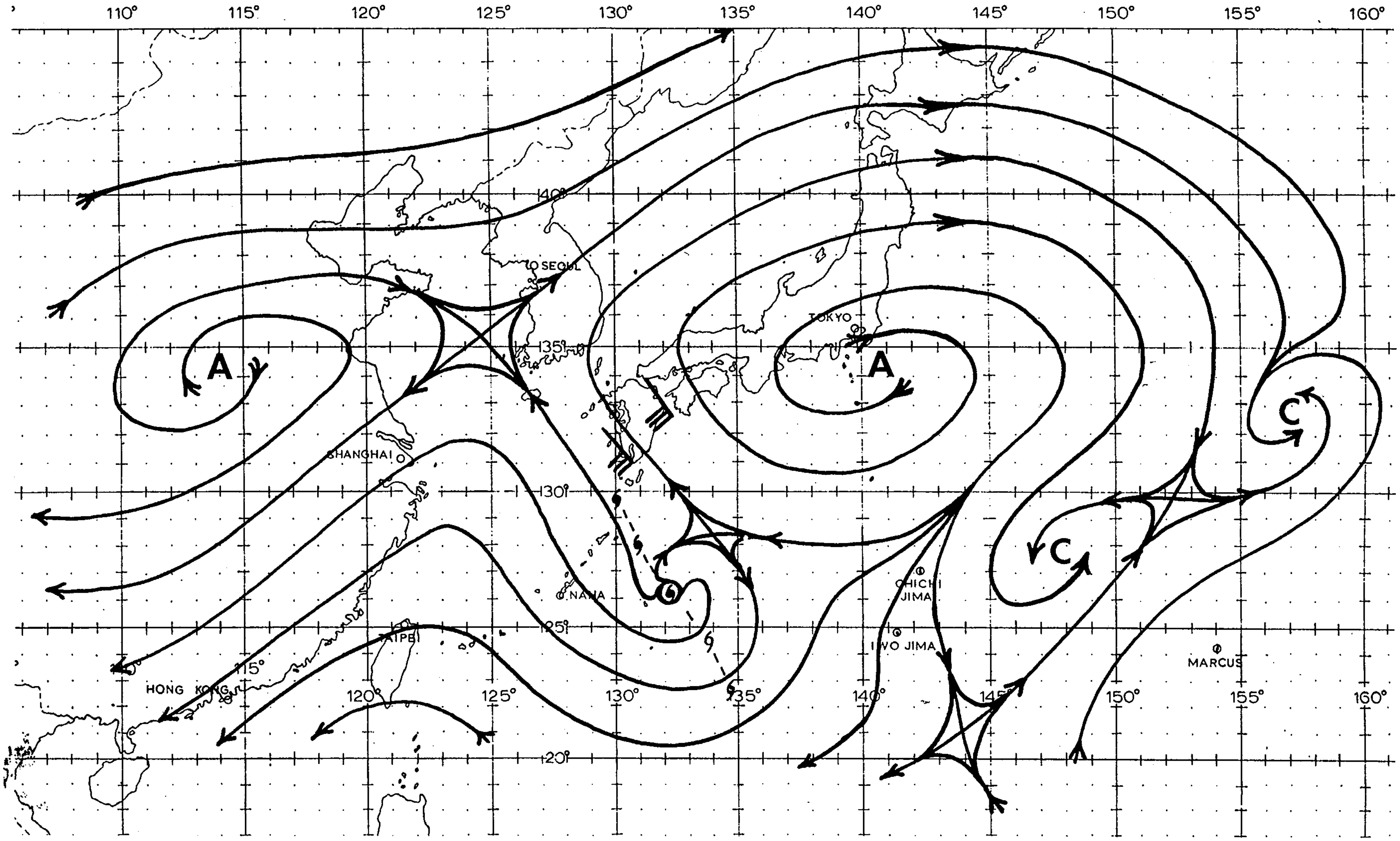


Figure A.7. A 200 mb streamline analysis depicting a synoptic condition under which a summer regime tropical cyclone would move toward recurvature. Dashed line shows past (tropical storm symbols) and future (typhoon symbols) cyclone movement. Wind barbs are in knots. (After Guard, 1977)

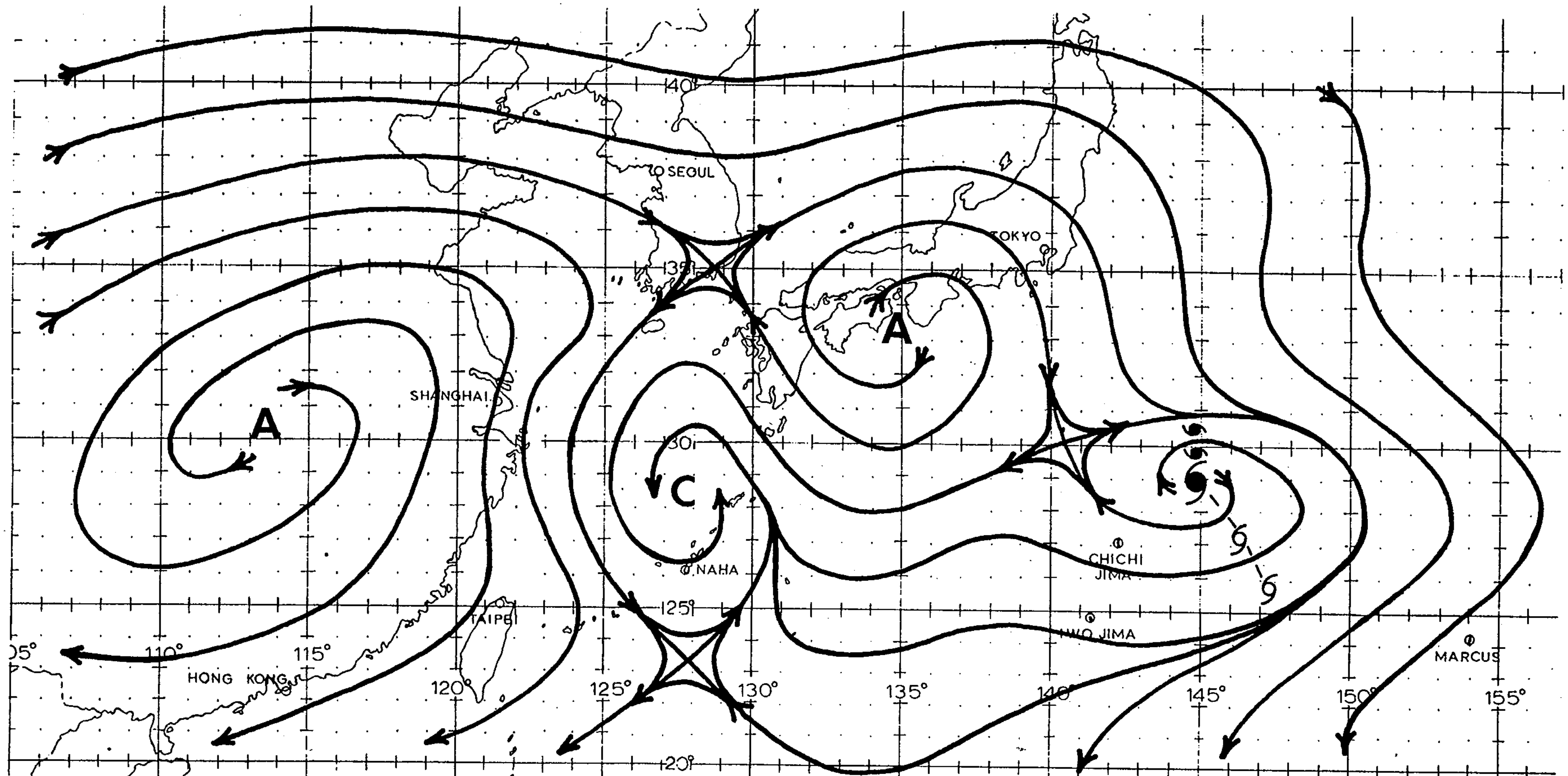


Figure A.8. A 200 mb streamline analysis illustrating a synoptic situation conducive to reducing a summer regime tropical cyclone's northward component of motion. Tropical storm symbols indicate past cyclone movement and typhoon symbols indicate future cyclone movement. (After Guard, 1977)

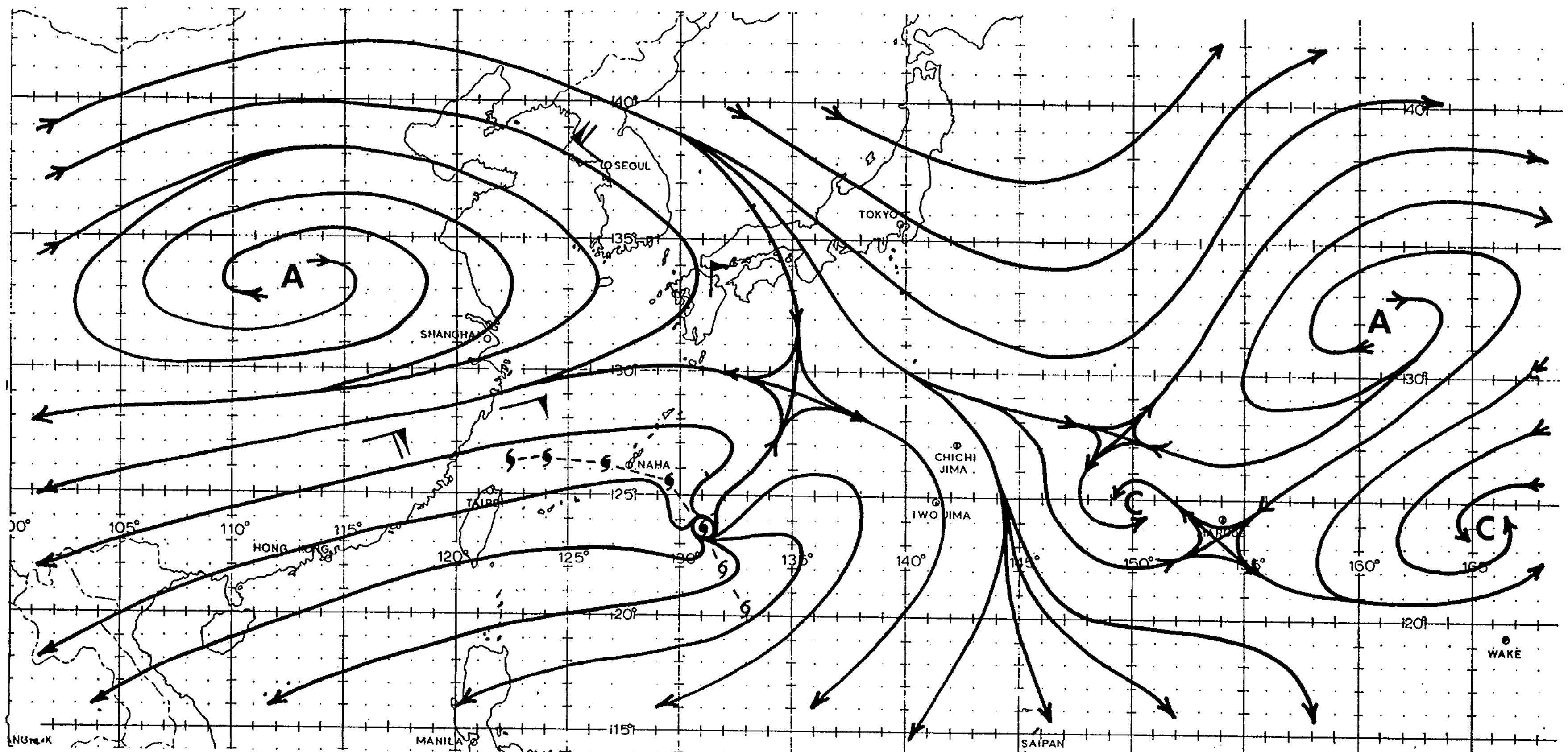


Figure A.9. A 200 mb streamline analysis illustrating a non-recurvature situation during a summer regime. Dashed line shows past (tropical storm symbols) and future (typhoon symbols) movement of tropical cyclone. Wind barbs are in knots. (After Guard, 1977)

APPENDIX B

TYPHOON ACCELERATION PREDICTION TECHNIQUE (TAPT)

(An abridged version of Weir, 1982)

The purpose of this technique is to provide tropical cyclone forecasters with a real-time synoptic prediction technique for determining where and/or if a northward-moving tropical cyclone will undergo a significant increase in speed of movement as it approaches the domain of the mid-latitude westerlies.

This technique assists in the identification of specific flow patterns at the upper-tropospheric (mean 200 mb) level which have been associated with the acceleration of previous tropical cyclones. It further provides guidance in identifying northward-moving tropical cyclones which do not experience significant accelerations.

Application of the technique requires use of the most-recent 200 mb data and the 200 mb (numerical) prognostic series that covers the next 24- to 48-hour period. The essence of the technique is identification of the domain of the mid-latitude westerlies. The forecaster must carefully review all 200 mb wind data prior to conducting the TAPT evaluation; raw data, i.e., rawinsonde/pibal winds, AIREPS and cloud motion winds, are preferred over gridded analysis winds. If sufficient raw data exists the technique will provide:

- a YES/NO decision for a significant increase in the speed of movement;

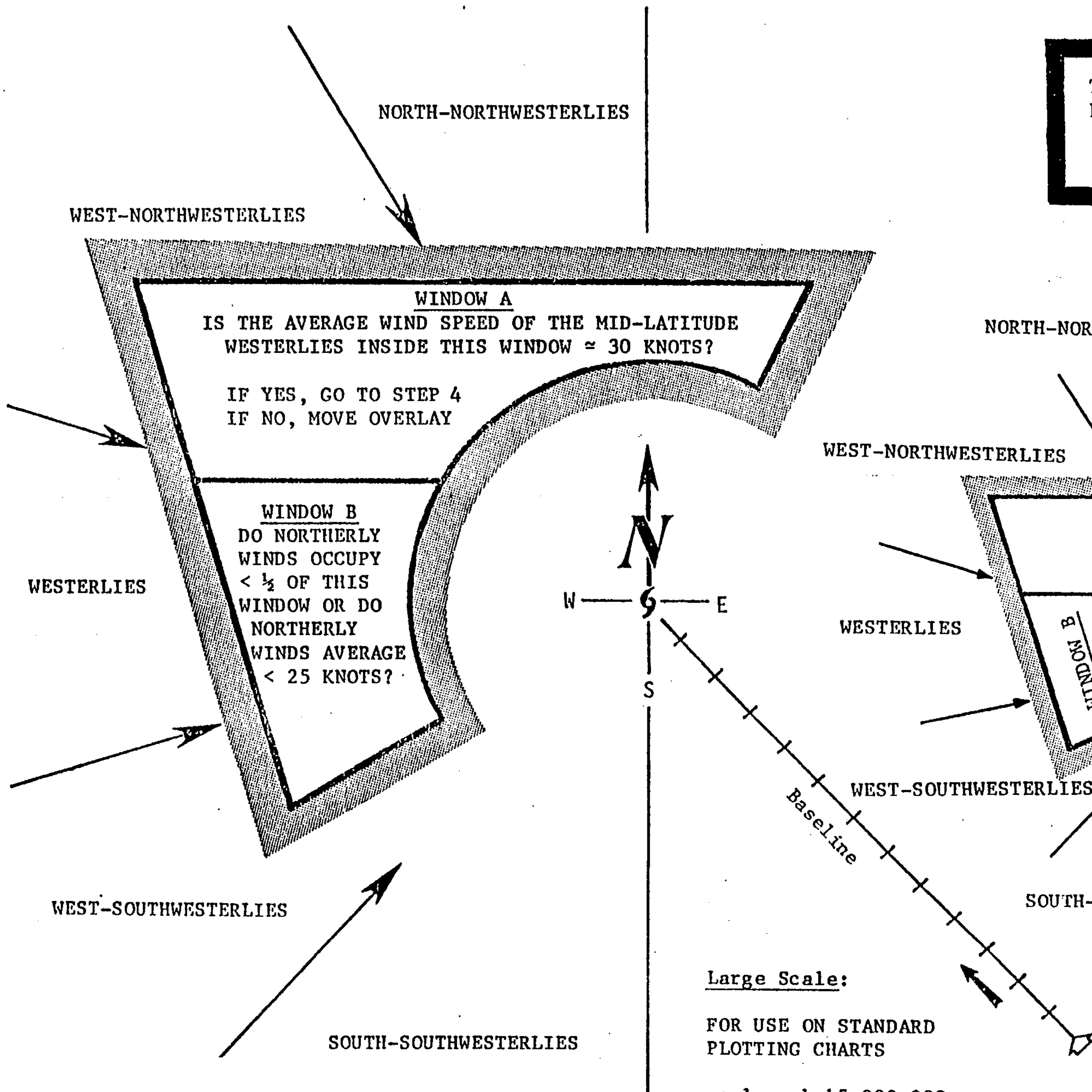
- a "best" location (latitude) for the initiation of the acceleration process;

- speed of movement guidelines including duration and upper-limits;

- insight on the probable path of the tropical cyclone.

It should be noted that it is imperative that the forecaster closely evaluate the applicability of the TAPT conclusions each time the technique is attempted. The validity of the results is highly dependent on: the 200 mb chart containing a sufficient amount of data to depict the southern extremity of the mid-latitude westerlies; the wind data present on the 200 mb chart being representative of a deeply penetrating layer of mid-latitude westerlies, i.e., 200-700 mb stratum; and the tropical cyclone maintaining a northward movement and being in position to be affected by the mid-latitude westerlies.

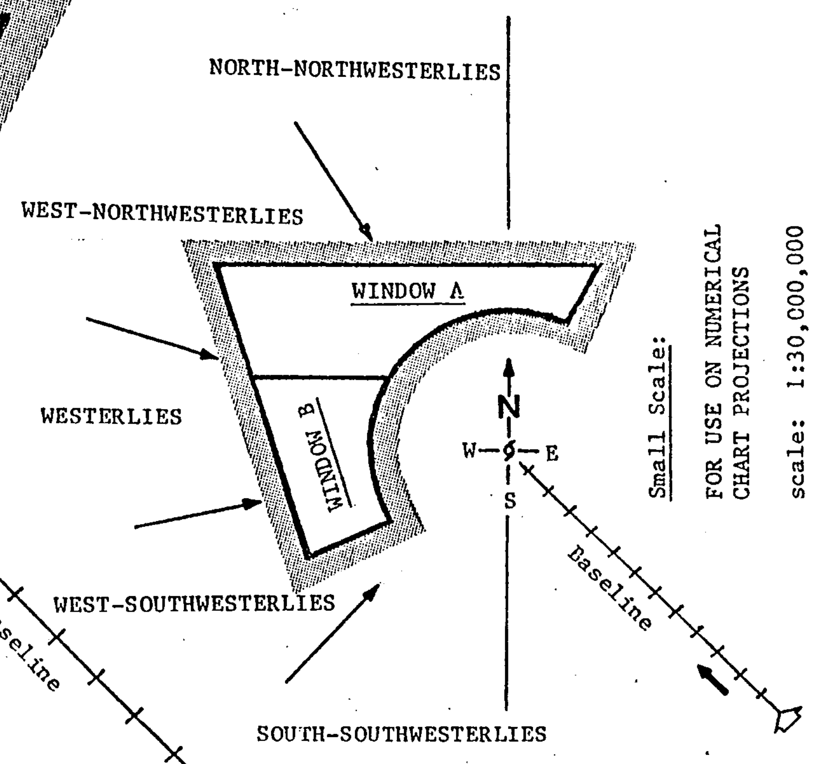
TYPHOON ACCELERATION PREDICTION TECHNIQUE (TAPT) OVERLAY



Large Scale:

FOR USE ON STANDARD PLOTTING CHARTS

scale: 1:15,000,000



Small Scale:

FOR USE ON NUMERICAL CHART PROJECTIONS

scale: 1:30,000,000

WINDOW A DIRECT	WINDOW A AVG WIND	DURATION ACCEL	ACCEL MAX SPD
SSWly	-- 40 kt	24-36 hr	> 30 kt
WSWly	-- 40 kt	> 30 hr	> 30 kt
Wly	--- 30 kt	18-30 hr	20-30 kt
WNWly	-- 30 kt	12-24 hr	< 20 kt
NNWly	-----	(nil acceleration)	

The following environmental factors have also been observed to affect the subsequent acceleration of the tropical cyclone and may be at variance with the TAPT forecast:

A. A strong northerly or easterly low-level flow that will impede tropical cyclone movement. Normally, when this effect occurs early in the predicted acceleration period, the tropical cyclone will drift northward for one to two degrees latitude before acceleration commences. If it occurs later in the acceleration period, it often marks the end of the acceleration process. Thus, a check on low-level steering is necessary prior to applying this technique.

B. A poorly-defined or very small mid- or upper-level circulation center which does not (directly) link the tropical cyclone's low-level center to the mid-latitude westerlies. In such cases, the low-level steering should be more representative of the tropical cyclone's movement.

C. A well-defined tropical upper-tropospheric trough (TUTT) lying between the tropical cyclone and the mid-latitude westerlies. Interaction with the TUTT will often slow a tropical cyclone and alter its upper-level circulation pattern, causing it to respond to steering influences at lower levels.

1. Instructions

Step 1. Locate the position of the tropical cyclone at the valid-time of the 200 mb chart. Annotate this position with an "X". From 15 to 20 degrees of longitude west of the tropical cyclone, locate the southern extremity of the mid-latitude westerlies by sketching the 30 kt isotach eastward to the longitude of the tropical cyclone. Be careful not to drop the isotach into the low originating from the tropical latitudes (see Fig. B-1).

Step 2. Place the overlay [Facing Page] on the 200 mb chart with the "large-scale" TAPT diagram's typhoon symbol above the chart's "X" symbol. Orient the overlay to true north and maintain this orientation throughout the evaluation. Use the "small-scale" diagram with the numerical prognostic charts.

Step 3. With the TAPT overlay in place, average the wind speeds present in Window A. If the average wind speed is less than 30 kt, continue the evaluation by moving the TAPT overlay northwestward while maintaining the chart's "X" symbol under the overlay's baseline.

Step 4. STOP the evaluation when the average wind speed is 30 kt or greater in Window A (Go to step 5), or when the "X" symbol is located beyond the "arrow" at the end of the baseline. If the evaluation has been stopped at the end of the baseline and if a prolonged northward track is still likely, climatology may be used to estimate the latitude where acceleration may begin.

Step 5. If the evaluation has been stopped with 30 kt or greater in Window A, then the following instructions will identify the potential for acceleration. **TO OBTAIN THE "BEST LATITUDE" FOR SIGNIFICANT ACCELERATION TO BEGIN, THE PATTERN OF THE UPPER-TROPOSPHERIC, MID-LATITUDE WESTERLIES MUST BE IDENTIFIED NEXT.**

Step 6. If the overlay's typhoon symbol is within two degrees of the chart's "X" position, then the current analysis chart and the 24-hour prognostic chart should be used to determine the upper-tropospheric wind pattern that will prevail during acceleration. Evaluate any differences between the wind pattern shown in the analysis and the prognostic chart before deciding on the future upper-tropospheric wind pattern.

Step 7. If the overlay's typhoon symbol is greater than two degrees from the chart's "X" position, then refer to the numerical prognosis charts with valid-times closest to the forecast arrival of the tropical cyclone at the latitude shown under the typhoon symbol to determine the upper-tropospheric wind pattern that should prevail during the acceleration.

Step 8. From Figures B-2 through B-6 that follow, identify the upper-tropospheric wind pattern that best suits the pattern determined in Step 7 or 8. Follow the instructions given for the selected figure. When completed, review the Discussion Section before applying the technique (TAPT) to the forecast.

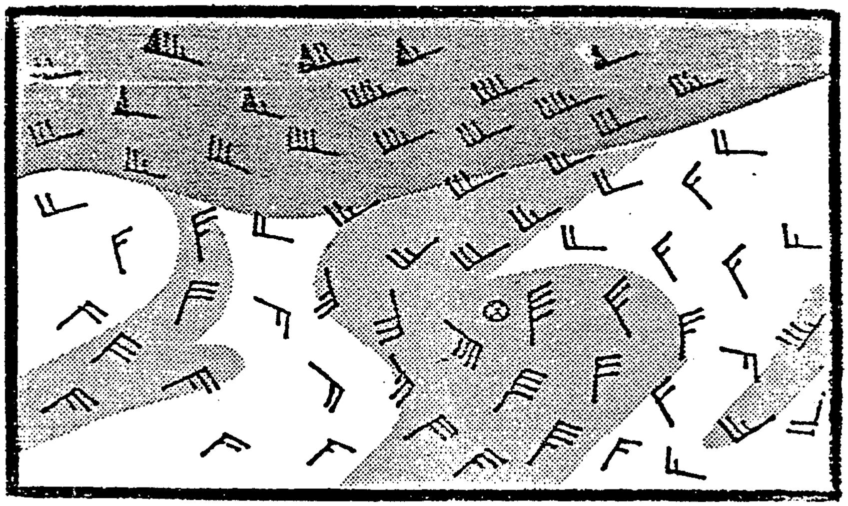
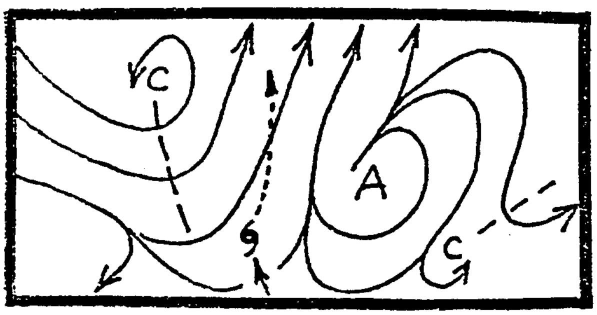


Figure B-1. Shaded areas indicate winds greater than or equal to 25 kts. Dark gray shading indicates the domain of the mid-latitude westerlies; light gray shading shows the areas of strong upper-tropospheric winds <u>outside</u> of the mid-latitudes. These light gray areas are normally associated with upper-tropospheric currents whereas, in the dark gray area, the westerlies normally penetrate into the mid- and lower-tropospheric levels. It is this deeply penetrating current of mid-latitude westerlies which tends to draw the tropical cyclone poleward and acceleration follows.

2. PATTERN RECOGNITION

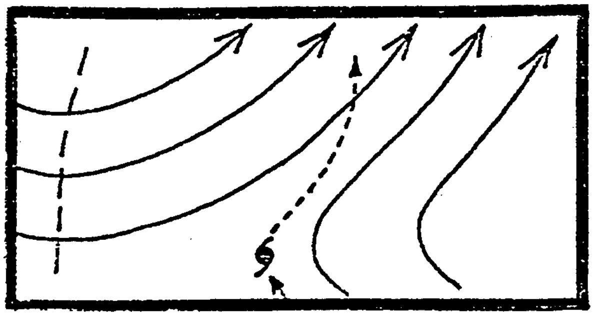


<u>SOUTH-SOUTHWESTERLIES</u> (180 to 200 degrees) Generally a very favorable pattern for acceleration. Pattern usually develops from a WEST-SOUTHWESTERLY. Common pattern from early summer to early autumn.

Figure B-2. South-Southwesterlies

<u>SIGNIFICANT ACCELERATION</u> will commence when wind speeds average **40 knots** or greater in Window A. Move the TAPT overlay toward the northwest (with the "X" symbol remaining under the baseline) to meet the 40-knot criterion. Refer to Table B-1 to determine the recommended acceleration rate.
<u>DURATION & UPPER LIMITS:</u> With this pattern, acceleration is usually very sudden and a fairly rapid extratropical transition normally follows. Thus, most of the acceleration occurs within 24 to 36 hours and may reach speeds above 30 knots (often ahead of those predicted in the acceleration tables).
<u>TRACK:</u> Normally the track will be toward the north-northeast or the north-northwest moving from 10 to 20 degrees left of the upper-level wind pattern.

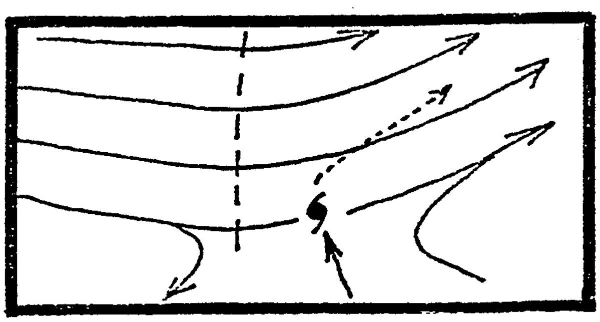
CAUTION: This pattern often sets-up within 12 hours of acceleration, aided by interaction of the tropical cyclone with the westerlies, a ridge building process often occurs east of the upper-level trough.



WEST-SOUTHWESTERLIES (225 to 255 degrees) Generally the most favorable pattern for a sustained acceleration. A common pattern from late September to early November, also seen from late April to early June.

Figure B-3. West-Southwesterlies

SIGNIFICANT ACCELERATION will commence when wind speeds average 40 knots or greater in Window A. Move the TAPT overlay toward the northwest (with the "X" symbol remaining under the baseline) to meet the 40-knot criterion. Refer to Table B-1 to determine the recommended acceleration rate.
DURATION & UPPER LIMITS: If this pattern is maintained throughout the acceleration process, the acceleration will normally be sustained for over 30 hours and may well exceed 30 knots before extratropical transition.
TRACK: Given a persistent pattern, the track will recurve toward the northeast and will move from 10 degrees (initially) to 25 degrees (in later stages) left of the upper-level wind pattern.
CAUTION: This pattern can quickly change to a **SOUTH-SOUTHWESTERLY** which will noticeably affect both the duration and track.



WESTERLIES (260 to 285 degrees) Generally a favorable pattern for acceleration. Common pattern in high zonal situations, especially in the spring, late autumn and winter months.

Figure B-4. Westerlies

SIGNIFICANT ACCELERATION will commence when wind speeds average 30 knots or greater in Window A. Refer to TABLE B-1 to determine the recommended acceleration rate.

DURATION & UPPER LIMITS: Normally this is a very stable upper-level pattern and the effects of the westerlies on a tropical cyclone will usually weaken the system due to increasing vertical wind shear. Acceleration will peak within 18 to 30 hours with speeds reaching the 20- to 30- knot range.
TRACK: A fairly sharp recurvature track toward the east-northeast moving from 10 to 15 degrees left of the upper-level wind pattern.
CAUTION: In the late fall, winter and early spring, this pattern may be present in the upper-levels while a strong northeast monsoonal flow is dominating the low-levels. In such cases the tropical cyclone will often draw toward an upper trough then turn toward the west-southwest with the low-level flow.

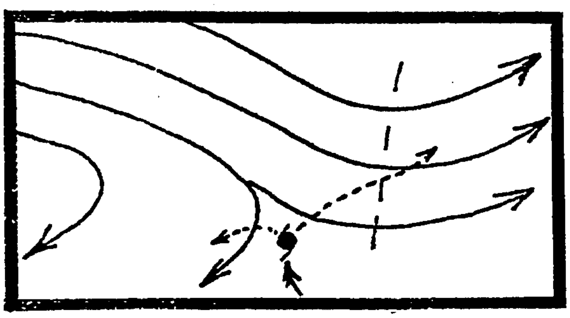


Figure B-5. West-Northwesterlies

WEST-NORTHWESTERLIES (290 to 325 degrees) Generally an unfavorable pattern for significant acceleration. Common pattern in transition periods, especially in May and November.

SIGNIFICANT ACCELERATION should not occur with this pattern. However, some acceleration may occur before the shearing process weakens the tropical cyclone. When wind speeds average <u>30 knots</u> or greater in Window A the shearing and limited acceleration process should commence. Refer to TABLE B-1 to determine the recommended acceleration rate.
DURATION & UPPER LIMITS: Acceleration will be limited to 12 to 24 hours with the maximum speed generally less than 20 knots.
TRACK: If the tropical cyclone recurves, the track will be toward the northeast and moving 30 to 50 degrees left of the upper-level wind pattern. If a strong northeast monsoon flow is present in the lower levels, the tropical cyclone will normally track west-southwestward with the low-level flow instead.
CAUTION: The more northwest the upper-level wind pattern, the more rapid will be the shearing process and the shorter the acceleration period, if any.

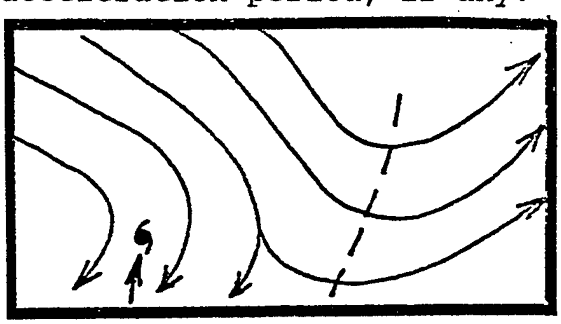


Figure B-6. North-Northwesterly

NORTH-NORTHWESTERLY (330 to 360 degrees) A very unfavorable pattern for acceleration. This pattern can develop from the WEST-NORTHWESTERLY pattern in low zonal situations.

ACCELERATION should not occur with this pattern. A northward-moving tropical cyclone would encounter very rapid shearing (within 12 to 24 hours) and would quickly become non-tropical in nature. However, surface wind speed may remain fairly high for 24 to 36 hours after the shearing process has begun. When this process occurs at relatively low latitudes, 15N to 25N, possible regeneration as a significant tropical cyclone may occur if upper-level wind conditions change fairly rapidly and the tropical cyclone ceases its northward movement.
TRACK: Quasi-stationary or erratic until the shearing is completed, then the surviving low will track with the low-level steering.

TABLE B-1. **Determination of the Rate of Acceleration (850 MB Winds**

If the low-level flow is:	850	850	850	850	850
approx 5 degrees north of TC is Easterly and	weak	mod	mod	strng	strng
approx 5 degrees south of TC is Westerly and	strng	strng	mod	mod	weak
and if Window B (Figure B8) is:					
answered YES, then use TABLE	B-2	B-2	B-3	B-4	B-4/*
answered NO, then use TABLE	B-2	B-3	B-4	B-4/*	*

Table B-2. **Sudden Significant Acceleration**

Average Speed	Hours Into Acceleration						
Past 12 Hours	+06	+12	+18	+24	+30	+36	+42
< 8 knots	10.6	14.2	18.8	25.0	33.3	44.3	***
9 knots	12.0	15.9	21.2	28.2	37.5	49.8	***
10 knots	13.3	17.7	23.5	31.3	41.6	***	
11 knots	14.6	19.5	25.9	34.4	45.8	***	
12 knots	16.0	21.2	28.2	37.5	***		
13 knots	17.3	23.0	30.6	40.7	***		
14 knots	18.6	24.8	32.9	43.8	***		
15 knots	20.0	26.5	35.3	46.9	***		
16 knots	21.3	28.3	37.6	***			
17 knots	22.6	30.1	40.0	***			
18 knots	23.9	31.8	42.3	***			
19 knots	25.3	33.6	44.7	***			
> 20 knots	26.6	35.4	47.1	***			

Table B-3 **Typical Significant Acceleration**

Average Speed	Hours Into Acceleration							
Past 12 Hours	+06	+12	+18	+24	+30	+36	+42	+48
< 8 knots	10.0	12.5	15.6	19.5	24.4	30.5	38.1	47.7
9 knots	11.3	14.1	17.6	22.0	27.5	34.3	42.9	***
10 knots	12.5	15.6	19.5	24.4	30.5	38.1	47.7	***
11 knots	13.8	17.2	21.5	26.9	33.6	42.0	***	
12 knots	15.0	18.8	23.4	29.3	36.6	45.8	***	
13 knots	16.3	20.3	25.4	31.7	39.7	49.6	***	
14 knots	17.5	21.9	27.3	34.2	42.7	***		
15 knots	18.8	23.4	29.3	36.6	45.8	***		
16 knots	20.0	25.0	31.3	39.1	48.8	***		
17 knots	21.3	26.6	33.2	41.5	***			
18 knots	22.5	28.1	35.2	43.9	***			
19 knots	23.8	29.7	37.1	46.4	***			
20 knots	25.0	31.3	39.1	48.8	***			

Table B-4 **Delayed Significant Acceleration**

Average Speed	Hours Into Acceleration										
Past 12 Hours	+06	+12	+18	+24	+30	+36	+42	+48	+54	+60	+66
< 6 Knots	7.0	8.2	9.5	11.1	13.0	15.2	17.7	20.6	25.8	32.2	40.2
7 knots	8.2	9.5	11.1	13.0	15.2	17.7	20.6	25.8	32.2	40.2	***
8 knots	9.3	10.9	12.7	14.8	17.3	20.2	25.3	31.6	39.5	49.8	***
9 knots	10.5	12.3	14.3	16.7	19.5	24.4	30.5	38.1	47.6	***	
10 knots	11.7	13.6	15.9	18.5	21.6	27.0	33.8	42.2	***		
11 knots	12.8	15.0	17.5	20.4	25.5	31.9	39.8	49.8	***		
12 knots	14.0	16.3	19.1	23.9	29.8	37.3	46.6	***			
13 knots	15.2	17.7	20.7	25.9	32.3	40.4	***				
14 knots	16.3	19.1	23.9	29.8	37.3	46.6	***				
> 15 knots	--------------use table B-2 -------------------										

3. DISCUSSION

To this point, the most-recent 200 mb analysis and prognostic charts have been evaluated and an upper-level wind pattern has been identified which has provided a prediction of the best latitude where acceleration will begin, the duration and upper-limits of the acceleration, and the track of a typical tropical cyclone most common in the upper-level wind pattern. Additionally, the rate of acceleration has been determined by evaluating upper- and lower-level winds near to the tropical cyclone.

This technique (TAPT) is a combination of synoptic and statistical predictors which, in most cases, will provide a good approximation of tropical cyclone movement into the mid-latitudes. There are, however, many other factors which the forecaster should consider before applying the results of this technique to the forecast. Some of the meteorological factors which might be at variance with the TAPT forecast are listed below.

A. A weak tropical cyclone with little or no mid- or upper-level support cannot be expected to draw into the westerlies and accelerate similar to the strong typhoon.

B. A very compact or midget tropical cyclone with a very tight upper-level circulation may not accelerate unless it is adjacent to a deep-tropospheric steering current.

C. A well-established low-level wind regime which is directed against the upper-level wind pattern will most often overcome the upper-level steering and move the tropical cyclone southwestward. A good example is a strong northeast monsoon off Asia and Japan in the late fall through early spring.

D. Rapidly changing upper-level wind patterns that may suggest one forecast scenario, then another. Any forecast during this situation is difficult and, accordingly, the reliability of TAPT is highly dependent on the identification of the upper-level wind pattern when interaction with the westerlies begins.

E. Movement of the tropical cyclone away from a predicted northward track. Obviously, if the tropical cyclone fails to attain enough latitude in a presumed period of time, the expected interaction with the westerlies will be delayed or never occur.

F. Interaction with a tropical upper-tropospheric trough (TUTT). If a strong TUTT lies between the tropical cyclone and the main belt of the westerlies, interaction with the westerlies may be denied. The TUTT may weaken the tropical cyclone (vertical wind shear); the TUTT may also slow the tropical cyclone as they interact.

G. Interaction with another tropical cyclone or other warm-core cyclone may cause one or both cyclones to rotate about a common point at the expense of moving toward interaction with the mid-latitude westerlies as would be expected in a single cyclone situation.

H. A significant displacement of the low-level (surface, 850 or 700 mb) westerlies northward of the upper-level westerlies. In such cases, the surface center must overcome the influence of the low-level steering, which is often in opposition to the upper-level steering, before the tropical cyclone can accelerate. If the upper-level circulation does not shear away from the low-level center and if the tropical cyclone continues the drift northward, then the acceleration will tend to be gradual until the effects of low-level steering have been overcome. Table B-4 can assist in blending in this gradual acceleration.

I. Nonrepresentative analyses and/or prognostic data might produce the wrong interpretation of the upper-level wind regime and affect the viability of a northward-moving track.

If acceleration appears to be occurring much earlier than predicted (more than one degree latitude south), double-check the data and the TAPT results. If the reason for acceleration is not known, only apply further acceleration if it is certain that the acceleration is in response to mid-latitude westerlies and not due to normal fix accuracies.

If acceleration does not occur as predicted (tropical cyclone is located more than one degree north of predicted latitude) and cannot be explained by one or more of the items (1-9) above, phase in the acceleration to reach the predicted location by 30 hours. If the tropical cyclone exhibits strong shearing of its upper-level circulation, then only a modest (12 to 24 hours) acceleration should be forecast if the low-level steering favors a continued northward track.

If the TAPT results appear to be questionable, i.e., too low a latitude, check the results against the climatological recurvature prediction for the month. If there is a great difference (more than five degrees), the forecaster will have to make a decision consistent with the data at hand.

If it appears that there are no limiting factors to the TAPT results, then the forecaster is encouraged to apply the technique, consistent with good forecast judgement.

APPENDIX C

A SYSTEMATIC APPROACH TO TRACK FORECASTING

L.E. CARR, III, LCDR, USN and R.L. Elsberry, Professor
Naval Postgraduate School, Monterey, CA

In contrast to the existing forecasting techniques and procedures discussed in the main body of this report, Carr and Elsberry (1994) have developed a new systematic and integrated approach to tropical cyclone (TC) forecasting in the western North Pacific (WESTPAC) region, hereafter referred to as the systematic approach. The systematic approach provides the forecaster with a comprehensive track forecast methodology that combines traditional concepts such as pattern typing and environmental steering with the latest dynamical insights into how tropical cyclones interact with their environment, and thus affect their track. The following discussion provides a brief overview of the entire systematic approach followed by a schematic summary of the environmental pattern and steering concepts. For additional details, the reader is referred to Carr and Elsberry (1994).

1. ORGANIZATION OF THE SYSTEMATIC APPROACH

The systematic approach is organized into three phases: Numerical Guidance Analysis, Objective Techniques Analysis, and Official Forecast Development (Fig. C.1). One of the major problems facing the forecaster is how to organize and logically apply all the available data, techniques, and dynamical concepts to solving the TC forecast problem. The systematic approach addresses this concern by organizing each forecast phase into resource, knowledge base, and process components. Resources are defined to be the raw materials that the forecaster may use to answer certain questions relevant to the forecast phase. Knowledge bases are defined to be the bodies of understanding that enable the forecaster to utilize the available resources in answering questions relevant to the forecast phase. The processes are defined to be a logical sequence of steps that assist the forecaster in accomplishing tasks by applying the knowledge bases to the resources within each phase in a consistent manner.

1.1 Phase I. Numerical Guidance Analysis

1.1.1 <u>Resources</u>

The principal resource to be used by the forecaster during the Numerical Guidance Analysis Phase is the standard set of analysis and forecast fields generated by the numerical TC prediction model serving the warning center, which for JTWC is provided by Fleet Numerical Meteorology and Oceanography Center's (FNMOC) Navy Operational Global Atmospheric Prediction System

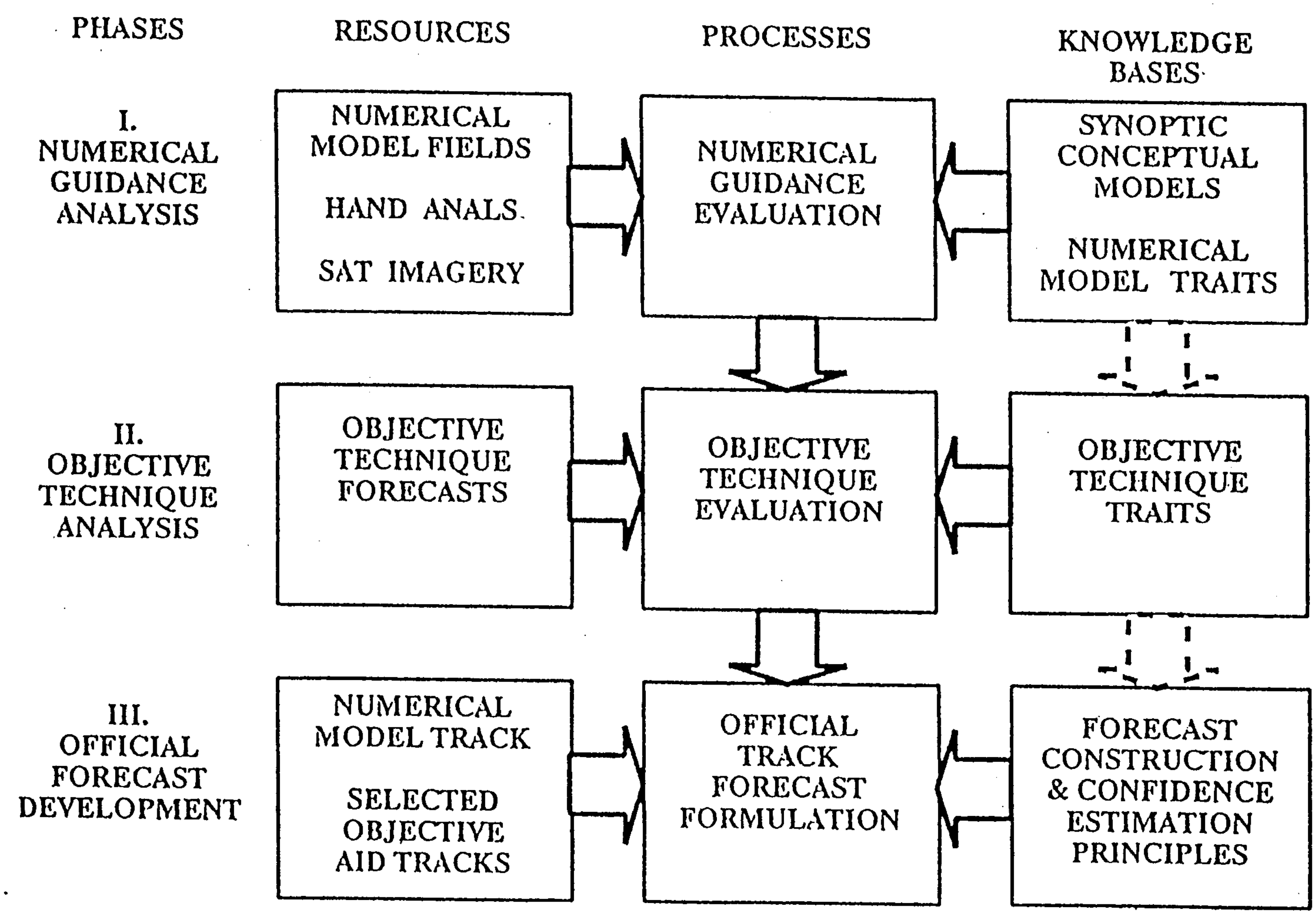


Figure C.1. Schematic of the 3-phase, integrated and systematic approach to TC track forecasting.

(NOGAPS). Numerical products from other numerical weather prediction centers could also be used with NOGAPS but this aspect will not be discussed here. Additional resources that may be used to evaluate the likely accuracy of the numerical guidance include manual analyses and satellite imagery.

1.1.2 Knowledge Base

The Numerical Guidance Analysis Phase employs two important knowledge bases. The first is a comprehensive and organized set of conceptual models to assist the forecaster in characterizing the TC-environment situation. In contrast to existing approaches, the systematic approach includes models for TC structure and TC-environment interaction in addition to the models for the environment structure. The second knowledge base is a set of the traits and biases of the numerical TC prediction model organized in accordance with the TC-environment conceptual model knowledge base.

1.1.3 Process

The Numerical Guidance Evaluation Process of the first phase in Figure C.1 assists the forecaster in accomplishing two principal tasks. The first task is to develop a comprehensive understanding of the synoptic context in which the TC forecast problem is set as depicted by the numerical guidance via use of the TC-environmental conceptual model knowledge base. The second task is to estimate the extent to which the numerical guidance characterization of the TC-environment evolution and the associated TC motion will depart from reality, based on the numerical model traits knowledge base.

1.2 Phase II - Objective Techniques Analysis Phase

1.2.1 Resources

The principal resource for the Objective Techniques Analysis Phase in Figure C.1 is the set of present and recent forecasts of the various objective techniques, which are primarily track techniques used by the warning center. It is emphasized that for the purposes of the systematic approach, the term objective technique is restricted to mean those simplified statistical, climatological, steering, or numerical models that are designed to forecast the TC track and/or intensity. Objective techniques currently (1993-94) used by JTWC include: (1) One-way influence Tropical Cyclone Model (OTCM); (2) shallow, medium, and deep Beta and Advection models; (3) the statistical-dynamical Colorado State University and JTWC-92 models (CSUM; JT92); (4) Climatology and Persistence (CLIP); and (5) Typhoon Analogs (TYAN). Sophisticated numerical prediction models, such as NOGAPS, are treated separately in the systematic approach (i.e., Numerical Guidance

Analysis Phase) because they produce an inherently (although inaccurate) integrated forecast of TC evolution.[1]

1.2.2 Knowledge Base

The principal knowledge base of this phase is the expected traits/biases of the objective track forecasts, organized in accordance with the TC-environmental conceptual model knowledge established in the first phase.

1.2.3 Process

The Objective Techniques Evaluation Process of the Objective Techniques Analysis Phase in Figure C.1 assists the forecaster in accomplishing three tasks. The first task is to confirm, or modify as applicable, the expected TC-environment evolution forecast by the numerical guidance. The degree to which the objective technique forecasts are employed in this way will in general vary inversely with how accurate the recent numerical guidance has been, or is expected to perform for the present scenario. The second task is to estimate the biases expected for objective track forecasts, using the objective technique traits knowledge base, and in light of the TC-environment picture determined during the Numerical Guidance Analysis Phase. The third task is to select a subset of objective technique traits that are most consistent with the TC-environment evolution predicted by the numerical guidance, and thus will be considered with the numerically-predicted TC track in formulating the official forecast.

1.3 PHASE III - OFFICIAL FORECAST DEVELOPMENT

1.3.1 Resources

The resources of the Forecast Formulation Phase, the third and final phase in Figure C.1, are the TC track predicted by the numerical guidance and the subset of objective technique tracks determined from the Objective Technique Evaluation Phase.

1.3.2 Knowledge Base

The knowledge base consists of a number of forecast construction and confidence estimation principles.

OTCM is technically a numerical prediction model. However, because of its coarse vertical (3 layers) and horizontal resolution (205 km), crude TC specification, and use of analytic heating to maintain the TC, OTCM will be treated as an objective track forecast technique for the purposes of the systematic approach.

1.3.3 <u>Process</u>

The Official Track Forecast Formulation Process assists the forecaster in accomplishing two tasks. The first task is to construct an Expected Forecast Envelope from the numerical guidance track and subset of objective technique tracks, which incorporates the expected track biases derived from the previous two phases. The second task is to construct the official TC track forecast from the Expected Forecast Envelope, employing the dynamical and synoptic insights gained in the first two phases, and using various weighting and blending techniques. Due to the inherently integrated nature of the numerical guidance, the numerically-predicted TC track will generally be given precedence over the objective technique tracks. In a minority of situations, the numerically-predicted track may be highly inaccurate and even unusable. In these cases, the tracks from the other objective techniques must take precedence.

2. TC-ENVIRONMENT CONCEPTUAL MODEL KNOWLEDGE BASE

Carr and Elsberry (1994) have developed a set of TC-environmental conceptual models to assist the forecaster in formulating a preliminary understanding of the TC-environment context within which the TC forecasting problem is set. The inherently complex nature of WESTPAC TC forecast scenarios has necessitated a rather broad array of conceptual models. Since this TC-environment conceptual model knowledge base is effectively the heart of the systematic approach, it is crucial that provision be made to facilitate efficient and consistent utilization of this large knowledge base in an operational setting. Thus, a system has been developed for organizing the individual models into related groups of models. This overall system is discussed first, before addressing the individual models of the synoptic framework.

2.1 Organization. The set of conceptual models is organized into three general groups:

2.1.1 <u>Environment Structure</u>

Characterizations of environmental flows, excluding the symmetric circulation of the TC being forecast, and without any TC-environment interactions (Table C.1). Within the Environment Structure group, the conceptual models are further organized into two subsets based on scale:

o Synoptic Patterns Classifications of the large-scale environment surrounding the TC based on the existence and orientation of various synoptic features such as cyclones, anticyclones, ridges, and troughs.

Environment Structure

Models

* **Synoptic Patterns**
    * **Standard (S)**
    * **North-oriented (N)**
    * **Monsoon Gyre (G)**
    * **Multiple Tropical Cyclone (M)**

* **Synoptic Regions**
    * **Dominant Subtropical Ridge (DR)**
    * **Weakened Subtropical Ridge (WR)**
    * **North-oriented (NO)**
    * **Accelerating Midlatitude Westerlies (AW)**
    * **Multiple TC Southerly Flow (SF)**
    * **Multiple TC Northerly Flow (NF)**

Table C.1. Listing of the Synoptic Pattern and Synoptic Region conceptual models within the Environment Structure group.

o Synoptic Regions   Identification of smaller areas within the synoptic patterns where certain characteristic types of TC motion may be expected to occur.

A further description of these pattern and region models is given in sections C.2 and C.3 below.

2.1.2 TC Structure

Characterizations of the intensity and size of the symmetric TC (Table C.2). Within the TC Structure group, the conceptual models are organized into two subsets based on TC Intensity and TC Size (Table C.2) Since the definitions of TC intensity and size are rather straightforward, no further discussion is given here.

2.1.3 TC-Environment Transformations

Characterizations of one- and/or two-way advections or energy exchanges between the TC and the environment (Table C.3). Within the TC-Environment Transformations group (Table C.3), the conceptual models are organized into three subsets based on the primary direction of influence between the TC and the environment:

A. TC Modifications: Changes in the structure of the TC due to the influence of the environment, without significant changes in environment structure; and

B. Environment Modifications: Changes in the structure of the environment due to the influence of the TC, without significant changes in TC structure; and

C. TC-Environment Interactions: Changes in both the structure of the TC and the environment due to their mutual influence.

Based on this framework of TC-environment conceptual models, the TC-environment context at any time may be characterized in terms of: (1) one synoptic pattern, or a transition state between two synoptic patterns; (2) one synoptic region, or a transition zone between two synoptic regions; (3) one TC size class; (4) one TC intensity class; and (5) one or more TC-environment transformations, if applicable. Although the knowledge base consists of many individual models that must be considered as candidates, only a relatively small subset applies in each forecast situation. The relationships among the various model groups and subsets that define the complete TC-environment context are shown in Figure C.2. Notice that selection of models within the TC-Environment Transformation group depends on information derived from both the Environment Structure and TC Structure groups.

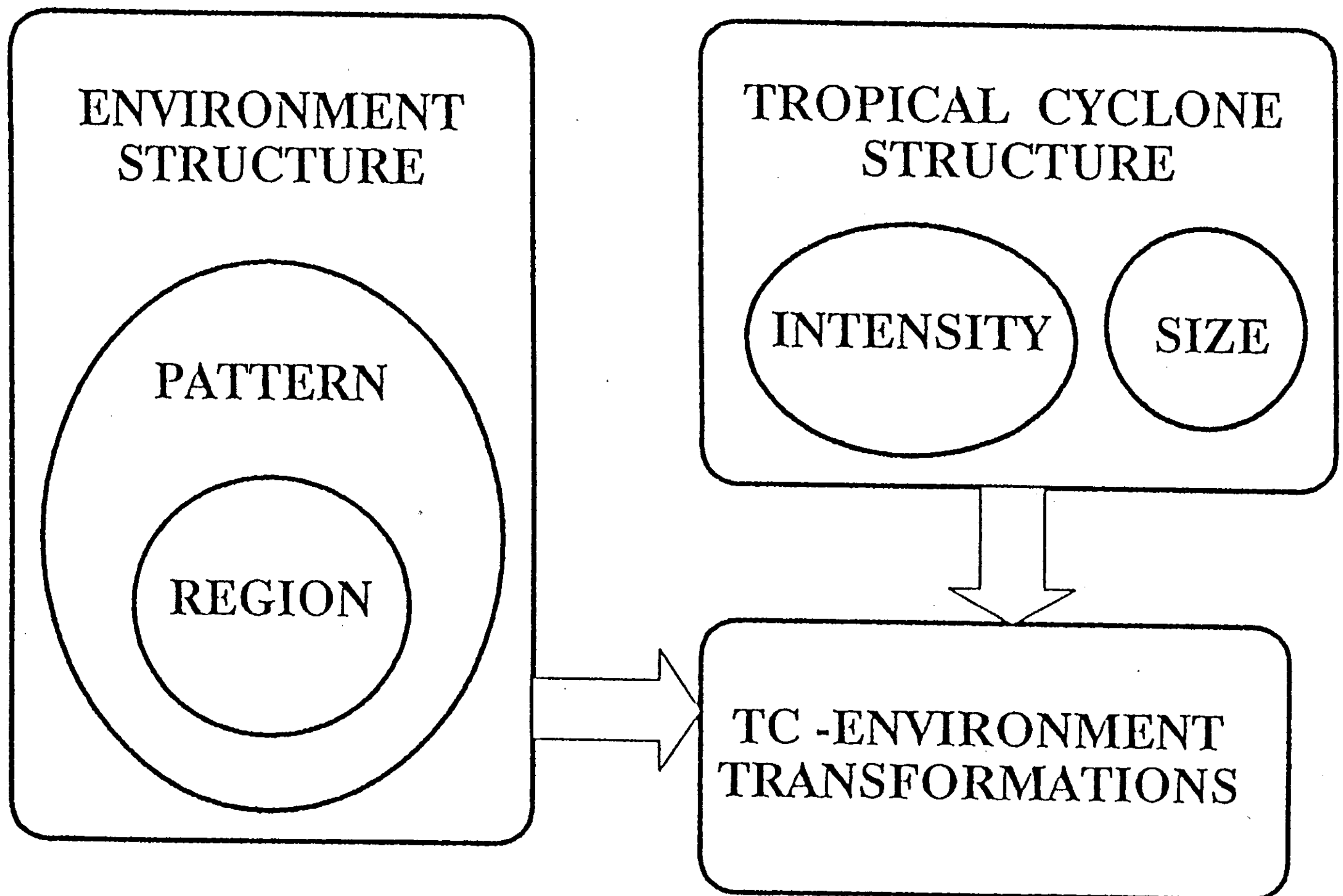


Figure C.2. Pictorial of the relationships among the Environmental Structure, TC Structure, and the TC-Environment Transformation conceptual models within the complete conceptual picture of the TC track forecast problem.

Tropical Cyclone Structure Models

- **TC Intensity**
  - **Exposed Low-level Circulation**
  - **Tropical Depression/Storm ($25 \leq V_m \leq 60$)**
  - **Typhoon ($65 \leq V_m \leq V100$)**
  - **Intense Typhoon ($V_m \geq 105$)**

- **TC Size**
  - **Midget TC**
  - **Small TC**
  - **Typical TC**
  - **Large TC**

Table C.2. Listing of the TC Intensity and TC Size conceptual models within the TC Structure model group. TC intensities are based on the maximum wind speed (V_m) in knots. The TS and TY thresholds of 35 and 65 kt, respectively, are used to be consistent JTWC warnings, which report wind speeds in 5-kt increments.

2.2 Environment Structure Conceptual Models

The following sections define the individual Environment Structure conceptual models and illustrate the models using either a pictorial presentation or numerical model simulations. All of the Environment Structure models are for the mid-troposphere, which is approximately the 500 mb level. The structure and orientation of the mid-tropospheric subtropical ridge is the prominent feature in many of the conceptual models. The term "ridge" will hereafter be understood to mean "mid-tropospheric subtropical ridge", unless another ridge such as a mid-latitude or subequatorial is intended and specified.

2.3 Synoptic Patterns

2.3.1 Standard Pattern (S)

For the environmental pattern surrounding the TC to be classified as Standard (S), the axis of the ridge circulation influencing the steering of the TC must be approximately zonally-oriented. In an idealized S pattern (Fig. C.3), an east-west oriented ridge separates tradewind easterly flow to the south from mid-latitude westerly flow to the north. The ridge structure may be modulated by a principal mid-latitude trough that produces a col region (usually called a "break") in the ridge south of the mid-latitude trough. The idealized S pattern also includes a clockwise-rotating circulation with a zonally-oriented axis to the south of the tradewind easterlies, and westerly flow farther south. This circulation will usually represent the monsoon trough.

Notice that TC symbols and concentric circles have been placed at various positions in Figure C.3 to indicate where the TC circulation may be found relative to the ridge. Typical circulation sizes are depicted for small, medium, and large radii by one, two and three dashed rings respectively. Although pattern orientation relative to the TC is important, by definition the circulation of the TC being forecast is excluded. An experienced forecaster will mentally remove the TC circulation from the NOGAPS fields. However, a filter would be required for an automated version of the systematic approach.

Although the S pattern pictorial is for a single instant in time, connecting sequences of the TC symbols in Figure C.3 gives the general sense of the basic types of TC tracks that may occur. TC symbol sequence 1-2-3 represents the straight or "straight-runner" track, and sequence 1-4-5 represents the recurvature or "recurver" track. However, this assumes that the S pattern is not transitioning to another pattern (e.g., due to the influence of TC-environment transformations).

The possible TC positions in Figure C.3 are distinct from the idealized monsoon trough. However, it is recognized that large TCs do not clearly separate from the monsoon trough early in their lifecycle; rather, the large TC and monsoon troughs tend to temporarily move together. This situation is ignored in defining and recognizing the S pattern, and does not affect the utility of the definition because it is assumed that the ridge structure will dominate TC motion as long as the large-scale

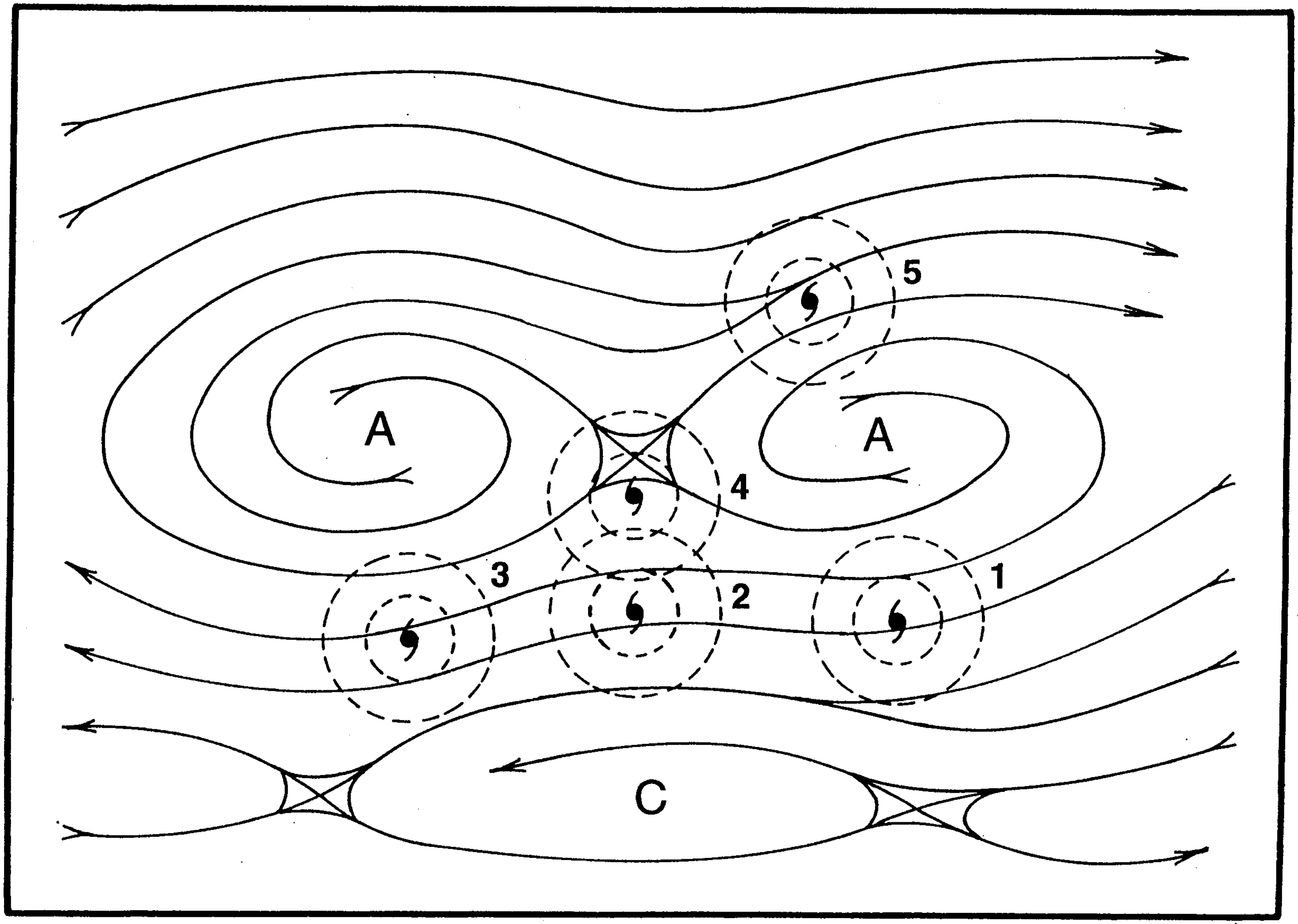


Figure C.3. Idealized pictorial of the Standard Pattern (s) synoptic conceptual model. TC symbols and dotted concentric circle denote possible positions for TC within the S pattern.

environment conforms to the S pattern and TC-environment transformations are not expected.

The S pattern pictorial is intended to be a basic template for the most common TC environment. Thus, it must be adapted to conform to particular synoptic situations; e.g., by a shift in latitude or longitude. During the Northern Hemisphere (NH) summer monsoon season, the S pattern appears farther north so that the clockwise-rotating circulation represents the monsoon trough with westerlies to the south. During the fall and spring transition seasons, the S pattern will appear farther south, and hence the clockwise-rotating circulation typically will represent a near-equatorial trough. During the NH winter, the S pattern will be shifted even farther south so that the near-equatorial trough is along the equator and becomes a buffer zone.

Important and frequently observed variants of the S pattern include:

A. absence of a significant break in the ridge in the general vicinity of the TC;

B. different latitudes of the east and west ridge circulations so that the ridge axis has a west-southwest to east-northeast or west-northwest to east-southeast orientation; and

C. unequal meridional extents of the ridge circulations on either side of the main break in the ridge.

The first variant produces predominantly easterly steering, and may result in prolonged and nearly due westward TC motion if the S pattern persists and no significant TC-environment transformations are taking place. The remaining two variants produce steering that deviates significantly from easterly, and may result in significant increases or decreases in latitude while the TC is equatorward of the ridge axis.

2.3.2 <u>North-Oriented Pattern (N)</u>

The conditions for classifying an environmental pattern as North-oriented (N) are: (1) a significant break in the ridge must be present to the north of the TC; and (2) a prominent, and primarily north-south oriented, ridge to the east of the ridge break that extends significantly south of the latitude of the TC. Such an anomalous ridge structure to the east of the TC can arise from either a TC-independent or TC-dependent situation:

N1. TC-independent: the development of a reverse-oriented (RO) monsoon trough as defined by Lander (1994; personal communication); or

N2. TC-dependent: the occurrence of one of the following TC-environment transformations (Table C.3): (1) modification of the ridge by a large TC (RMT); or (2) interaction of a monsoon gyre (MG; a large, relatively weak cyclone embedded in the monsoon trough) and a TC involving coalescence of the MG and TC (MTI). See Carr and Elsberry (1994b) for information concerning these two transformations.

In the N1 pattern pictorial (Fig. C4.a), the monsoon trough is depicted as an unbroken feature, despite the removal of the TC circulation. The southwest/northeast orientation of this RO monsoon trough is distinctively different from the climatological west-northwest to east-southeast orientation (cf. Elsberry 1987; Fig. 3.18a). Lander (1994) views the RO monsoon trough as one of several modes of deviation from the climatological monsoon trough, and notes that the RO monsoon trough typically persists for several weeks. Notice the anomalous ridge circulation to the east, which has an orientation that roughly parallels the RO monsoon trough. As suggested by the numbered sequence of TC symbols in Figure C.4a, TCs typically form in the generally southerly flow between the trough and ridge features, proceed on a roughly northward track, and recurve at a higher than normal latitude.

An N pattern is classified as N2 when one large TC is present as opposed to an RO monsoon trough with one or more smaller TC(s) embedded in it. In the N2 pictorial (Fig. C.4b), the removal of the circulation of the large TC circulation or coalesced MG-TC leaves a monsoon trough that is restricted to the southwestern portion of the pattern. Another important dissimilarity is that the position of the large TC in the N2 pattern is confined to a particular location relative to the anomalous eastern ridge circulation(s), whereas the TC position in the N1 pattern can be anywhere in the southerly flow between the trough and the anomalous ridge. Thus, the N2 pattern tends to move with the large TC, or coalesced MG-TC, which in turn moves generally northward in response to the southerly steering produced by the ridge to the east.

2.3.3 Monsoon Gyre Pattern (G)

The monsoon gyre pattern (G) (Fig. C.5) exists whenever the TC environment includes a particularly large MG, as described by Lander (1994). The gyre is the eastern-most circulation in the monsoon trough, and is displaced to the north, which gives the monsoon trough axis a southwest-northeast orientation that resembles the RO monsoon trough (Fig. C.4a). In the G pattern, the large MG circulation is so extensive (typically more than 2000 km in diameter) that it becomes the dominant circulation in the western North Pacific. Lander also notes that this large MG may be long-lived (up to three weeks), migrate slowly to the west during its lifecycle, and may evolve into a very large TC.

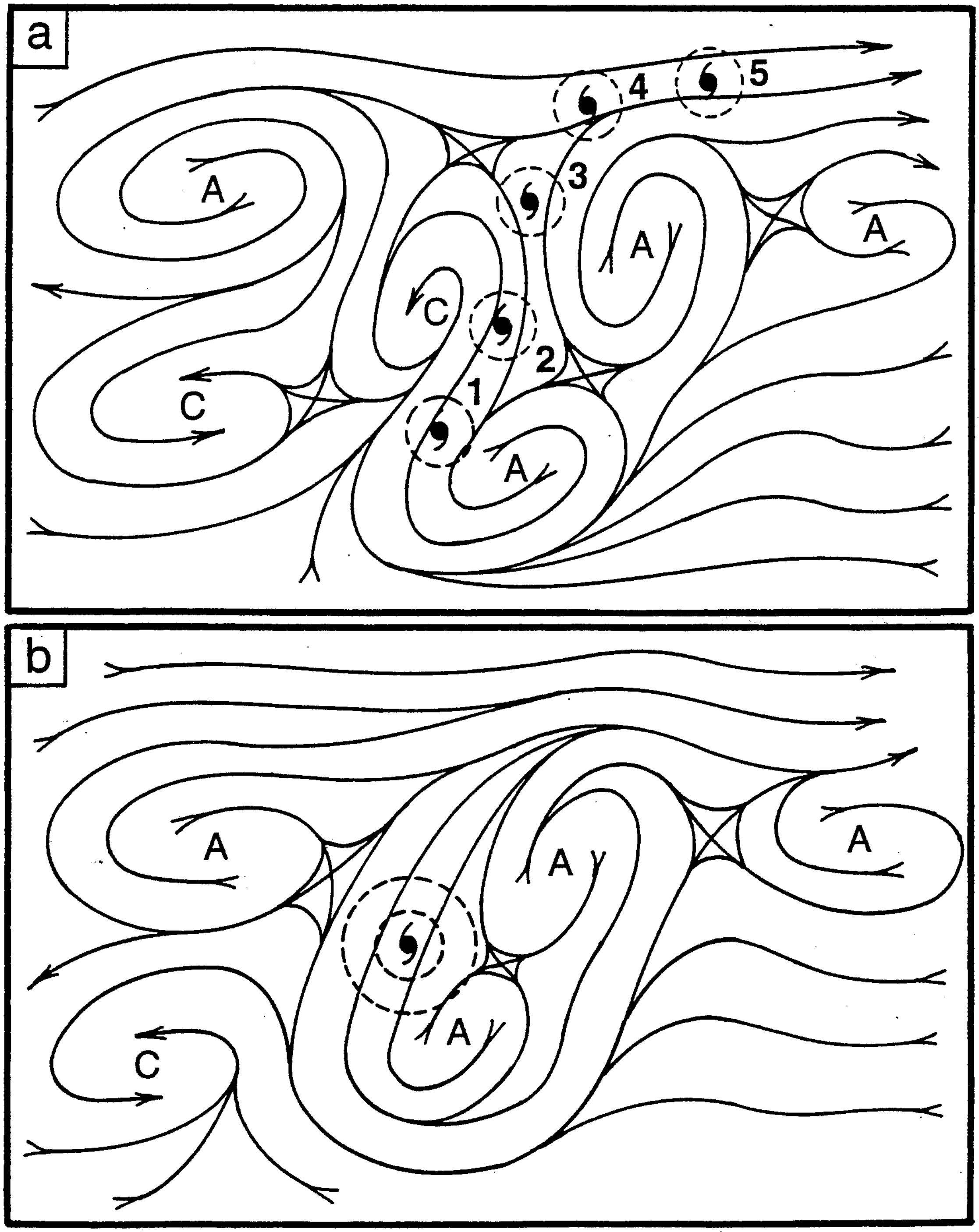


Figure C.5. As in Figure C.3, except for Monsoon Gyre Pattern (G).

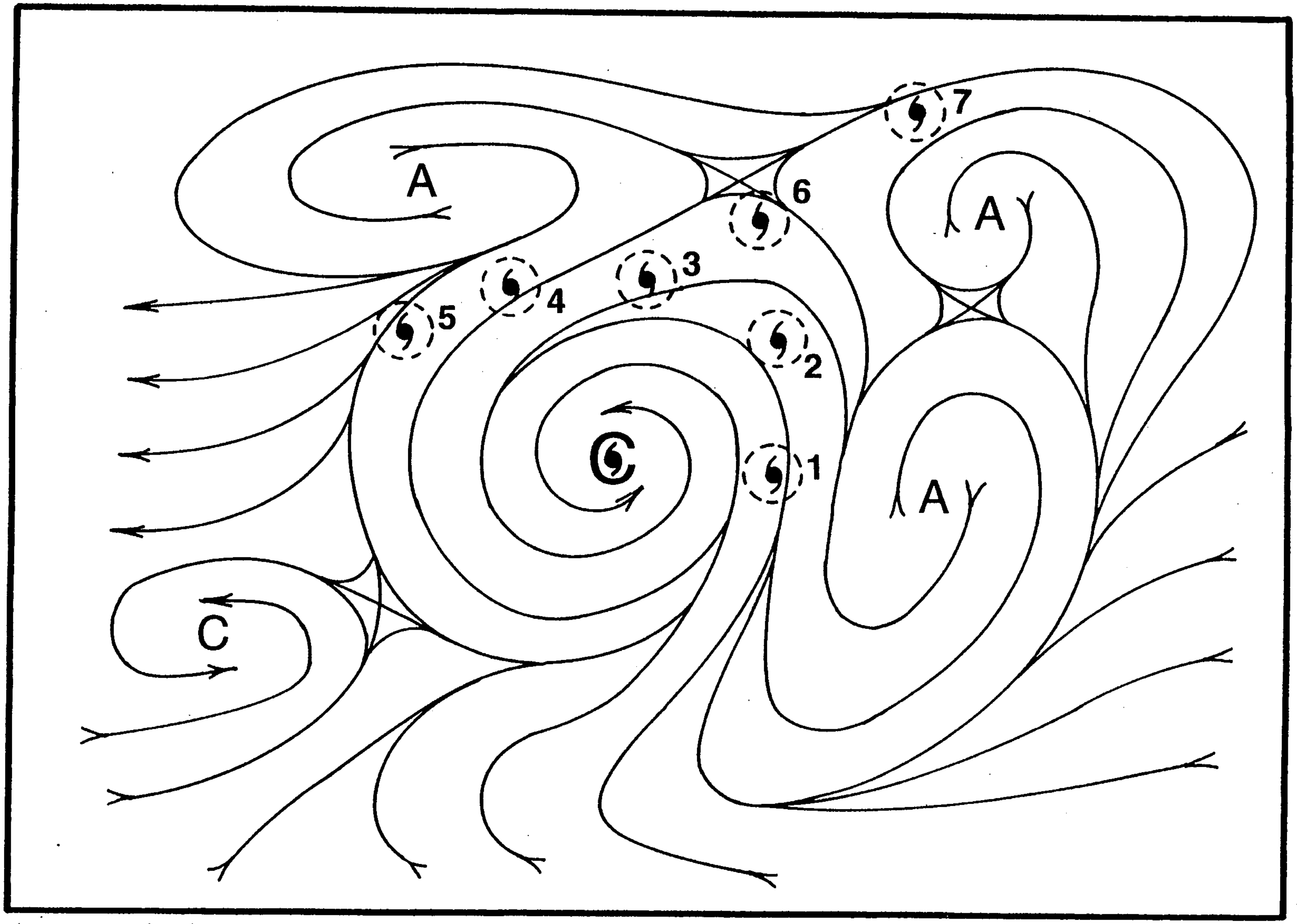


Figure C.7. Idealized pictorial of the Standard Pattern (S) synoptic conceptual model, except with the boundaries of the associated synoptic region conceptual models added. DR denotes the Dominant Ridge Region, WR the Weakened Ridge Region, and AW the Accelerating Midlatitude Westerlies Region.

The G pattern has an anomalous north-south oriented ridge circulation to the east of the large MG. Extensive, deep convection occurs in the confluent region between the large MG and the peripheral ridging, and the area of convection tends to be wrapped around the large MG, and takes on a characteristic "fish-hook" shape. The curvature of this large convective band would tend to produce enhanced subsidence to the west, which may partially explain the extensive area of suppressed cloudiness over most of the gyre within the radius of maximum winds.

Arakawa (1952) was evidently referring to the G pattern confluent area when describing a "convergence area in the sub-tropics", which he found to be a preferred location for the formation of midget typhoons. Such formations are illustrated in Figure C.5 by the relatively small circulations around the TC symbols. After forming in the confluent region, a midget TC will tend to move around the large MG and enter the east-northeasterly steering between the large MG and the ridge circulation to the northwest (TC symbol sequence 1-2-3-4-5). An alternate path is to continue northward and recurve through the break in the ridge (TC symbol sequence 1-2-6-7). The TC symbol at the gyre center indicates that in certain instances the large MG can evolve into a large TC as the outer convection band wraps and tightens around the center with associated central pressure falls and reduction of the radius of maximum winds.

2.3.4 Multiple Tropical Cyclone (M)

A classification of the environmental pattern as Multiple Tropical Cyclone (M) requires that the two TCs are: (1) in proximity to each other (less than about 20° lat.), but with a separation distance that would not result in a significant binary (Fujiwhara) interaction, which generally occurs at less than 10-12° lat. (Brand (1970); Dong and Neumann (1983)); (2) oriented approximately east-west; and (3) sufficiently close (north or south) to the ridge axis such that the height gradient between the western TC and the eastern ridge circulation subjects the eastern TC to moderately strong (10-15 kt) and predominantly southerly steering flow (Fig. C.6a), and/or the height gradient between the eastern TC and the western ridge circulation subjects the western TC to moderately strong and predominantly northerly steering flow (Fig. C.6b). By virtue of the above criteria, the two TCs that make up the M pattern have roughly fixed positions relative to the pattern. As long as the pattern exists (i.e., satisfies the defining criteria), it tends to move with the centroid of the two TCs. However, it is possible for additional TCs to be present to the southeast of the eastern TC and to the southwest of the western TC without setting up competing M patterns, as long as they are well south of the ridge axis.

In an M pattern, the eastern TC is acting to inhibit the recurvature of the western TC, and the western TC is concurrently

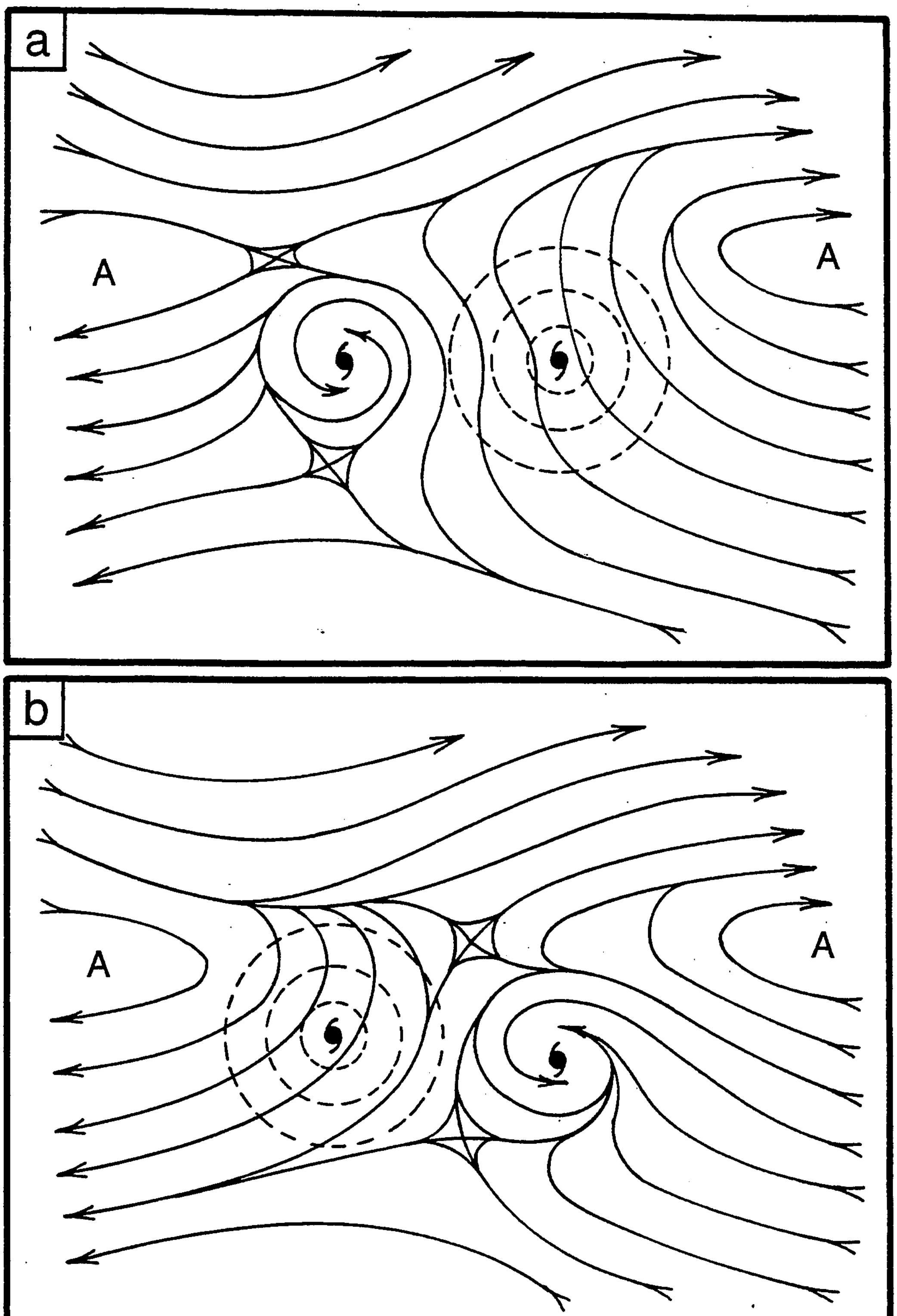


Figure C.9. As in Figure C.7, except for the monsoon Gyre Pattern (G) and associated synoptic regions.

In an M pattern, the eastern TC is acting to inhibit the recurvature of the western TC, and the western TC is concurrently acting to encourage the recurvature of the eastern TC. The "and/or" terminology in criterion (3) above, allows for variations in the mutual influence as determined by the relative outer wind strengths of the TCs and the strengths of the ridge circulations. The two extremes would be a one-way influence of the eastern TC-western ridge pair on the western TC, and vice versa.

If criteria (2) and (3) are satisfied, but (1) is not satisfied due to insufficient separation, then an M pattern still exists. However, a Fujiwhara interaction, which falls under the TC-Environment Transformations conceptual models (Table C.3) may be superimposed on the M pattern. The classical Fujiwhara effect arises when the circulations of two vortices are mutually advecting. That is, the separation distances and circulation sizes of the two TCs are sufficient to cause mutual track changes in the absence of any background flow. If a background flow does exist, its influence then combines with the Fujiwhara effect.

The M pattern concept is related to the Fujiwhara effect in the sense that the presence of each TC circulation is having an influence on the circulation of its counterpart. However, the key conceptual distinction between the classical Fujiwhara effect and the M pattern is in the role of the environment. In the M pattern, the presence of the environment, specifically the subtropical ridge, is necessary for the two TCs to have a mutual influence on each other at the separation distances given by criteria (1).

2.4 Synoptic Regions

Recall that the synoptic pattern conceptual models are adaptable templates to classify and characterize the large-scale environment of the TC. Similarly, the synoptic region conceptual models are adaptable templates to classify areas within the synoptic patterns that determine the environmental steering influence on TC motion. Notice that in figures C.7 through C.10 the synoptic regions are shown as solid lines for emphasis. TC symbols are numbered to depict the sequence of positions of TCs under the influence of various synoptic regions. A basic concept is that an unbroken, east-west oriented ridge may be viewed as a barrier to the northward movement of the TCs by virtue of its deep layer of dry, subsiding air, and the absence of any steering at the ridge axis. In the absence of TC-independent environmental evolutions to produce a break in the ridge, or TC-environment transformations that alter the ridge structure, the ridge circulation will dominate TC motion by constraining it to be roughly westward in the tropics. It is for this reason that the synoptic region will generally be in a specific orientation relative to ridge circulations. The region models will be depicted with well-defined boundaries. However, since the environment of the TC is a continuum of flow features, the synoptic regions are actually smoothly blended via transition areas.

TC-Environment

Transformation Models

* **TC Modifications**
    * **Basic ß-effect propagation (BEP)**
    * **Vertical Wind Shear (VWS)**

* **Environment Modifications**
    * **Ridge modification by large TC (RMT)**
    * **Mid-level trough modification by TC (TMT)**

* **TC-Environment Interactions**
    * **Monsoon gyre-TC interaction (MTI)**
    * **TC-TC interaction (TTI Fujiwhara effect)**

Table C.3. Listing of the TC Modification, Environment Modification, and TC-Environment Interaction conceptual models within the TC-Environment Transformation conceptual model group.

2.4.1 Dominant Subtropical Ridge (DR)

The DR region, which exists in all of the synoptic patterns, consists of all locations that satisfy the following criteria: (1) poleward of the monsoon or equatorial trough axis, or poleward of about 5° lat. if no trough axis exists; (2) equatorward of the axis of an east-west oriented ridge circulation that tends to dominate the motion of the TC by producing roughly easterly steering of about 10-15 kt; and (3) not in the vicinity of a "significant" break along the ridge axis (usually associated with a mid-latitude trough) that weakens the steering flow and makes it more southerly. In general, stronger and more zonally extensive ridge circulations have greater potential for the associated easterly steering to dominate TC motion. However, it is emphasized that whether or not a ridge steering actually will dominate TC motion, and whether or not a weakness/break in the ridge is "significant", depends greatly on TC size, and on any TC-environment transformations.

The locations and extent in the DR regions in the S, N, G, and M patterns are shown in Figures C.7 through C.10, respectively. By definition, the environmental steering in the DR region always has an easterly component. However, the relative contribution of a southerly or northerly component depends on the particular pattern and location of the DR region within the pattern.

In the Standard S pattern (Fig. C.7), a single extensive DR region is present, and the north-south extent of the DR region is zonally uniform, except in the vicinity of the ridge weakness. Various TC positions in the DR region are illustrated in Figure C.7. In a persistent S pattern a TC can remain continually in the DR region if it forms sufficiently close to the equator and eventually makes landfall before gaining enough latitude to encounter the ridge axis. Within the context of the systematic approach, the traditional "straight runner" TC is continually dominated by the ridge.

In the North-oriented N1 and N2 patterns (Fig. C.8a-b), two separate DR regions are present, one southeast of the anomalous ridging and another west of the RO monsoon trough or coalesced MG-TC. In the N1 pattern, the extensive confluent area between the RO monsoon trough and the ridging to the east is a highly preferred TC formation area. Extensive convective activity in the confluent area produces significant subsidence on either side, which tends to suppress TC development. Thus, the presence of TCs in the DR regions associated with the N1 pattern is rare. However, TC genesis is routinely observed in the eastern DR region of the N2 pattern.

In the Monsoon Gyre (G) pattern (Fig. C.9), two DR regions exist. The DR region to the southeast of the ridge is similar to

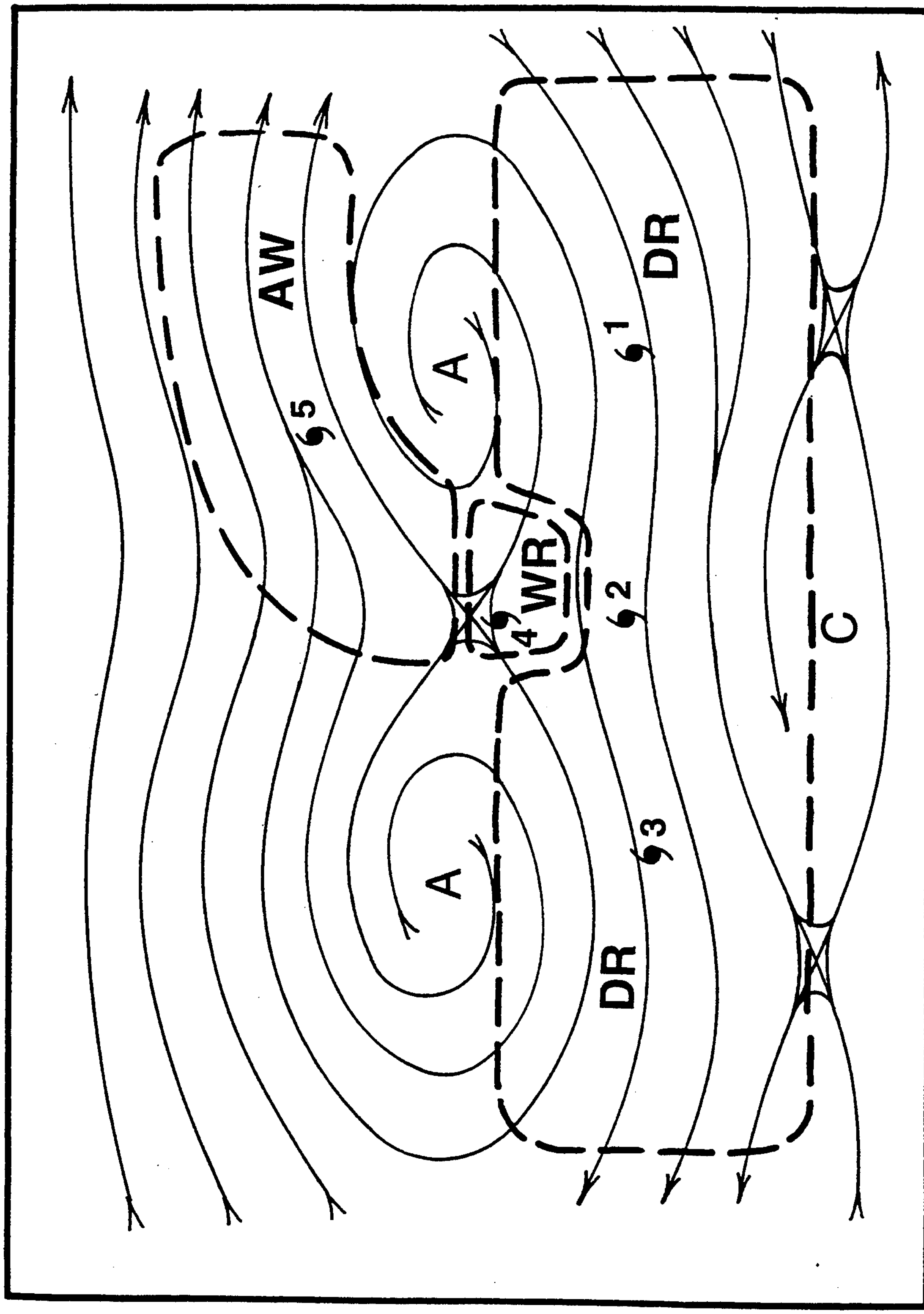


Figure C.4. As in Figure C.3, except for North-oriented Patterns (a) N1, and (b) N2.

In the Monsoon Gyre (G) pattern (Fig. C.9), two DR regions exist. The DR region to the southeast of the ridge is similar to those for the N patterns discussed above. The DR region to the northwest has a curved southern boundary that is outside the radius of maximum winds of the NSS gyre, which bounds a region with strong subsidence that would tend to inhibit TC formation and maintenance. The steering in this DR region is roughly east-northeasterly due to the gradient between the NSS gyre and the ridge circulation to the north. Thus, small TCs that form to the east and northeast of the NSS, and enter the northwest DR region would be expected to travel west to west-southwestward.

In the Multiple Tropical Cyclone (M) pattern, two DR regions exist: one to the southeast (Fig. C.10a) and one to the southwest (Fig. C.10b). By definition, the two TCs that form the M pattern cannot be in either of the DR regions. As noted earlier, a third TC could exist in one of these areas, which would not change the general character of the M pattern.

2.4.2 **Weakened Subtropical Ridge (WR)**

The WR region consists of locations within a synoptic pattern that are: (1) south of the subtropical ridge axis; (2) east of the center of a break in the ridge; and (3) close enough to the break to be in relatively weak (5-8 kt) and southeasterly-to-southerly steering. Ridges that have small north-south extents, but have large east-west extents, tend to have tight flow curvature, and thus low wind speeds, everywhere along the ridge axis. By contrast, more circular ridges tend to have low wind speeds only near the circulation center. By virtue of weak southerly steering in criterion (3), the WR region will tend to be associated more with the zonally-oriented ridge of the S pattern (Fig. C.7) rather than with the broader ridge circulation of the N (Fig. C.8) and G (Fig. C.9) patterns. Criterion (3) in Section C.2.4 excludes the existence of the WR region in M patterns, which have "moderately strong" steering between the western TC and the eastern ridge.

TCs are found in the WR region of the S pattern in two circumstances: (1) after leaving the DR region and before entering the AW (discussed later) region during recurvature (Fig. C.7; TC symbol sequence 1-4-5); or (2) after leaving the DR region and before returning to it during a "stair-step" maneuver (Fig. C.7; TC symbol sequence 1-4-3).

2.4.3 **North-Oriented (NO)**

The NO region exists only in the N and G patterns and consists of locations that are in the predominantly southerly flow to the west of the anomalous, meridionally-broad ridge circulation. The location and extent of the NO region in the N1, N2, and G patterns are shown in Figures C.8a, C.8b, and C.9,

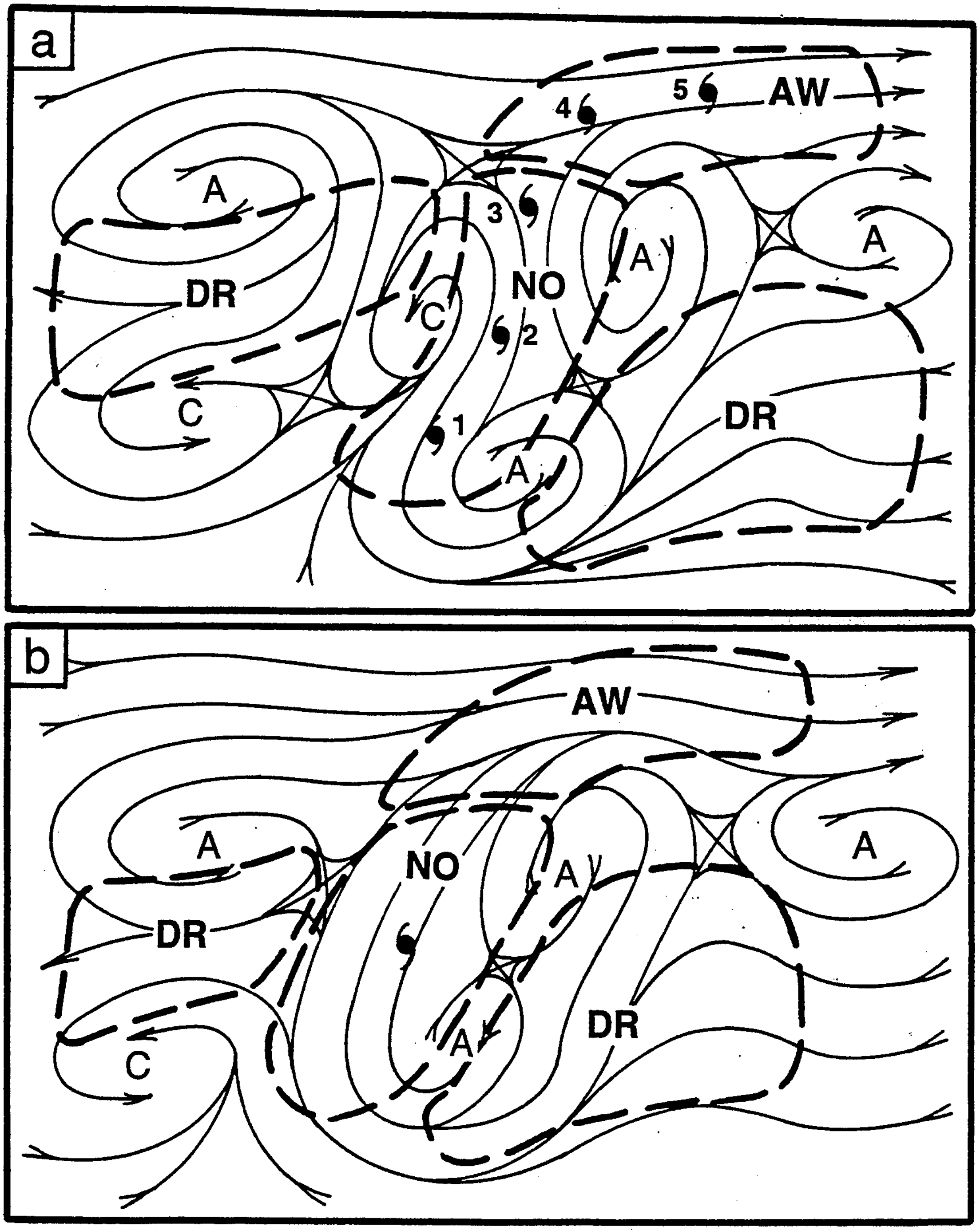


Figure C.6. As in Figure C.3, except for Multiple Tropical Cyclone Pattern (M).

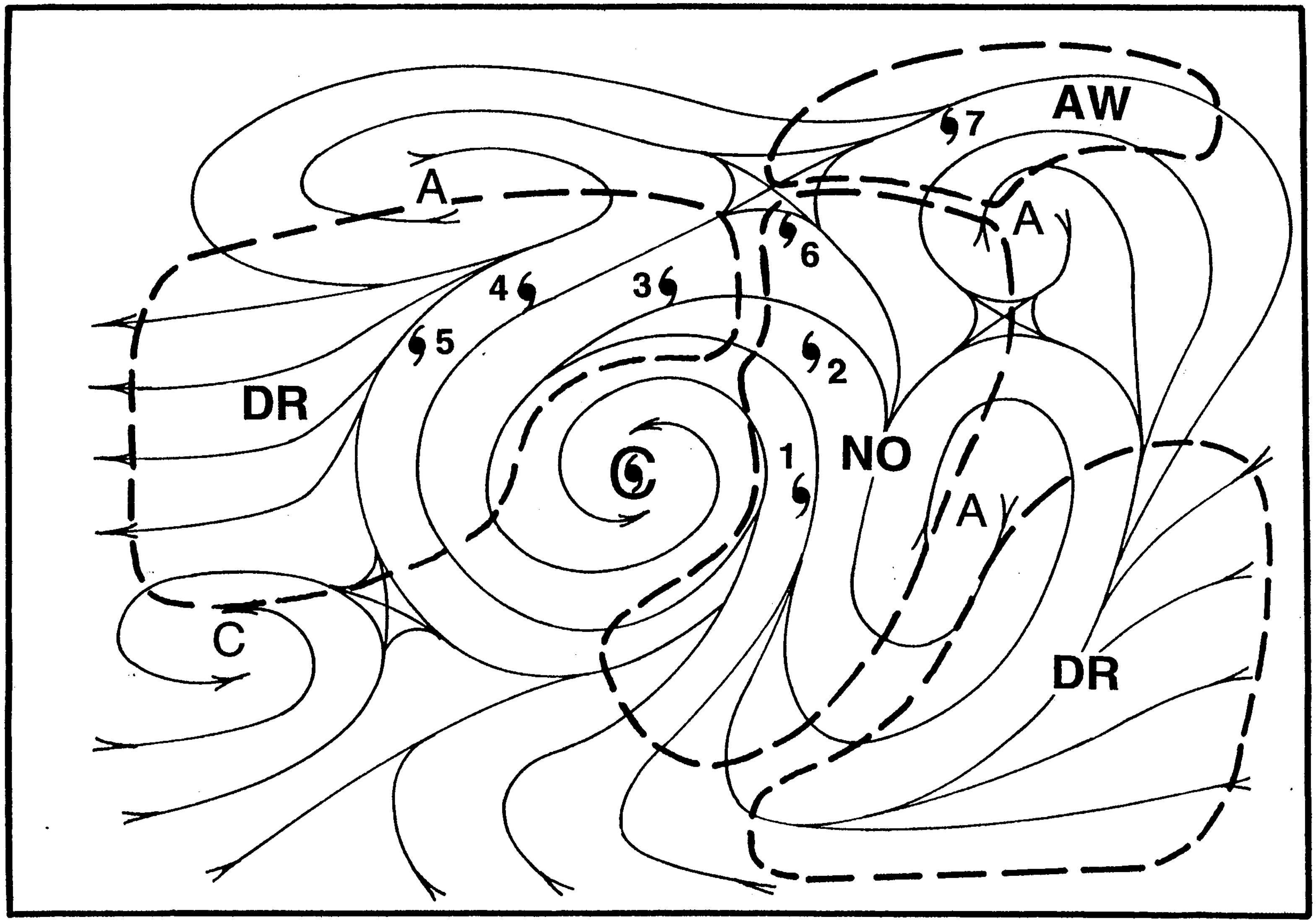


Figure C.8. As in Figure C.7, except for the North-oriented Patterns (a) N1, and (b) N2 and associated synoptic regions. NO denotes the North-oriented Region.

respectively. Recalling that the large TC or coalesced MG-TC in the N2 pattern has a fixed position relative to the pattern, it must always occupy the NO region. In the G pattern, the western boundary of the NO region curves around the NSS gyre, which avoids the region of the gyre where TC formations are hindered by strong subsidence.

2.4.4 Multiple TC Southerly Flow (SF) and Multiple TC Northerly Flow (NF)

The SF region (Fig. C.10a) consists of locations within an M pattern that are: (1) in the predominantly southerly environmental flow on either side of a line running from the center of the western TC to the center of the eastern ridge circulation; and (2) no closer than about 10 degrees of latitude to the western TC. Conversely, the NF region (Fig. C.10b) consists of locations within an M pattern that are: (1) in the predominantly northerly environmental flow on either side of a line running from the center of the eastern TC to the center of the western ridge circulation; and (2) no closer than about 10 degrees of latitude to the eastern TC. Since the two TCs in the idealized M pattern are at about the same latitude and have similar circulation sizes, the SF and NF regions are symmetric about a north-south line running through the centroid between the TCs. However, these idealized SF and NF conceptual models must be adapted to account for the variability of actual situations from the ideal.

2.4.5 Accelerating Mid-latitude Westerlies (AW)

The AW region consists of those locations within a synoptic pattern that are: (1) poleward of the ridge axis, and generally within about 10 degrees of latitude of the ridge axis; and (2) east of the ridge-break neutral point. The AW region is common to all the synoptic patterns, and its location and extent in the S, N, G, and M patterns models are shown in Figures C.7-C.10, respectively. In these pictorials, the AW regions are zonally oriented, and have associated steering flows that are predominantly zonal. In nature, the orientation and flow within the AW region can vary greatly depending on the structures of the ridge and adjacent mid-latitude trough and associated mid-latitude troughs/ridges (e.g., low versus high index situations). TCs in the AW region typically undergo significant accelerations as well. Accelerations of 20 kt/day are common, and translation speeds can exceed 40 kt. Determining the timing and magnitude of the acceleration period continues to be one of the more serious challenges confronting the TC forecaster.

2.5 Summary

The above material has been distilled from Carr and Elsberry (1994), and has been restricted to the environment structure

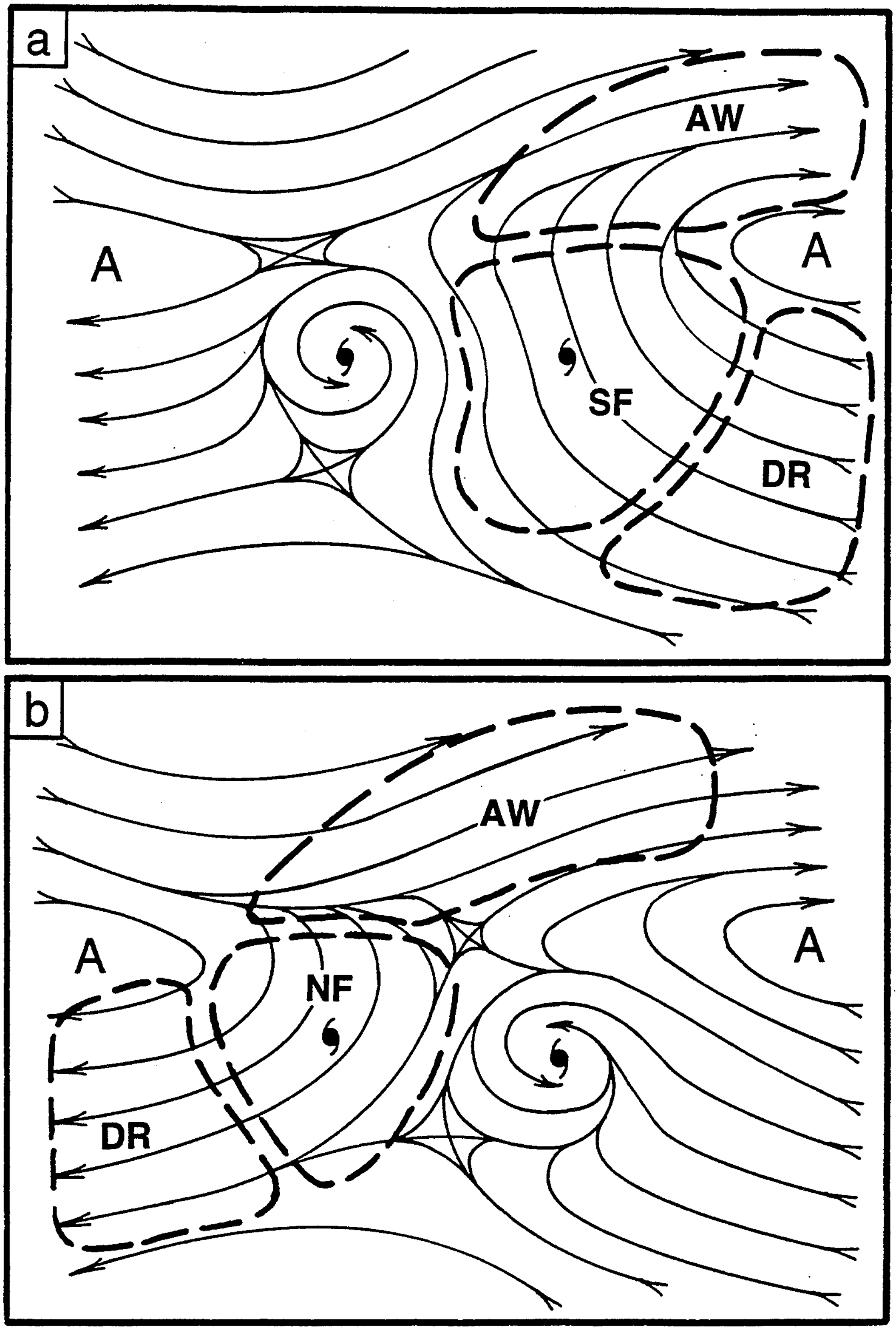


Figure C.10. As in Figure C.7, except for the Multiple Tropical Pattern (M) and associated synoptic regions. SF denotes Southerly Flow Region and NF denotes NF Northerly Flow Region.

portion of Figure C.2. The essence of the new systematic approach is given in the sequences of TC positions indicated in Figures C.7-C.10 for specific regions within the synoptic patterns. These sequences show qualitatively the types of TC motions that may be expected due to environmental steering only. Actual directions and translation speeds would depend on the particular structure of the relevant synoptic features analyzed and forecast by numerical models such as NOGAPS. The particular track that a TC will take also depends on the presence of any TC-environment transformations (see Figure C.2 and Table C.3), which depend quite sensitively on the outer structure of the TC (size). Each of these aspects may or may not be accurately predicted by the numerical guidance.

Thus, the first phase of the systematic approach in Figure C.1 is to assess the likely accuracy of the numerical guidance, which will have different biases depending on the synoptic pattern and region (environment structure), the structure of the TC, and the presence of TC-environmental transformations. This assessment of the numerical analyses and prognoses is therefore somewhat analogous to assessing the accuracy of numerical guidance for a mid-latitude cyclone forecast, which also depends on position of the cyclone within the large-scale (long-wave) pattern and on adjacent synoptic features (short-wave, jet streaks, etc.). It is expected that the readers of this report will have adequate meteorological analyses and forecasts and TC information to confirm the synoptic pattern and region, and thus to understand the forecast scenario(s).

The second phase of the systematic approach in Figure C.1 is to assess the compatibility of the objective aids with the environment and TC evolution depicted by the numerical guidance. This step is omitted in mid-latitude forecasting, which generally does not rely on statistical or climatological aids due to the comparative superiority of the numerical guidance. However, the use of objective aids continues to be an essential aspect of TC forecasting due to deficiencies in the numerical guidance. An intelligent assessment of the objective aids in the light of the numerical guidance, and especially with due consideration for the impact of TC structure, is best done at TC warning centers, such as JTWC and NHC, that do such assessments routinely and have advanced imagery analysis capabilities. Carr and Elsberry (1994) provide additional details of this phase for the objective aids available at JTWC for the western North Pacific. In other basins, a different set of objective aids may be utilized and the error characteristics in that basin may differ from the western North Pacific.

The final phase of the systematic approach in Figure C.1 is the incorporation of the results of the first and second phases into an official track forecast. A number of procedures for combining numerical guidance and objective aids tracks are described in Carr and Elsberry. These details are not included here, since the purpose of this discussion is to assist operational meteorologists in understanding and interpreting the JTWC prognostic reasoning messages as the systematic approach becomes incorporated into the JTWC operational routine.[2] However, an understanding of the environment patterns and regions will assist operational meteorologists in comprehending and briefing the reasoning process that JTWC forecasters used to develop the official forecast and any expected alternate scenarios.

The systematic approach was briefed at the 1994 Tropical Cyclone Conference in Tokyo, Japan. The approach was well-received, is expected to be tested by JTWC forecasters during the latter half of the 1994 typhoon season.

APPENDIX D

TROPICAL CYCLONE MOTION CLIMATOLOGICAL CHARTS

Tropical cyclone formation occurs in five ocean basins: the North Atlantic, the eastern North Pacific, the western North Pacific, the western South Pacific, and the Indian Ocean. Each of these basins has different synoptic influences that govern tropical cyclone motion. In general, tropical cyclones move westward in the tropics and strike land or move poleward into the middle latitudes and die over land or cooler water. An extensive tropical cyclone track climatology of the western (1945-87) and eastern (1949-82) North Pacific exists in paper form (Climatology of North Pacific Tropical Cyclone Tracks, Miller, et al., 1988). A worldwide tropical cyclone climatology has also been compiled (Crutcher and Quayle, 1974).

1. FORECAST DIFFICULTY BY BASIN

Table D-1 shows the variation of track forecast difficulty among basins. Large values indicate that tropical cyclones are less predictable. As expected, the Australian region tropical cyclone forecasts are the most difficult. The northern Indian Ocean tropical cyclone tracks are generally among the most predictable as their paths are usually limited to the tropics and therefore do not undergo recurvature. The tropical cyclones of the eastern North Pacific are also highly predictable due to the influence of a strong subtropical ridge which inhibits recurvature.

Table D-1 Average normalized forecast difficulty level (FDL) ranked by basin from most to least difficult (Pike, 1985).

	Rank of Basin	24HR	48HR	72HR
1.	SOUTHWEST PACIFIC	1.37	1.34	1.32
2.	NORTH ATLANTIC	1.19	1.24	1.24
3.	NORTHWEST PACIFIC	1.05	1.11	1.15
4.	SOUTHWEST INDIAN	0.91	0.91	0.91
5.	NORTHEAST PACIFIC	0.82	0.79	0.78
6.	NORTH INDIAN	0.66	0.61	0.60

2. NORTHWEST PACIFIC

The western North Pacific is the only region to be active throughout the year (Neumann, 1993). The average number of tropical cyclones is 25.3 per year. The majority of these occur between June and November.

Seasonal variations in western North Pacific tropical cyclone recurvature tracks have been noted (Table D-2). A recurvature rate near 50% exists during early and late tropical cyclone seasons while the frequency falls below 20% during July (Burroughs and Brand, 1972, Guard, 1983).

Although the reasons for the minimum in recurvature in July may be complex, seasonal fluctuations in the mid-latitude westerly winds may be a driving force. Northward migration and weakening of the westerlies during the summer months coincides with the minimum in recurvature and the northward migration of the average latitude of recurvature.

Table D-2 Recurvature statistics based on tropical cyclones occurring from 1965 to 1982. Month is the month of recurvature. REC means recurvature or recurving (Guard, 1983).

MONTH	# TC	# REC	% REC	LATITUDE OF REC RANGE/MEAN	LONGITUDE OF REC FAVORED
JAN	11	5	45	16N	
FEB	4	1	25	15N	
MAR	12	5	42	16N	
APR	16	10	63	13-21N 17N	125-130E 135-145E
MAY	20	14	70	14-23N 18N	116-126E 140-145E
JUN	29	13	45	13-27N 20N	112-122E 130-135E
JUL	75	8	11	23-36N 29N	124-129E 140-145E 160-165E
AUG	91	27	30	23-37N 30N	123-131E 138-148E
SEP	90	44	49	19-37N 26N	124-136E
OCT	68	33	49	14-30N 22N	126-136E 140-151E
NOV	44	16	36	16-22N 20N	126-132E 135-137E 145-151E
DEC	18	5	28	14-19N 17N	112-113E 119-130E
TOTAL	478	181	38%		

Figures D-1 through D-12 show the 300 mb monthly mean streamlines (Sadler, 1975) and the typical tropical cyclone tracks (Miller, et al., 1988).

3. NORTHEAST PACIFIC

An average of 12 tropical cyclones occur each year in this region and most occur between May and October. Tropical cyclones tend to track northwest and dissipate over the cooler open ocean north of approximately 20°N (Elsberry, et al., 1987).

An interesting seasonal change in the eastern North Pacific is the reduced frequency of recurving tropical cyclones during July (Allard, 1984). It appears that the presence of a strong upper level anticyclone over the southwestern United States, and cold water created by upwelling along the coast of North America during July, inhibit recurvature.

Figures D-13 through D-17 show monthly mean 300 mb streamlines (Sadler, 1975) and tropical cyclone tracks (Miller, et al., 1988) for the eastern North Pacific. Figures are not included for seasons in which tropical cyclones occur infrequently.

4. NORTH ATLANTIC

The annual number of tropical cyclones is highly variable (1 to 21 cyclones) with a mean of 9.4 per year. Tropical cyclones usually form in the SW Caribbean and Gulf of Mexico early and late in the year and in the central Atlantic during the height of the season.

Figures D-18 through D-23 show mean monthly 300 mb streamlines (Sadler, 1975) and typical tropical cyclone tracks (after Crutcher and Quayle, 1974) for the Atlantic. Figures are not included for seasons in which tropical cyclones occur infrequently.

5. NORTH INDIAN OCEAN

Tropical cyclones in this basin are usually a precursor to the onset of either the SW (summer) monsoon or the NE (winter) monsoon. Tropical cyclones are rare during mid-summer and mid-winter. An average of 5.7 tropical cyclones occur each year with the majority occurring in the Bay of Bengal. The onset of the summer monsoon occurs between April and July while the onset of the winter monsoon occurs between August and December. Tropical cyclones in the north Indian Ocean tend to track north-northwest and strike land because the Asian continent extends southward well into the tropics.

Figures D-24 and D-25 show mean monthly 300 mb streamlines (Sadler, 1975) and typical tropical cyclone tracks (after Crutcher and Quayle, 1974) for the North Indian Ocean. Figures for the months of April, May, July, August, September, November and

December are ommitted even though tropical cyclones have occurred during these months.

6. SOUTHWEST INDIAN OCEAN

Storms in this basin tend to track southwest, then recurve near the axis of the subtropical ridge. An average of 11.2 tropical cyclones occur in this basin each year.

Figures D-26 and D-29 show mean monthly 300 mb streamlines (Sadler, 1975) and typical tropical cyclone tracks (after Crutcher and Quayle, 1974) for the southwest Indian Ocean. Figures are not included for seasons in which tropical cyclones occur infrequently.

7. AUSTRALIAN REGION AND SOUTH PACIFIC

In the Australian region (western South Pacific and southeastern Indian Ocean), tropical cyclone tracks tend to be less predictable than in the other areas. In fact, Australian region tropical cyclones are considered predictable only for 24 hour forecasts. One of the reasons for the difficulty in track prediction in the Australian region is that these tropical cyclones occur closer to the equator where the observations are sparse, making it difficult to determine the environmental steering (Keenan, 1982).

An average of 14.8 tropical cyclones occur in the Australian Region and the South Pacific each year. Occasionally tropical cyclones occur as far west as 135°W. These tropical cyclones typically recurve east of Australia. Occasionally tropical cyclones will move ashore along the northeast coast of Australia.

Figures D-30 through D-34 show mean streamlines (Sadler, 1975) and typical tropical cyclone tracks (after Crutcher and Quayle, 1974) for the Australian region and South Pacific. Figures are not included for seasons in which tropical cylcones occur infrequently.

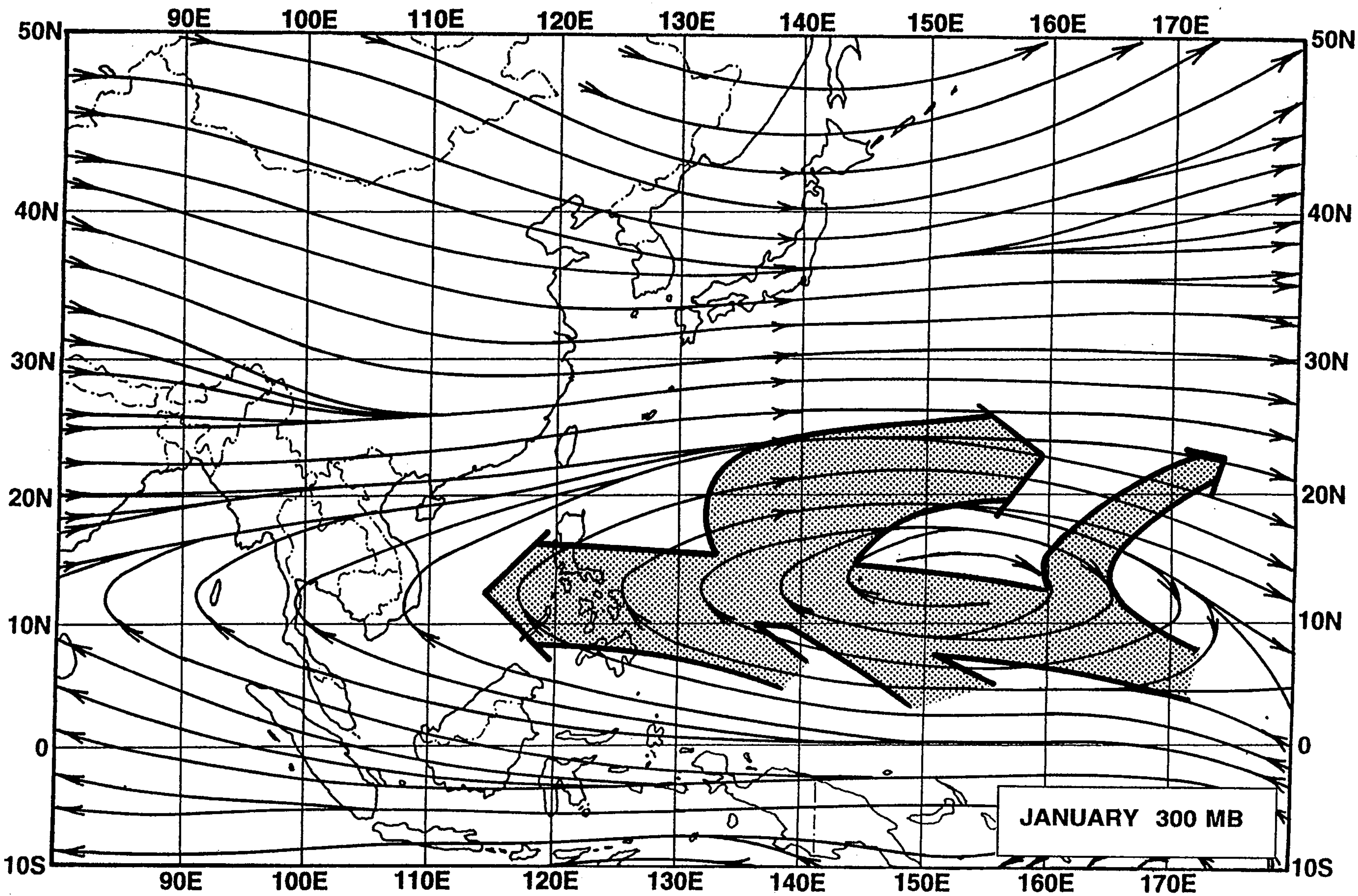


Figure D-1. January 300 mb streamlines and mean tropical cyclone paths for the Northwest Pacific Ocean. Streamlines adapted from Sadler, 1975. Tropical cyclone paths adapted from Miller, Tsui, and Schrader, 1988.

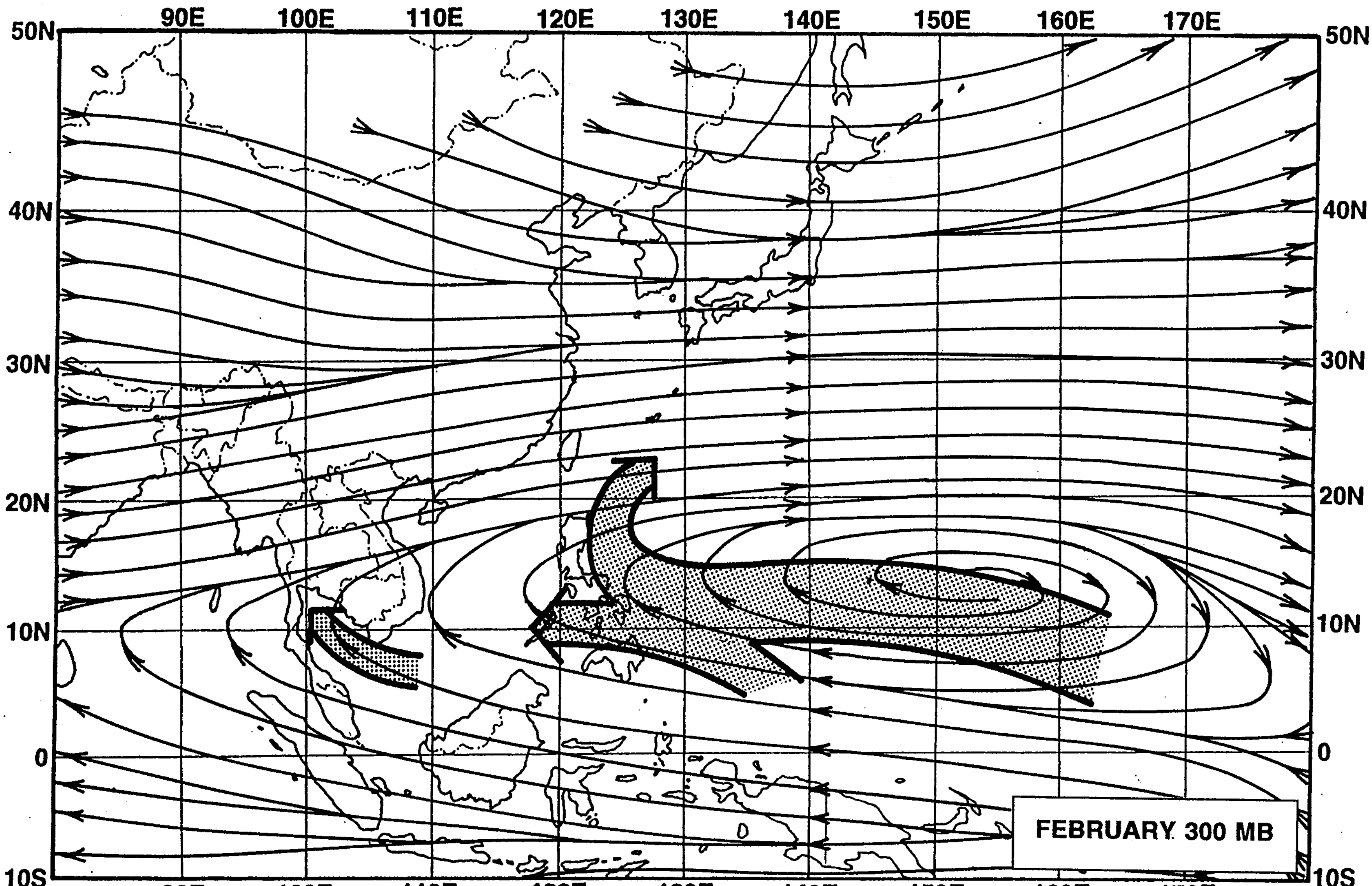


Figure D-2. February 300 mb streamlines and mean tropical cyclone paths for the Northwest Pacific Ocean. Streamlines adapted from Sadler, 1975. Tropical cyclone paths adapted from Miller, Tsui, and Schrader, 1988.

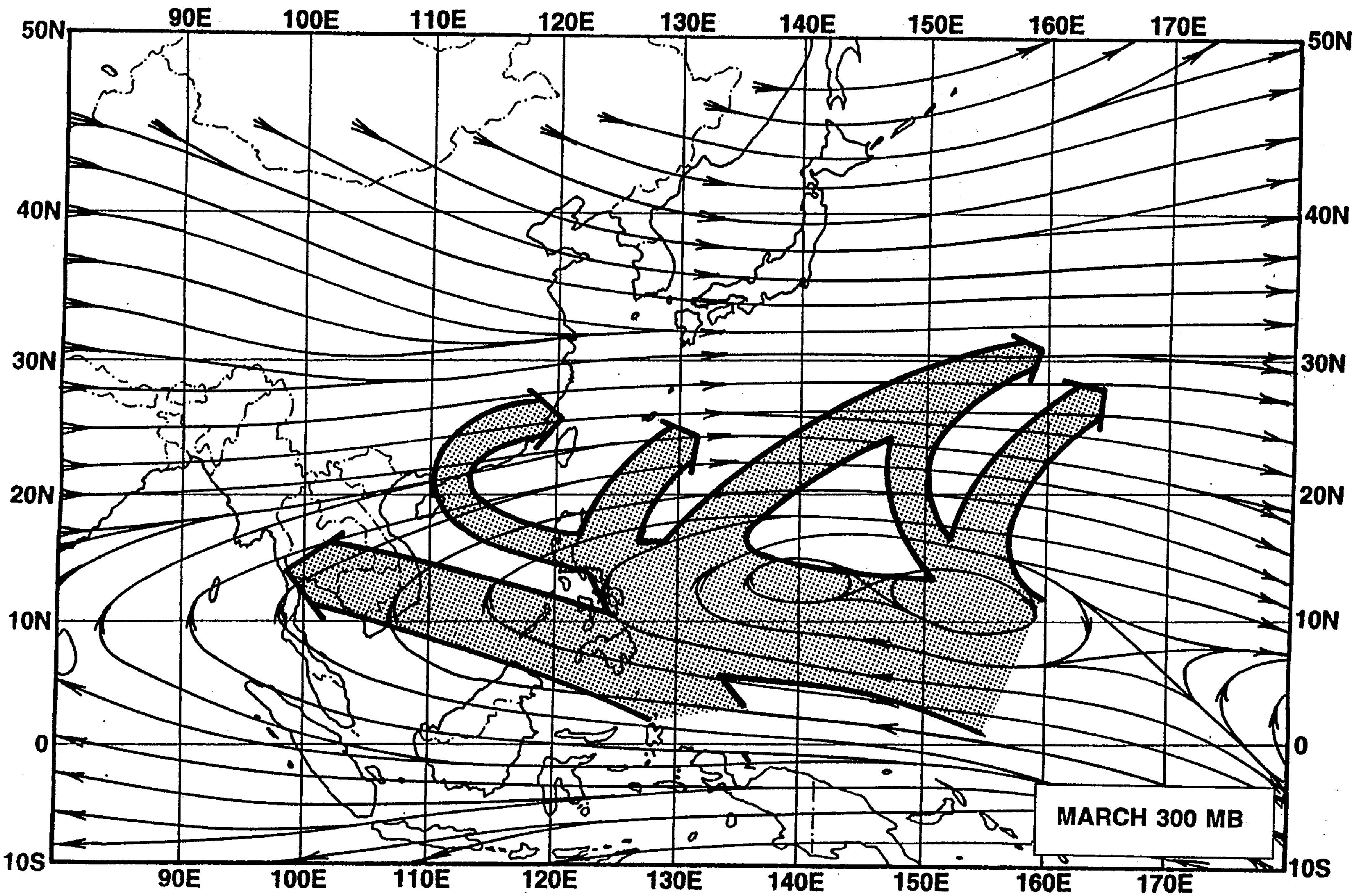


Figure D-3. March 300 mb streamlines and mean tropical cyclone paths for the Northwest Pacific Ocean. Streamlines adapted from Sadler, 1975. Tropical cyclone paths adapted from Miller, Tsui, and Schrader, 1988.

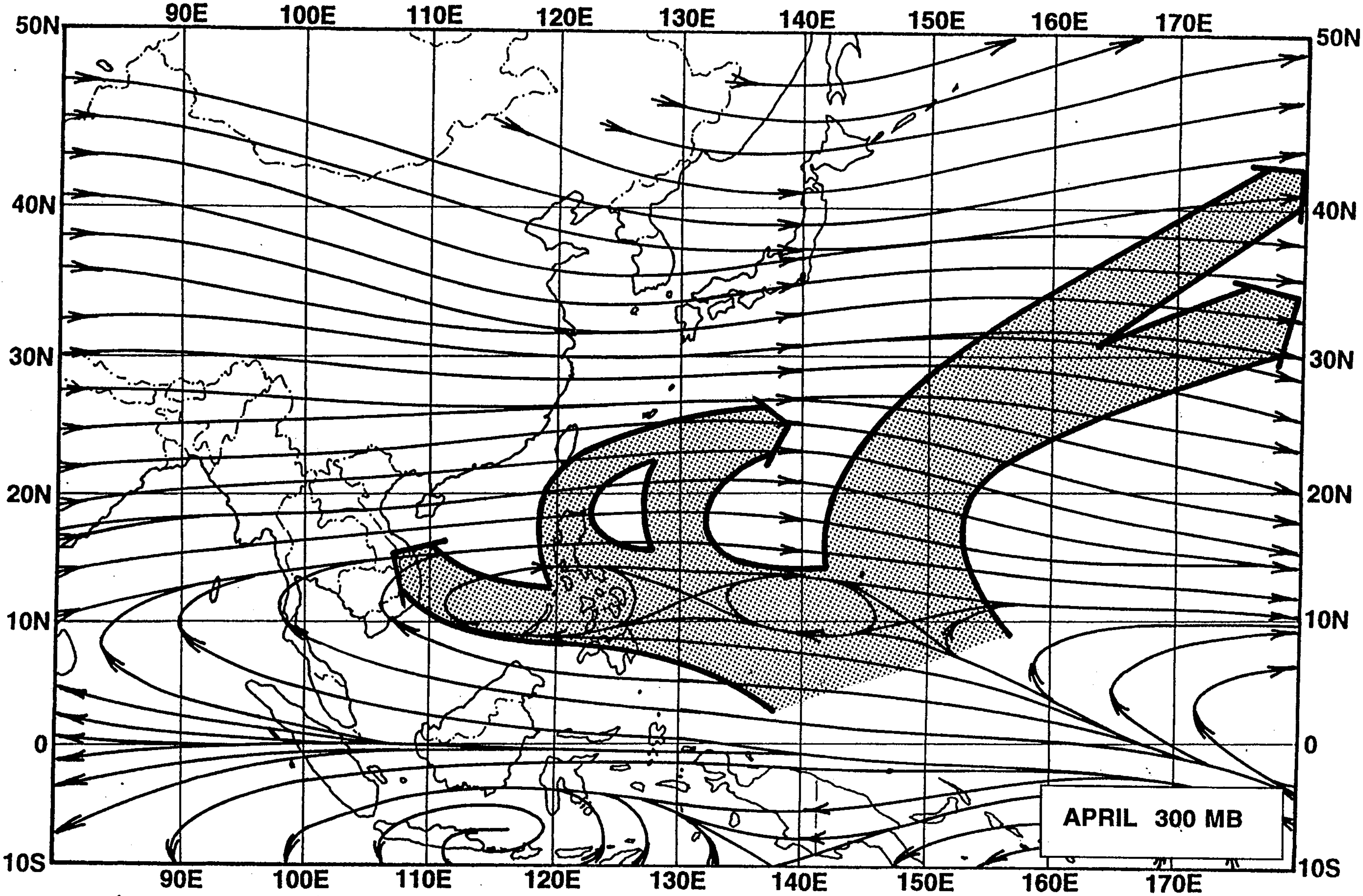


Figure D-4. April 300 mb streamlines and mean tropical cyclone paths for the Northwest Pacific Ocean. Streamlines adapted from Sadler, 1975. Tropical cyclone paths adapted from Miller, Tsui, and Schrader, 1988.

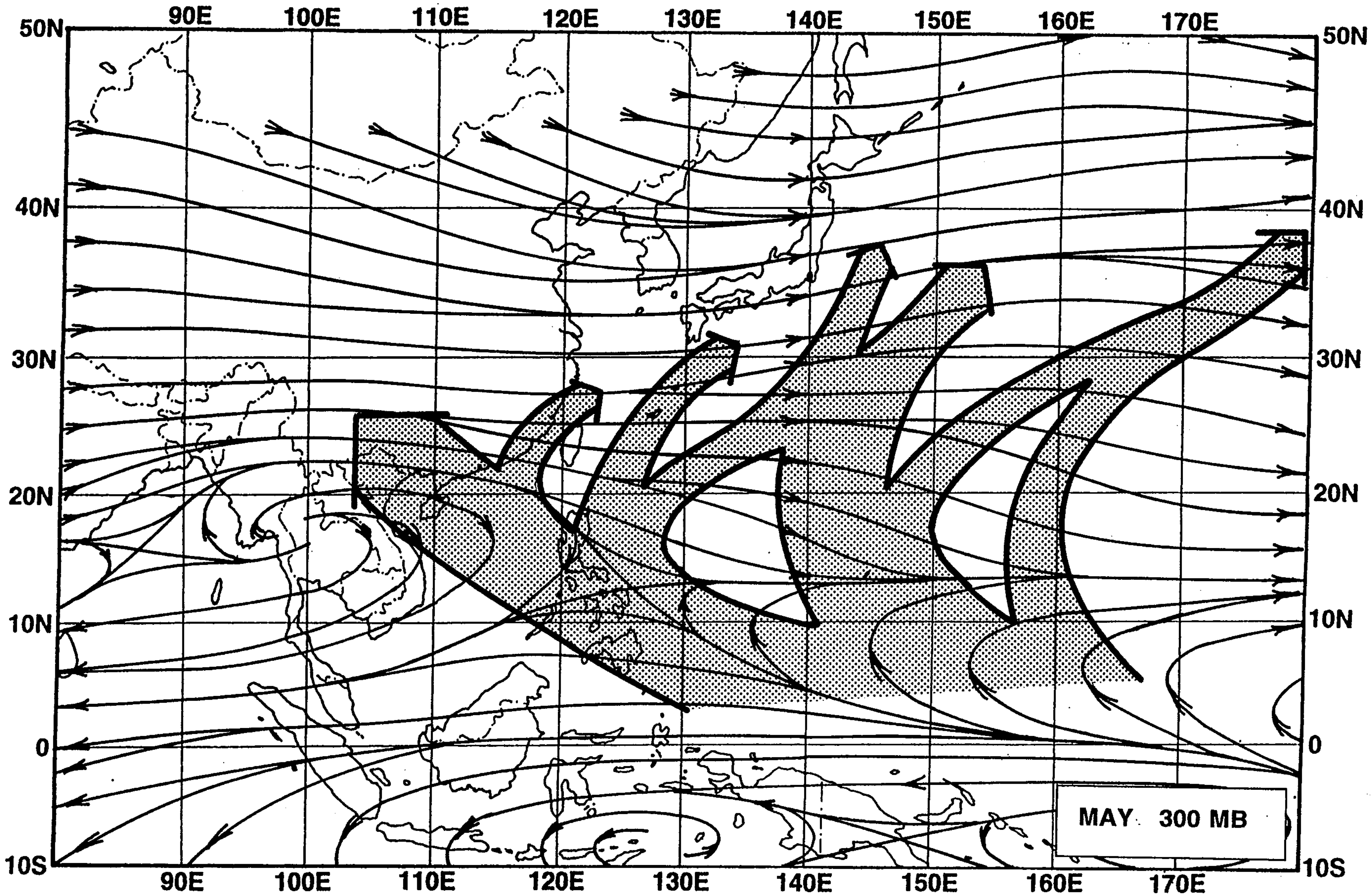


Figure D-5. May 300 mb streamlines and mean tropical cyclone paths for the Northwest Pacific Ocean. Streamlines adapted from Sadler, 1975. Tropical cyclone paths adapted from Miller, Tsui, and Schrader, 1988.

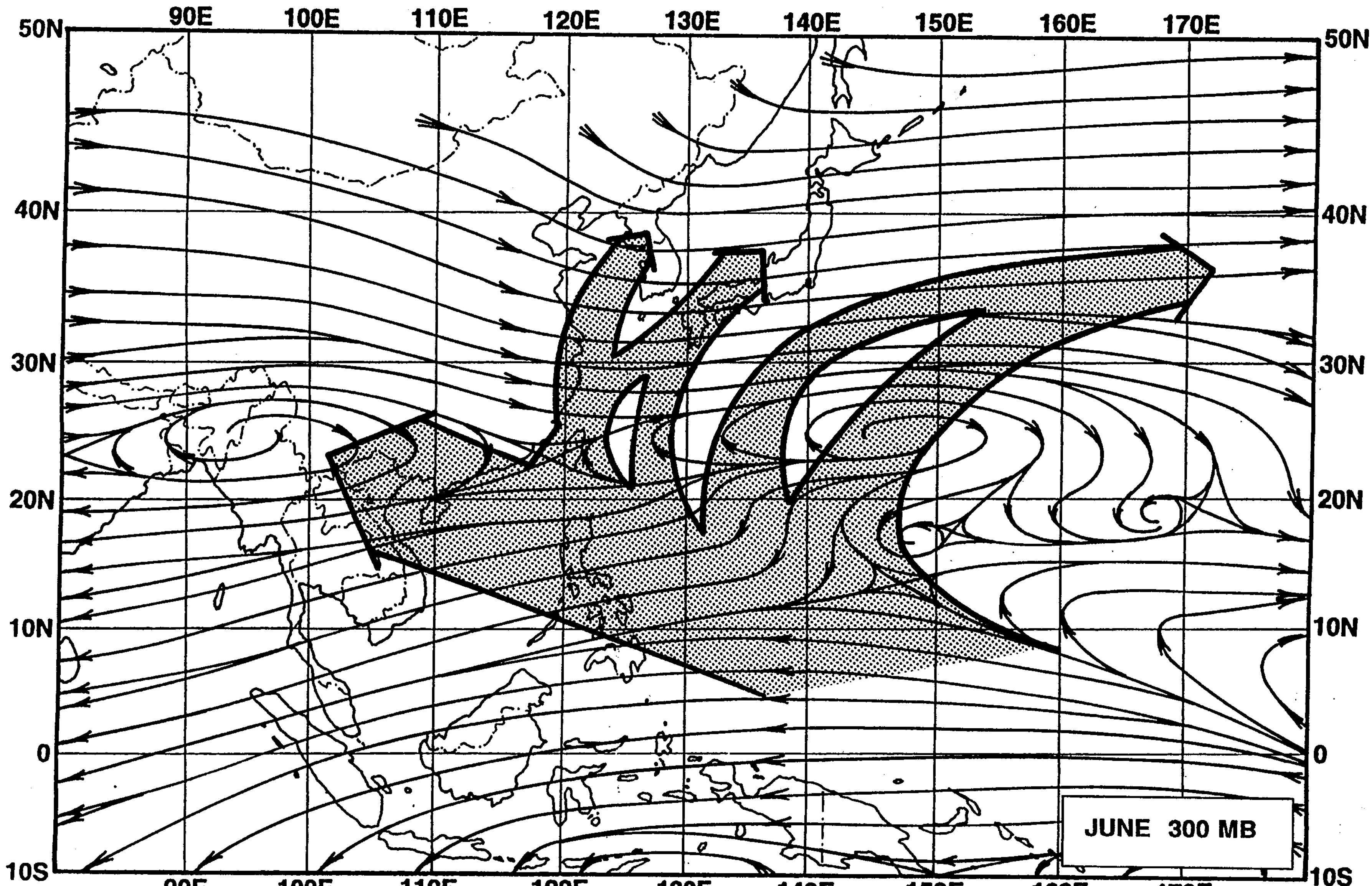


Figure D-6. June 300 mb streamlines and mean tropical cyclone paths for the Northwest Pacific Ocean. Streamlines adapted from Sadler, 1975. Tropical cyclone paths adapted from Miller, Tsui, and Schrader, 1988.

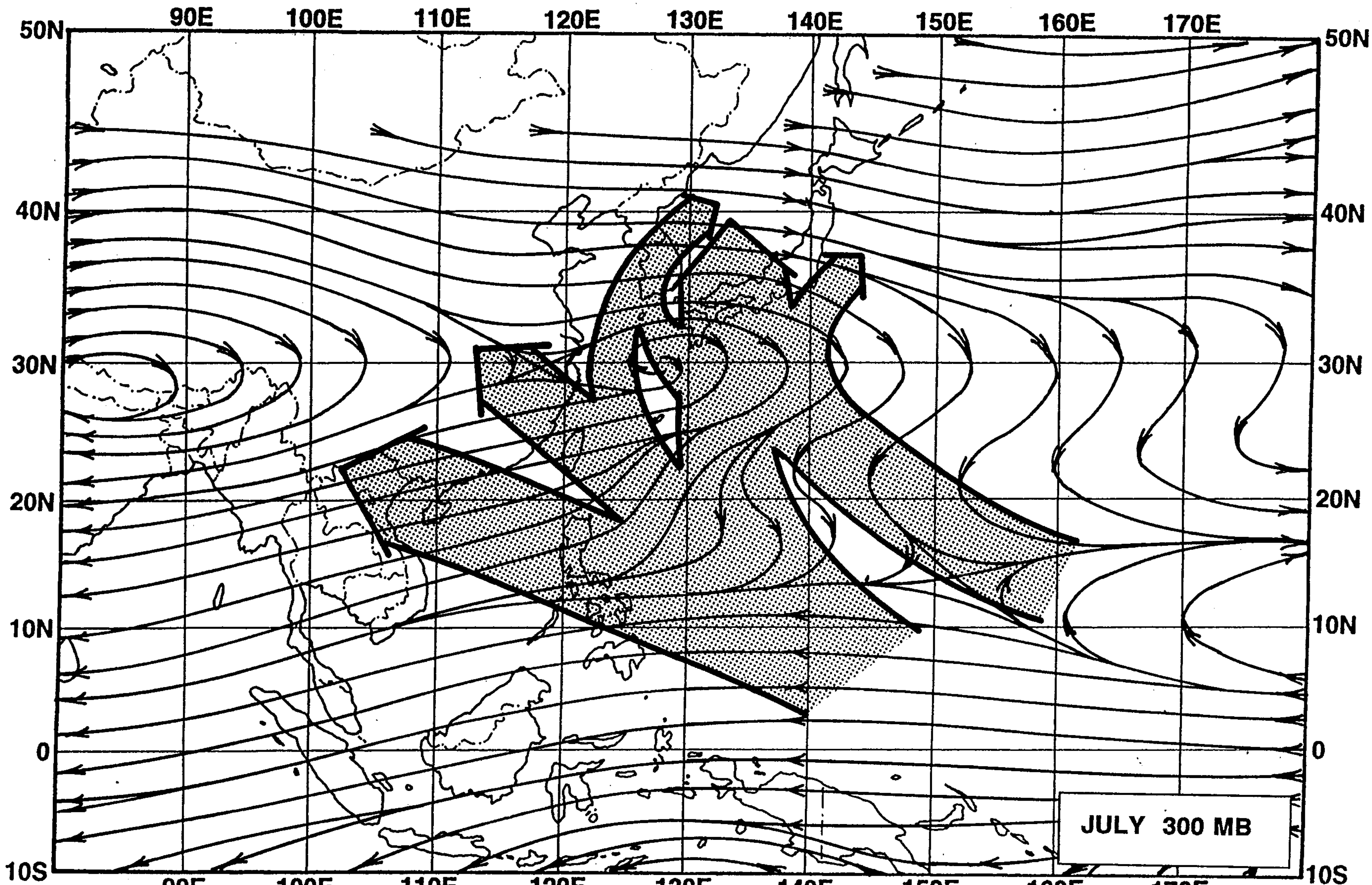


Figure D-7. July 300 mb streamlines and mean tropical cyclone paths for the Northwest Pacific Ocean. Streamlines adapted from Sadler, 1975. Tropical cyclone paths adapted from Miller, Tsui, and Schrader, 1988.

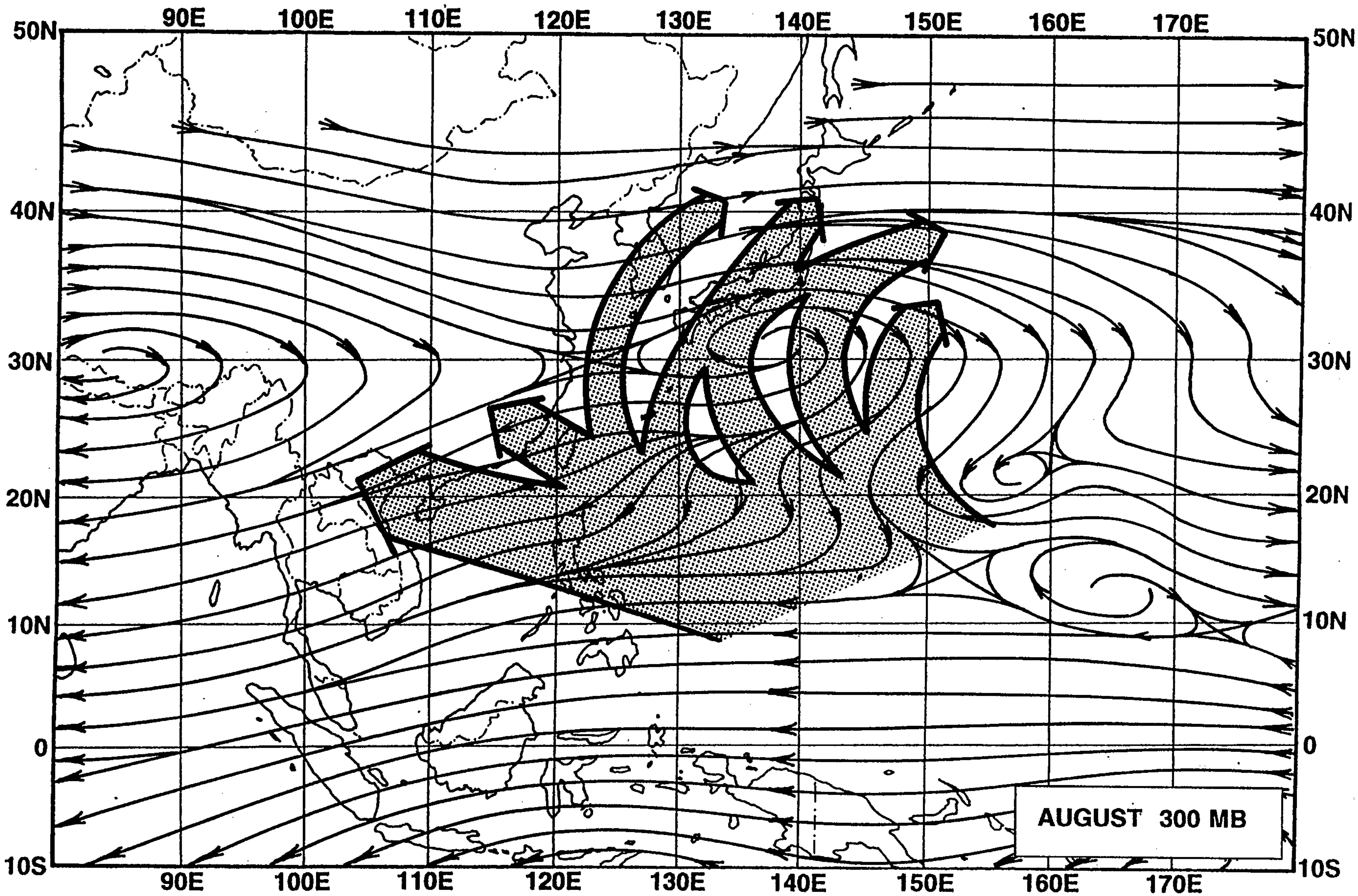


Figure D-8. August 300 mb streamlines and mean tropical cyclone paths for the Northwest Pacific Ocean. Streamlines adapted from Sadler, 1975. Tropical cyclone paths adapted from Miller, Tsui, and Schrader, 1988.

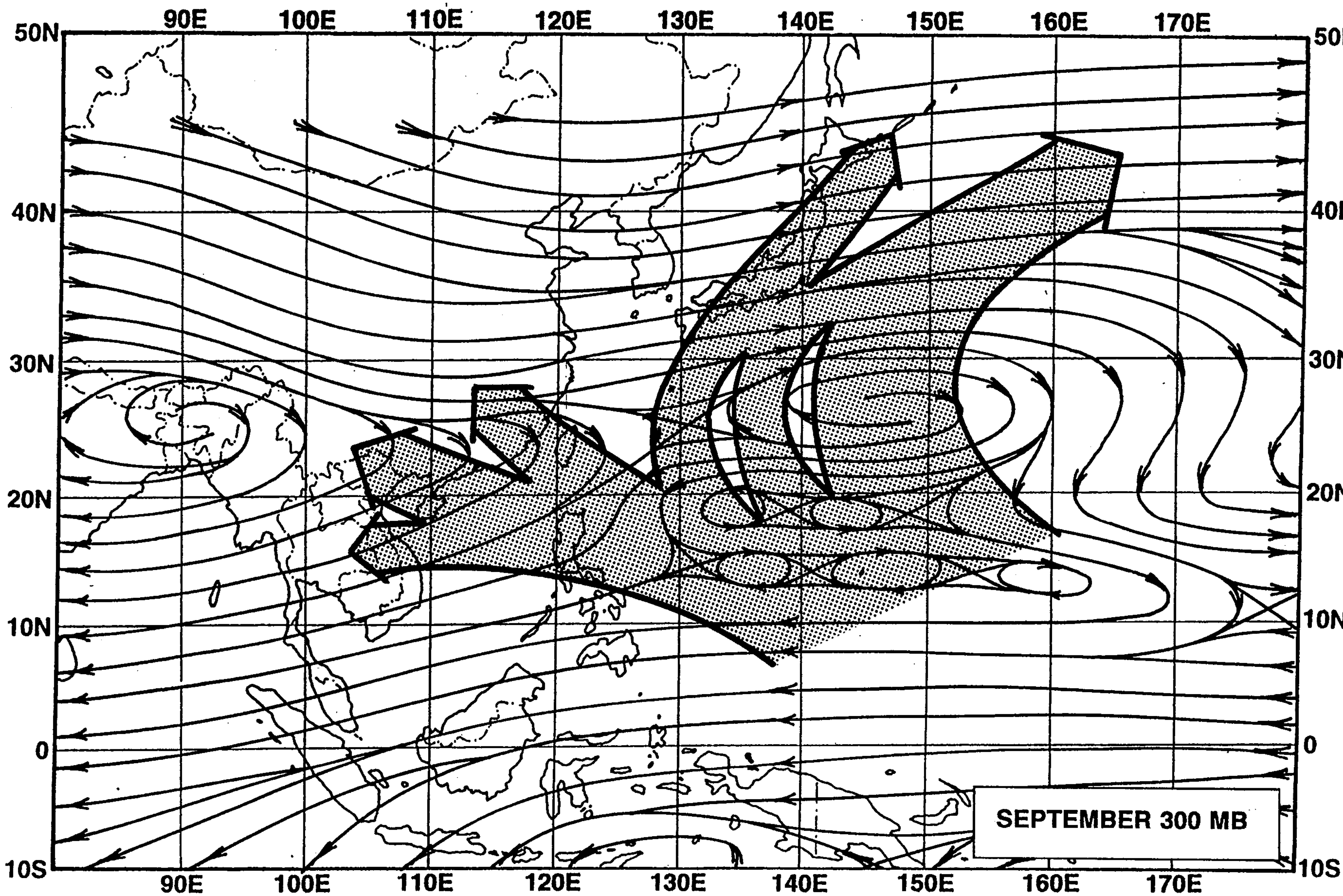


Figure D-9. September 300 mb streamlines and mean tropical cyclone paths for the Northwest Pacific Ocean. Streamlines adapted from Sadler, 1975. Tropical cyclone paths adapted from Miller, Tsui, and Schrader, 1988.

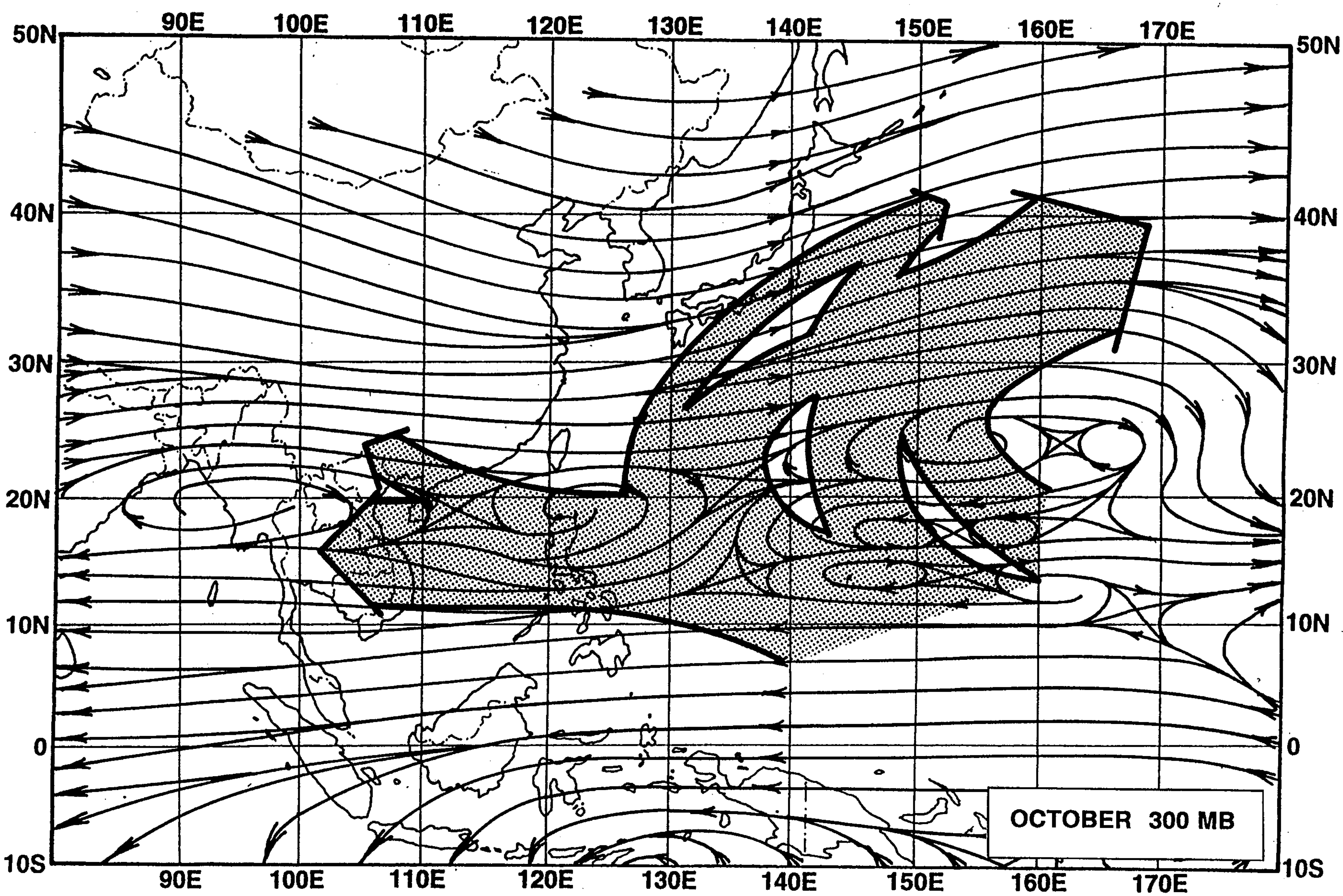


Figure D-10. October 300 mb streamlines and mean tropical cyclone paths for the Northwest Pacific Ocean. Streamlines adapted from Sadler, 1975. Tropical cyclone paths adapted from Miller, Tsui, and Schrader, 1988.

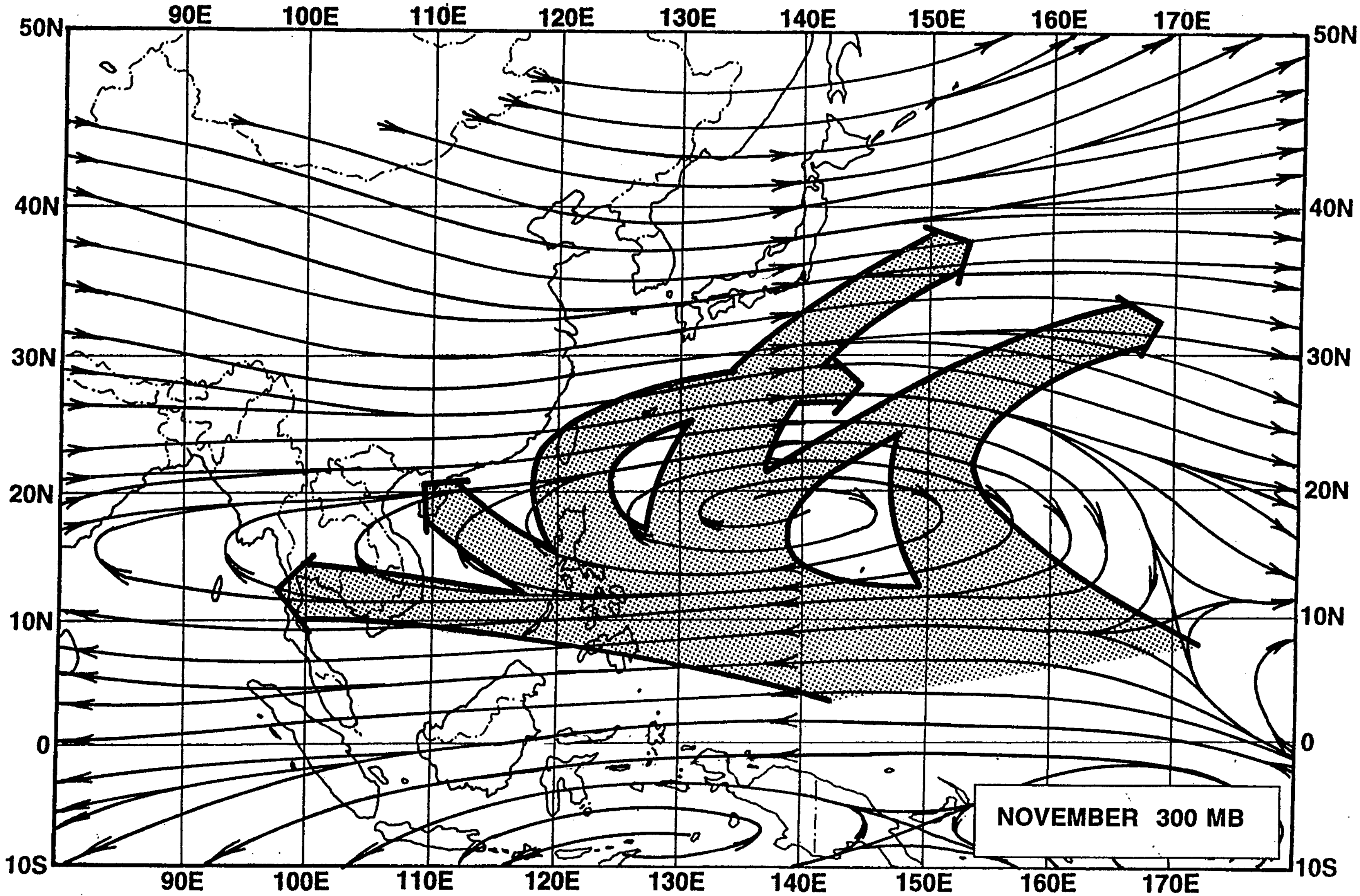


Figure D-11. November 300 mb streamlines and mean tropical cyclone paths for the Northwest Pacific Ocean. Streamlines adapted from Sadler, 1975. Tropical cyclone paths adapted from Miller, Tsui, and Schrader, 1988.

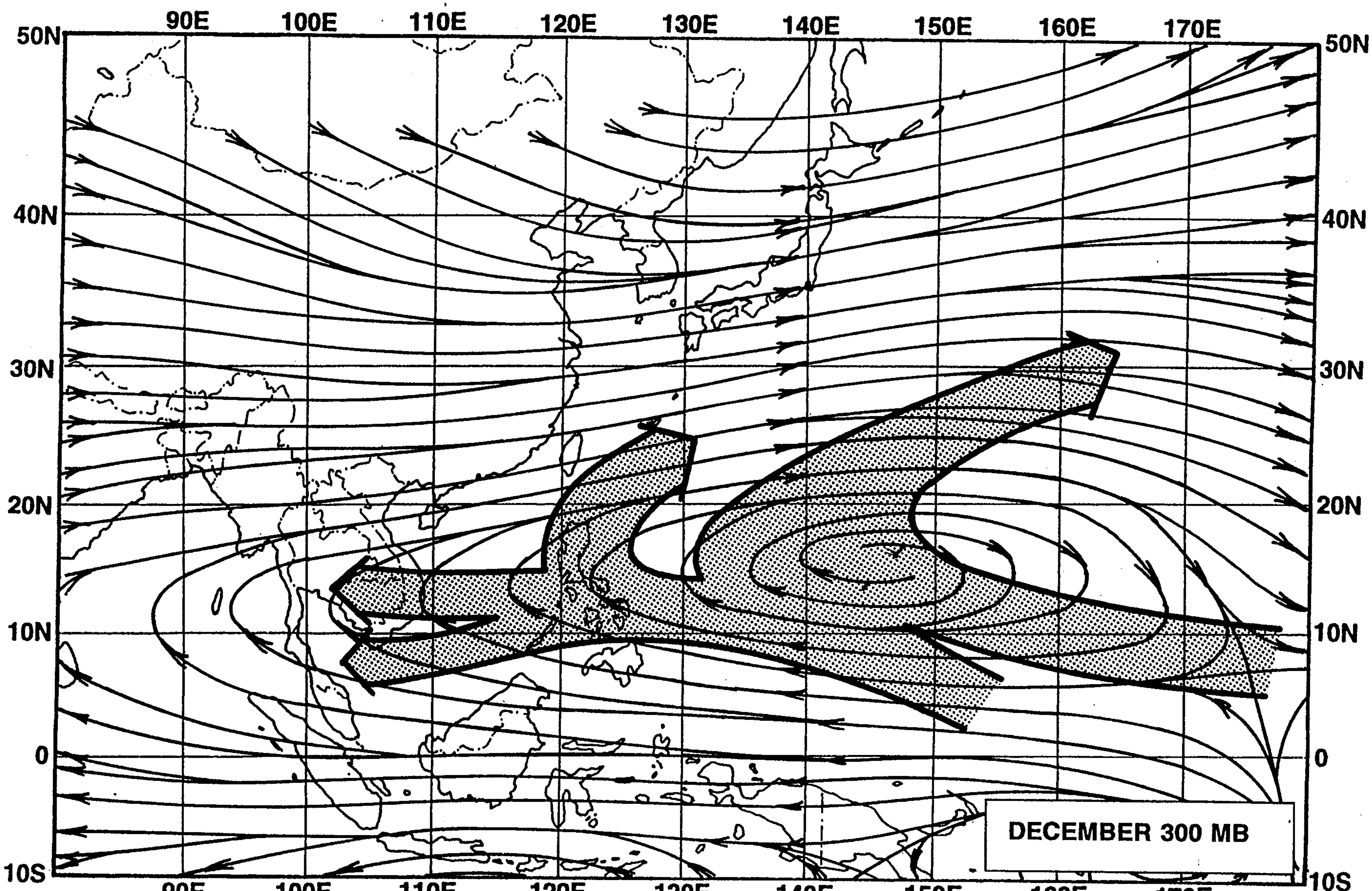


Figure D-12. December 300 mb streamlines and mean tropical cyclone paths for the Northwest Pacific Ocean. Streamlines adapted from Sadler, 1975. Tropical cyclone paths adapted from Miller, Tsui, and Schrader, 1988.

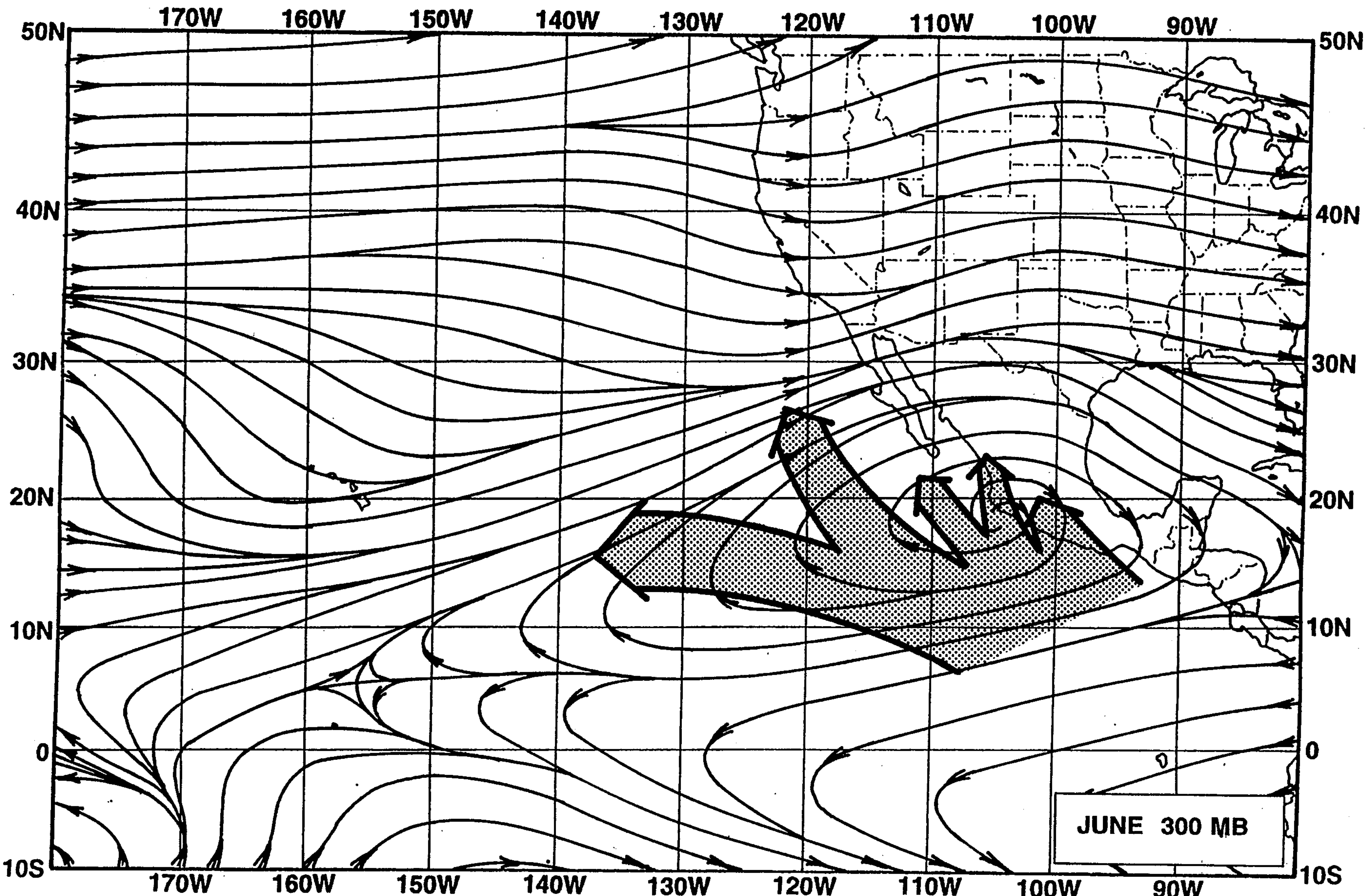


Figure D-13. June 300 mb streamlines and mean tropical cyclone paths for the Northeast Pacific Ocean. Streamlines adapted from Sadler, 1975. Tropical cyclone paths adapted from Miller, Tsui, and Schrader, 1988.

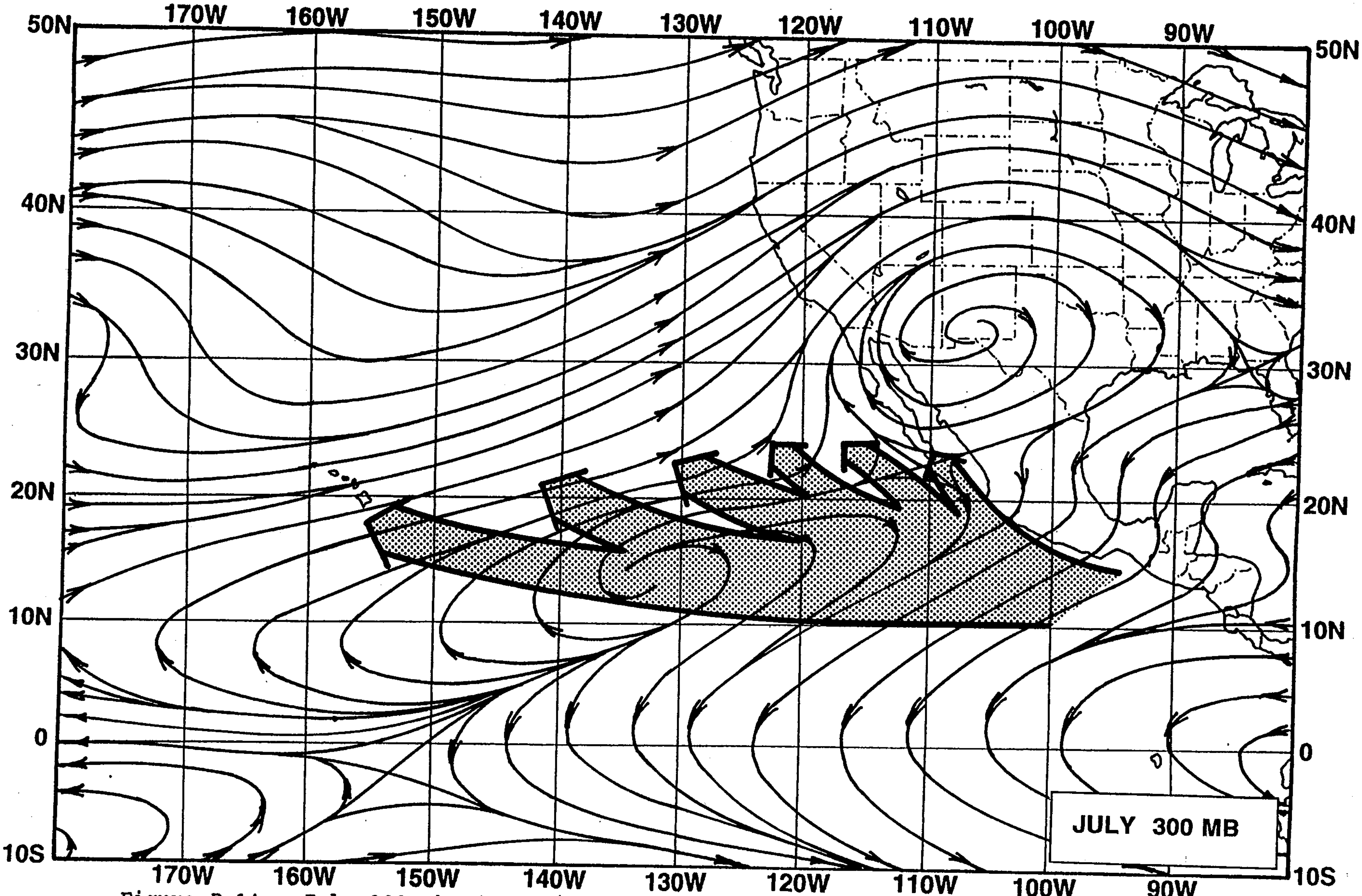


Figure D-14. July 300 mb streamlines and mean tropical cyclone paths for the Northeast Pacific Ocean. Streamlines adapted from Sadler, 1975. Tropical cyclone paths adapted from Miller, Tsui, and Schrader, 1988.

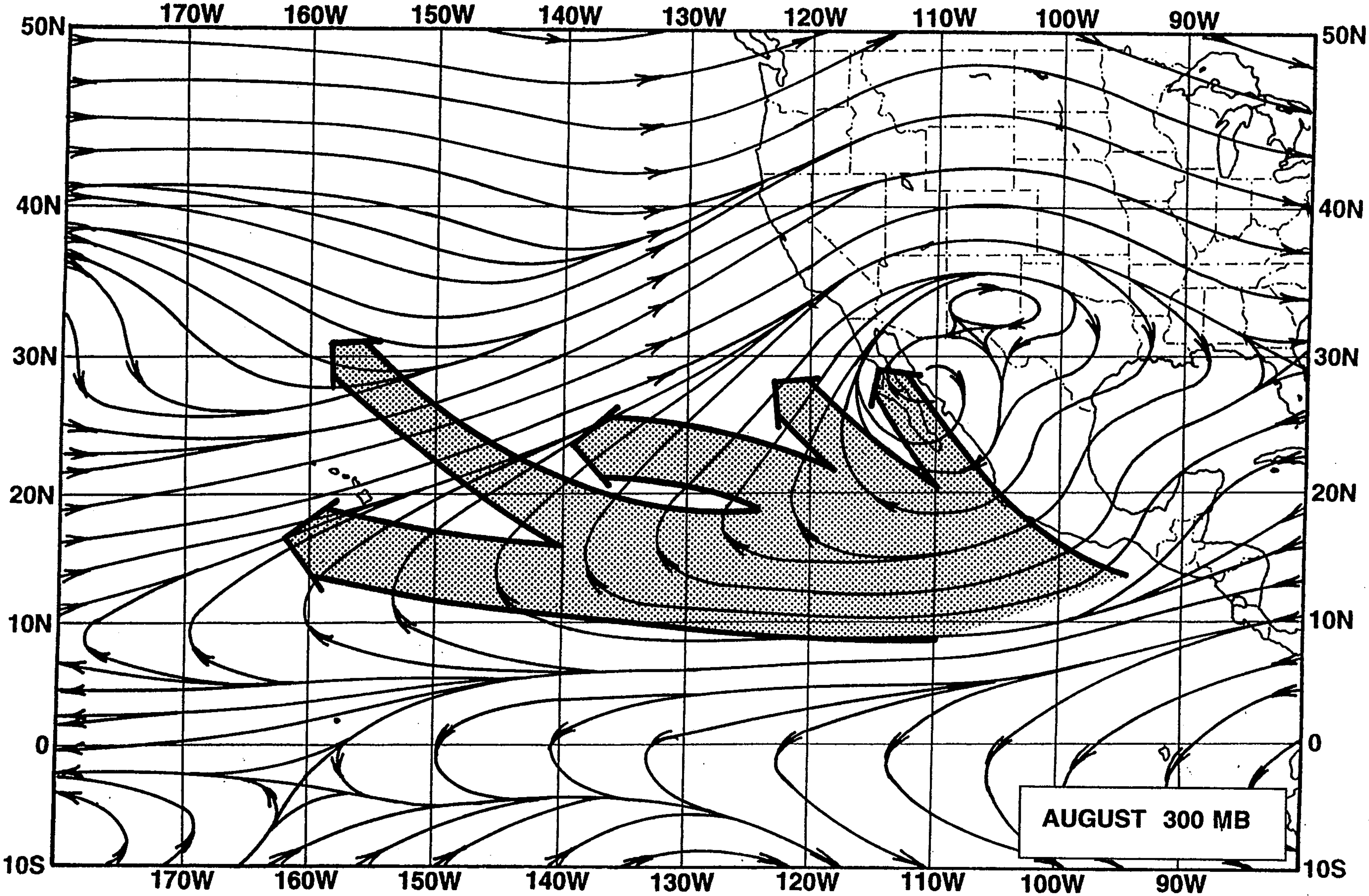


Figure D-15. August 300 mb streamlines and mean tropical cyclone paths for the Northeast Pacific Ocean. Streamlines adapted from Sadler, 1975. Tropical cyclone paths adapted from Miller, Tsui, and Schrader, 1988.

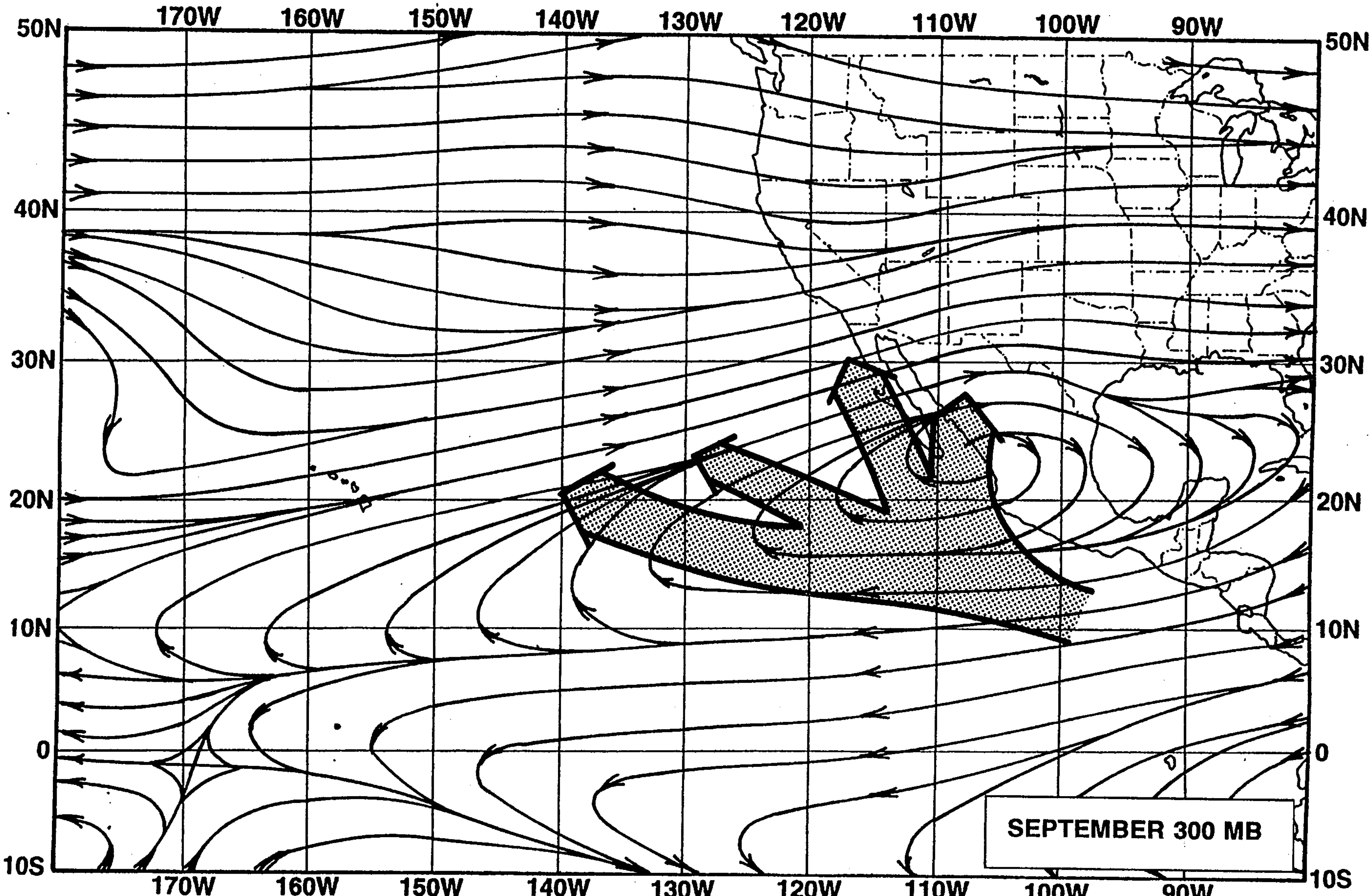


Figure D-16. September 300 mb streamlines and mean tropical cyclone paths for the Northeast Pacific Ocean. Streamlines adapted from Sadler, 1975. Tropical cyclone paths adapted from Miller, Tsui, and Schrader, 1988.

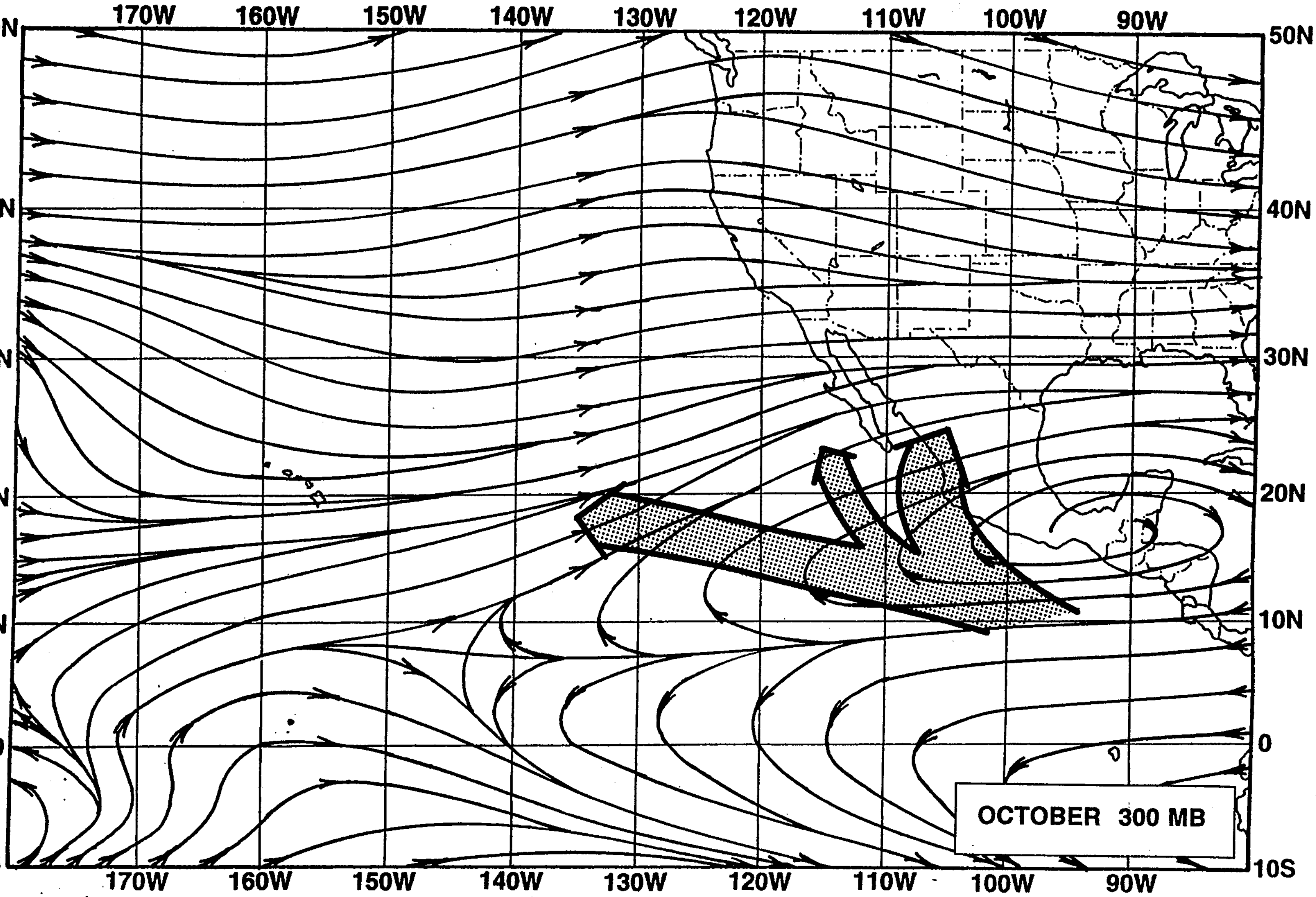


Figure D-17. October 300 mb streamlines and mean tropical cyclone paths for the Northeast Pacific Ocean. Streamlines adapted from Sadler, 1975. Tropical cyclone paths adapted from Miller, Tsui, and Schrader, 1988.

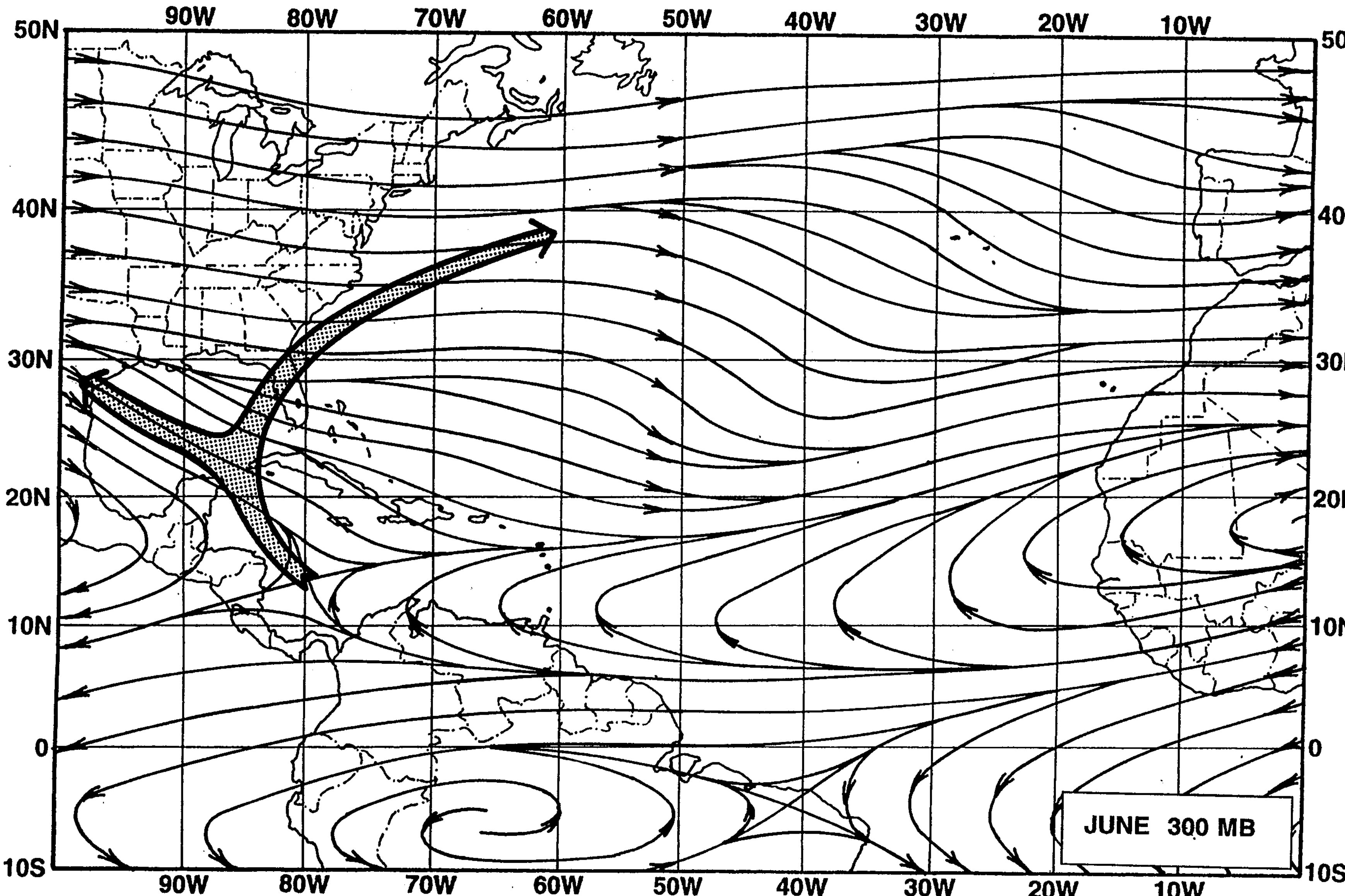


Figure D-18. June 300 mb streamlines and preferred tropical cyclone tracks for the North Atlantic Ocean. Streamlines adapted from Sadler, 1975. Tropical cyclone tracks adapted from Crutcher and Quayle, 1974.

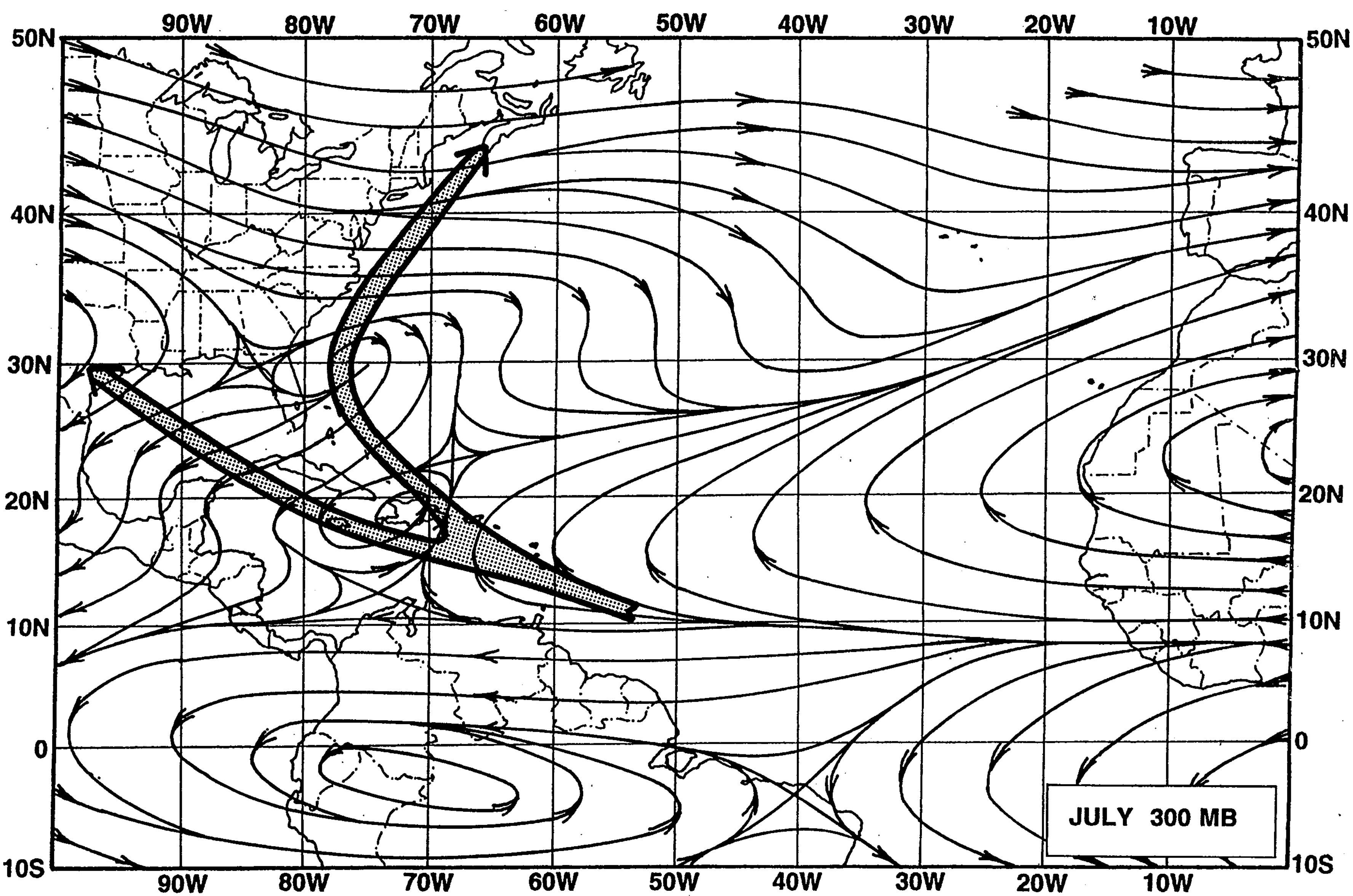


Figure D-19. July 300 mb streamlines and preferred tropical cyclone tracks for the North Atlantic Ocean. Streamlines adapted from Sadler, 1975. Tropical cyclone tracks adapted from Crutcher and Quayle, 1974.

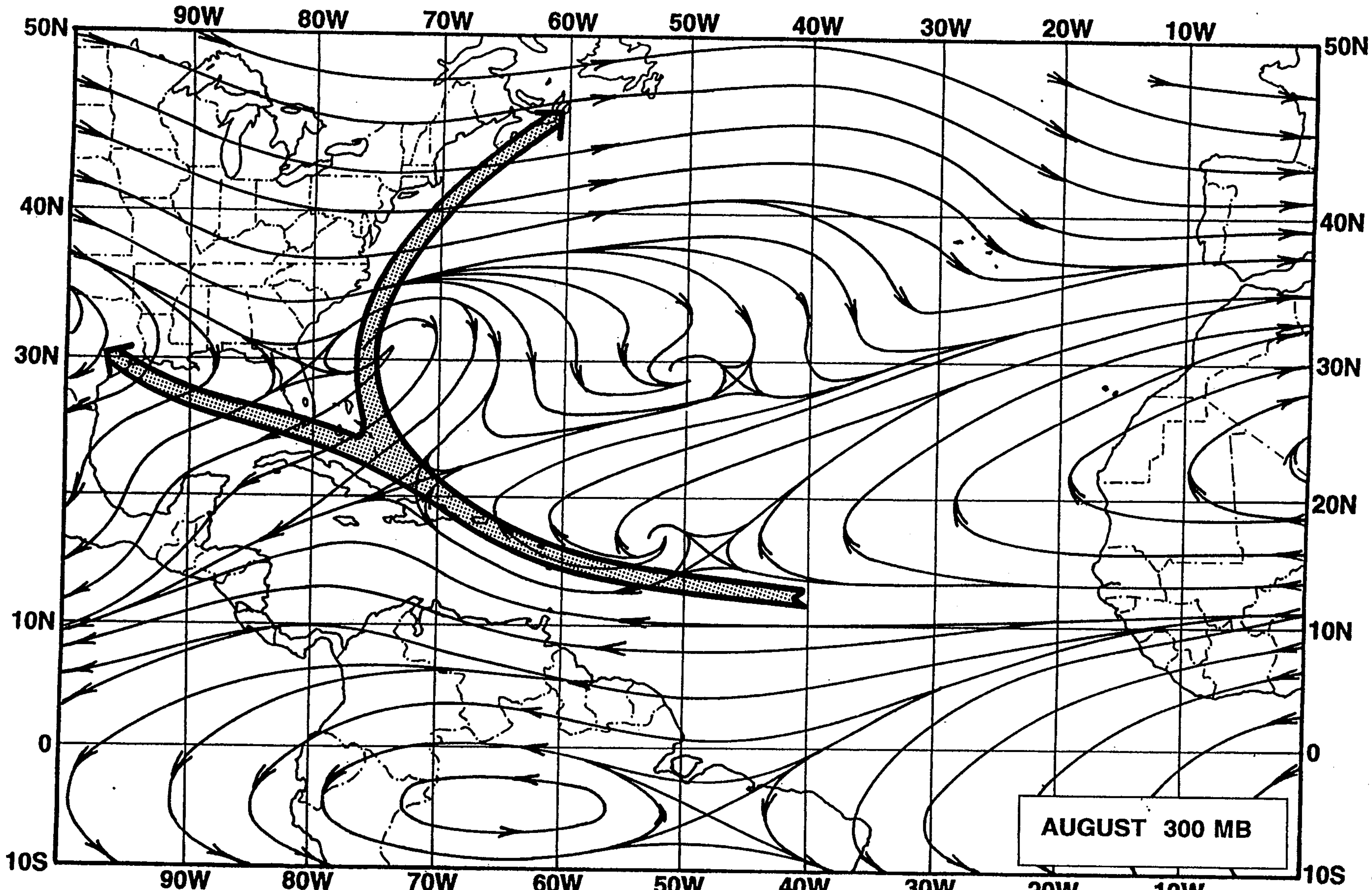


Figure D-20. August 300 mb streamlines and preferred tropical cyclone tracks for the North Atlantic Ocean. Streamlines adapted from Sadler, 1975. Tropical cyclone tracks adapted from Crutcher and Quayle, 1974.

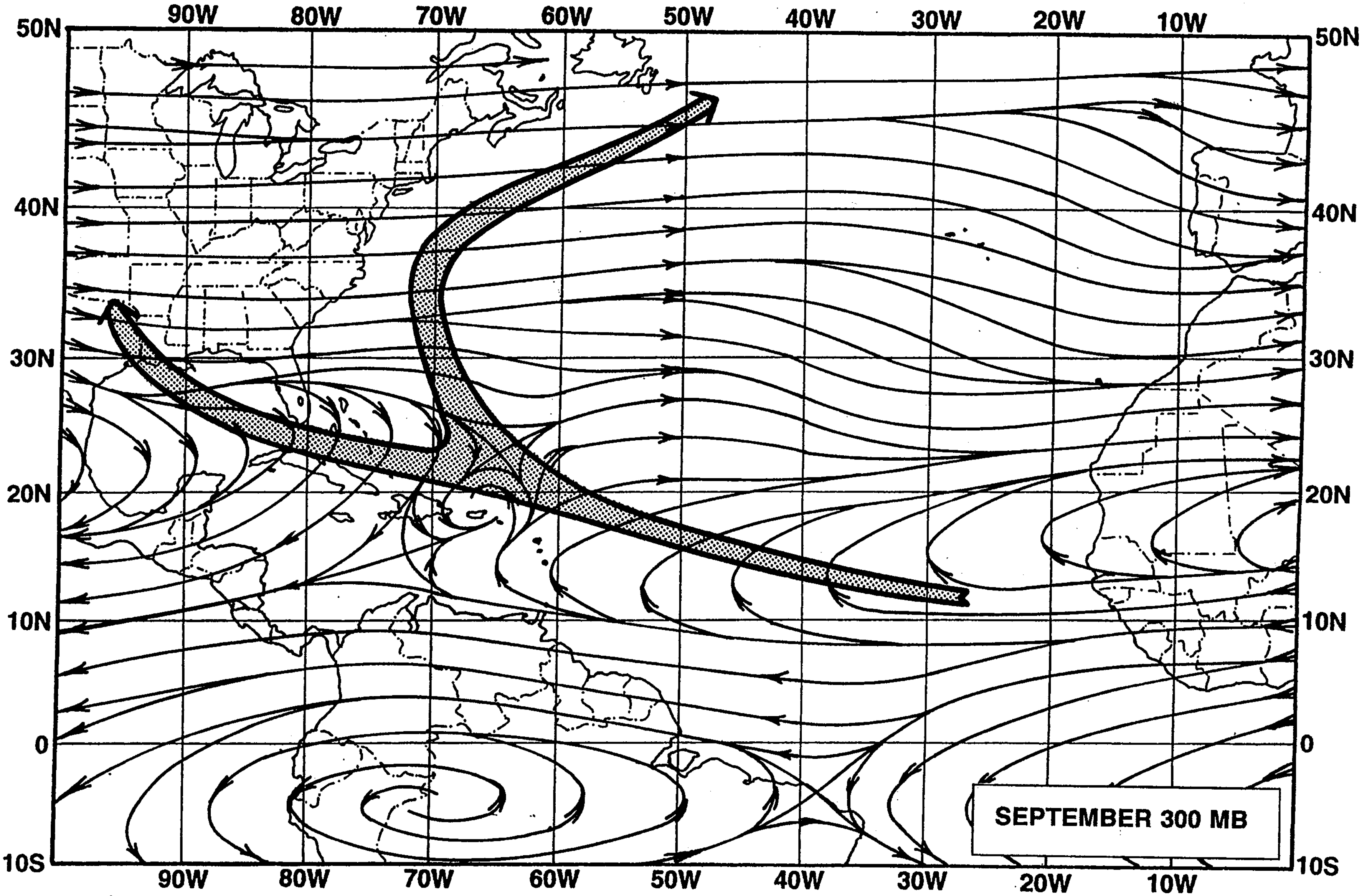


Figure D-21. September 300 mb streamlines and preferred tropical cyclone tracks for the North Atlantic Ocean. Streamlines adapted from Sadler, 1975. Tropical cyclone tracks adapted from Crutcher and Quayle, 1974.

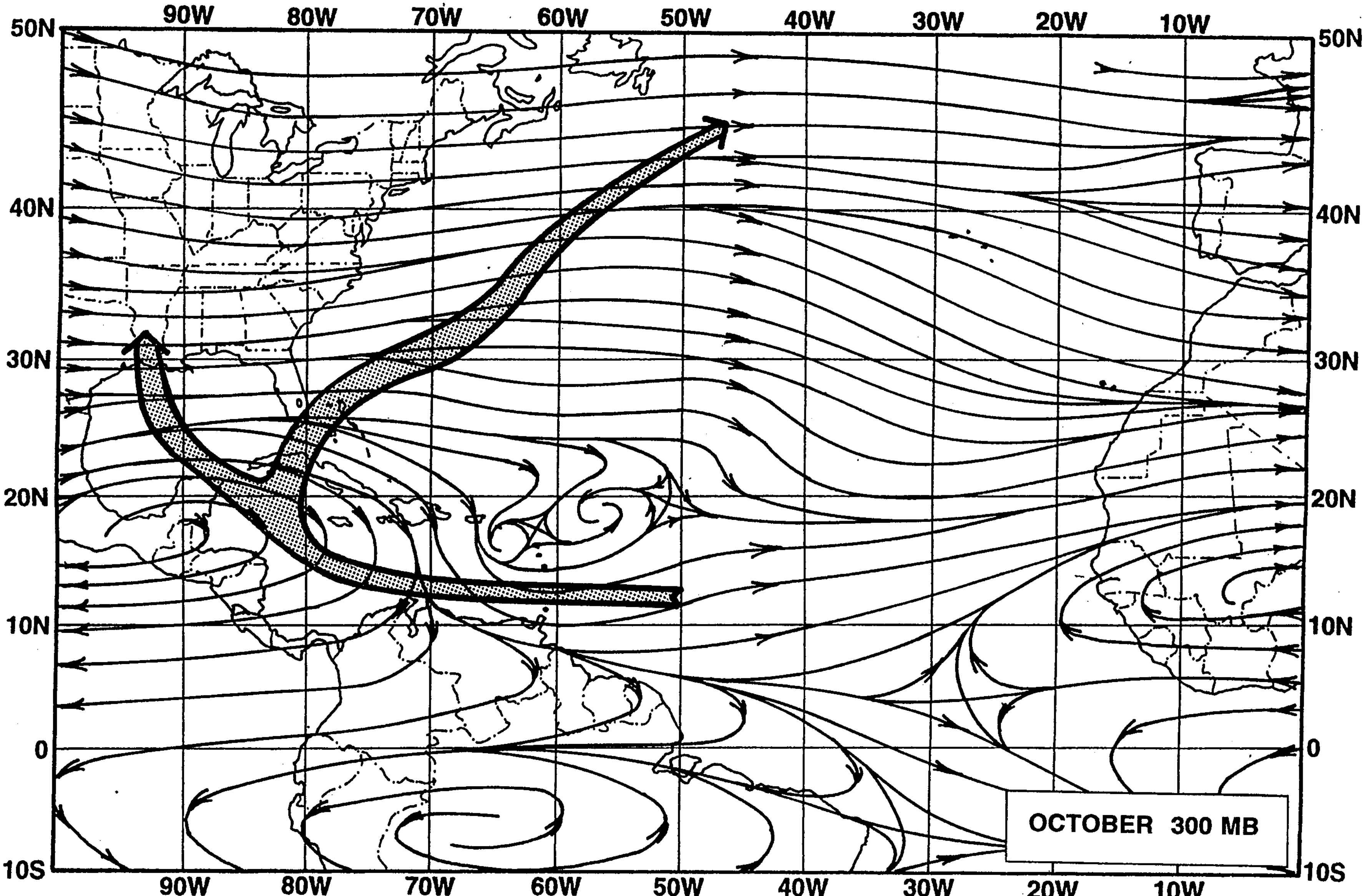


Figure D-22. October 300 mb streamlines and preferred tropical cyclone tracks for the North Atlantic Ocean. Streamlines adapted from Sadler, 1975. Tropical cyclone tracks adapted from Crutcher and Quayle, 1974.

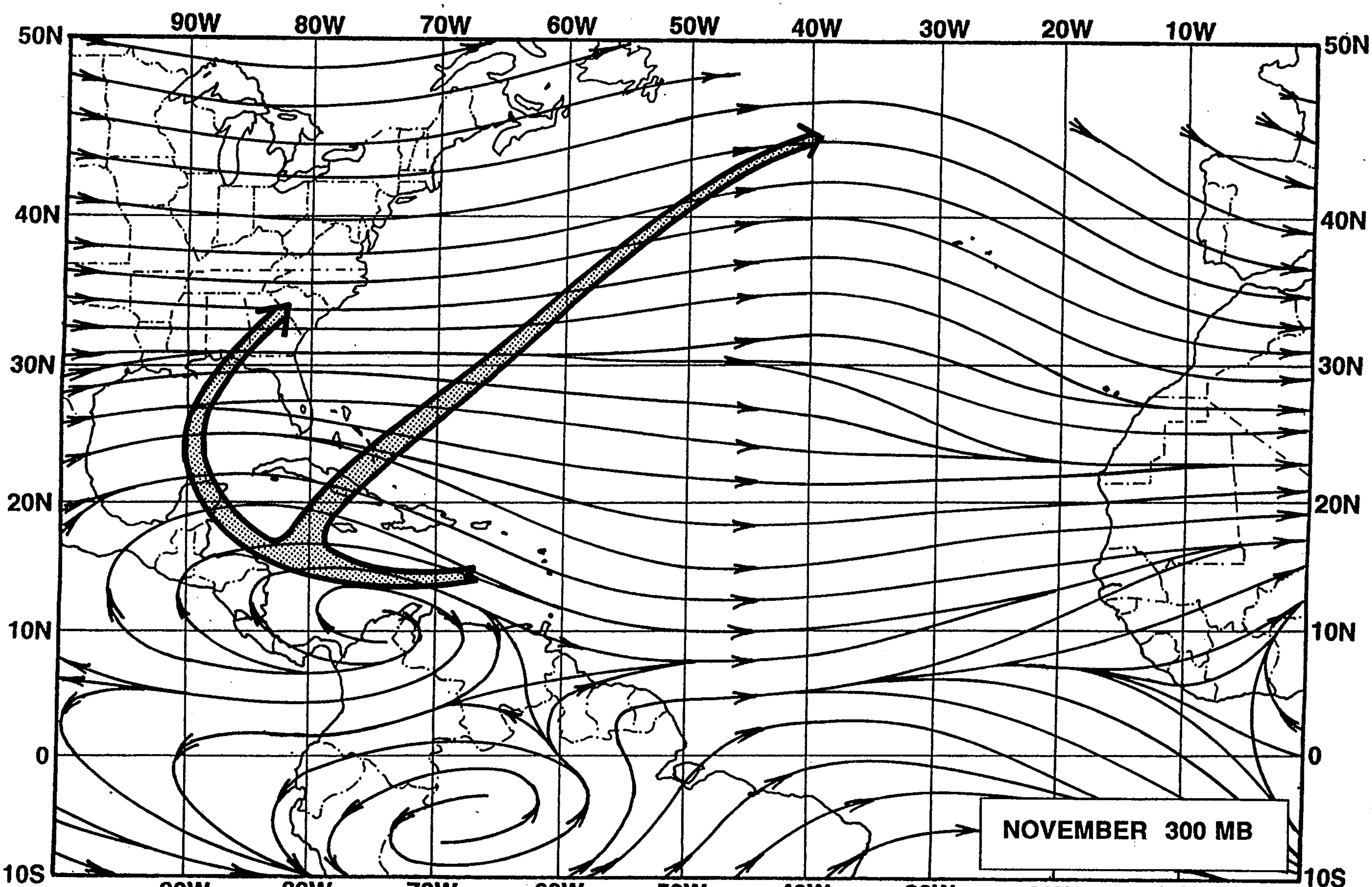


Figure D-23. November 300 mb streamlines and preferred tropical cyclone tracks for the North Atlantic Ocean. Streamlines adapted from Sadler, 1975. Tropical cyclone tracks adapted from Crutcher and Quayle, 1974.

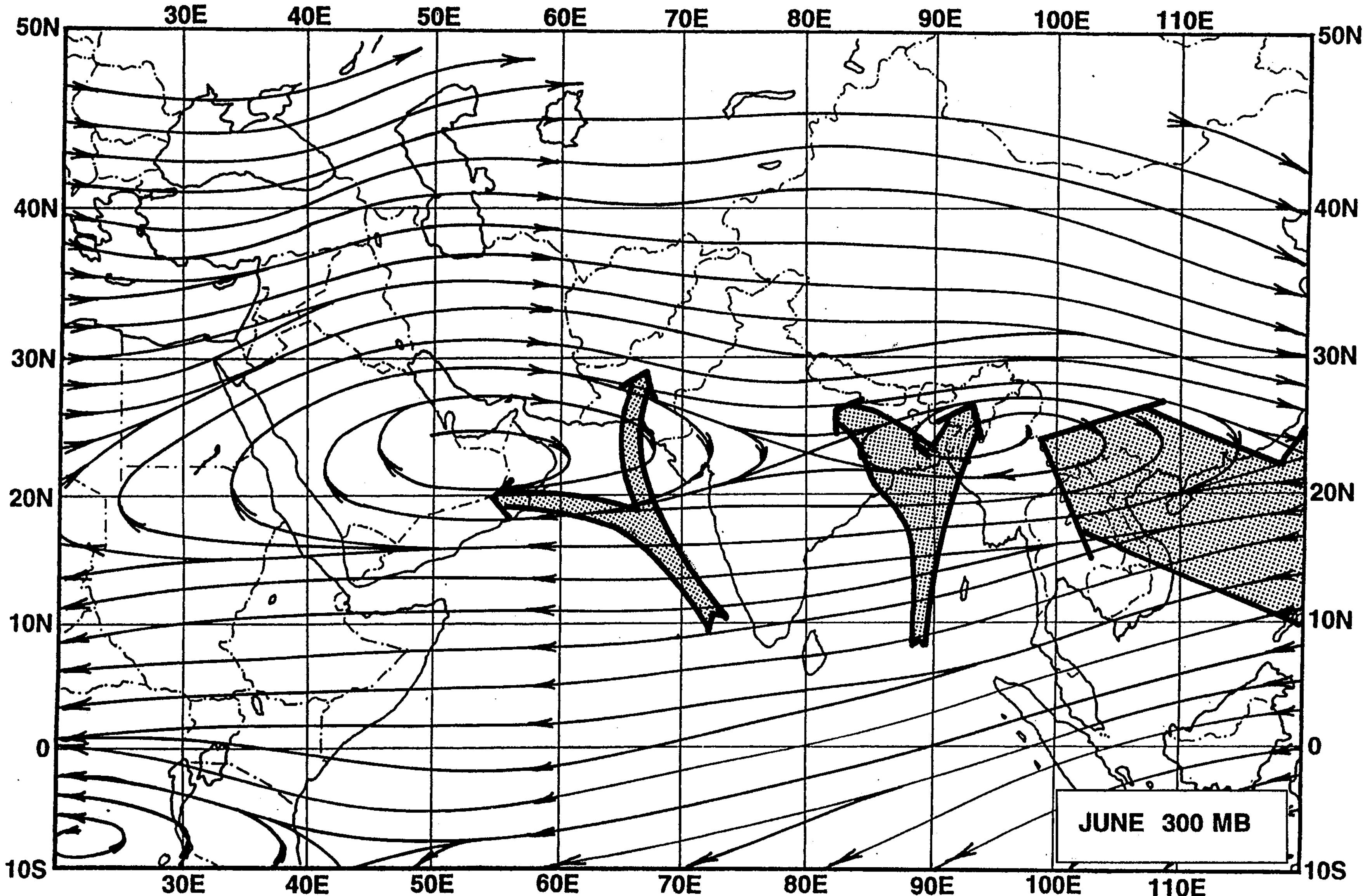


Figure D-24. June 300 mb streamlines and preferred tropical cyclone tracks for the North Indian Ocean. Streamlines adapted from Sadler, 1975. Tropical cyclone tracks adapted from Crutcher and Quayle, 1974 and Miller, Tsui, and Schrader, 1988.

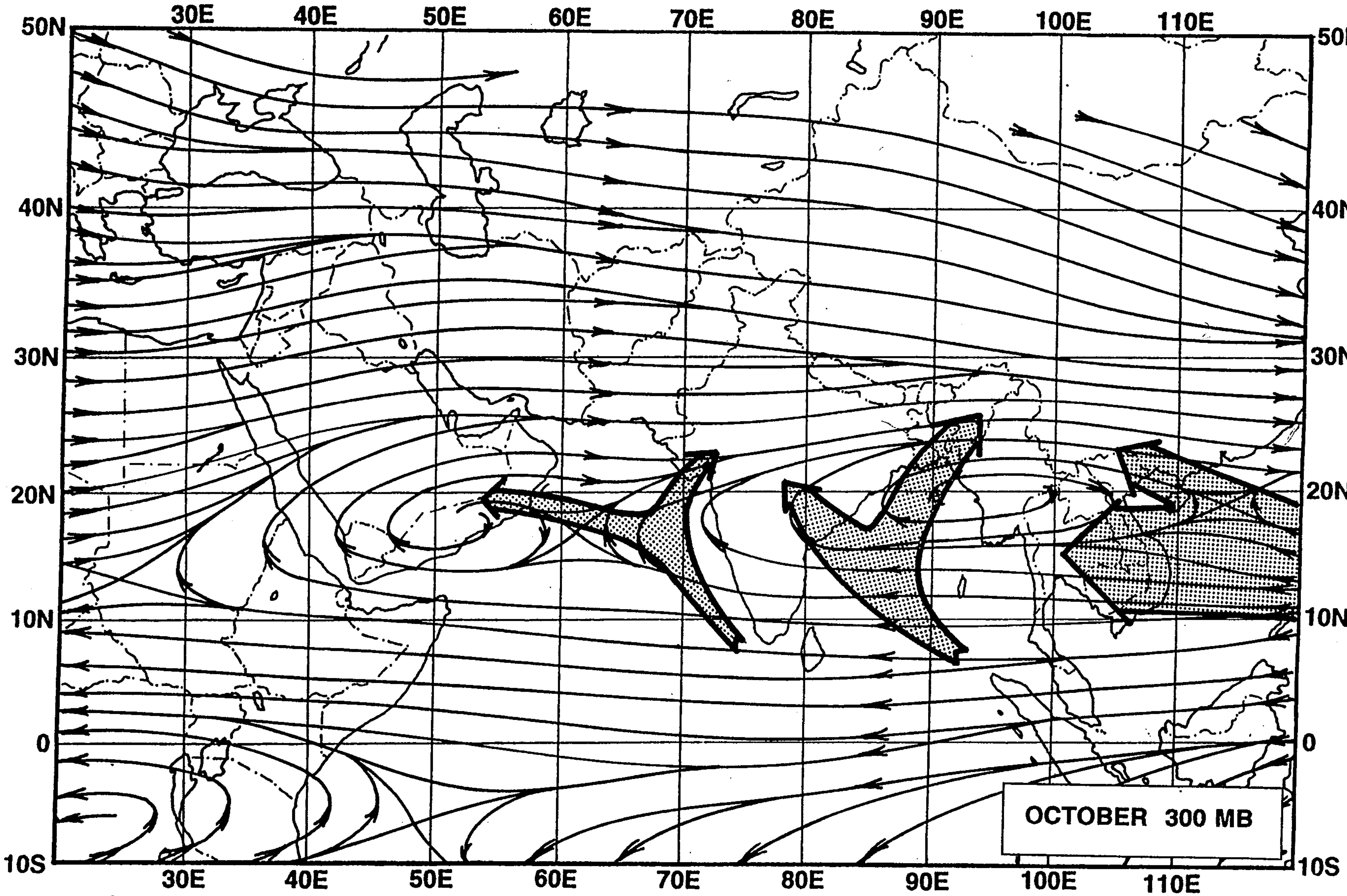


Figure D-25. October 300 mb streamlines and preferred tropical cyclone tracks for the North Indian Ocean. Streamlines adapted from Sadler, 1975. Tropical cyclone tracks adapted from Crutcher and Quayle, 1974 and Miller, Tsui, and Schrader, 1988.

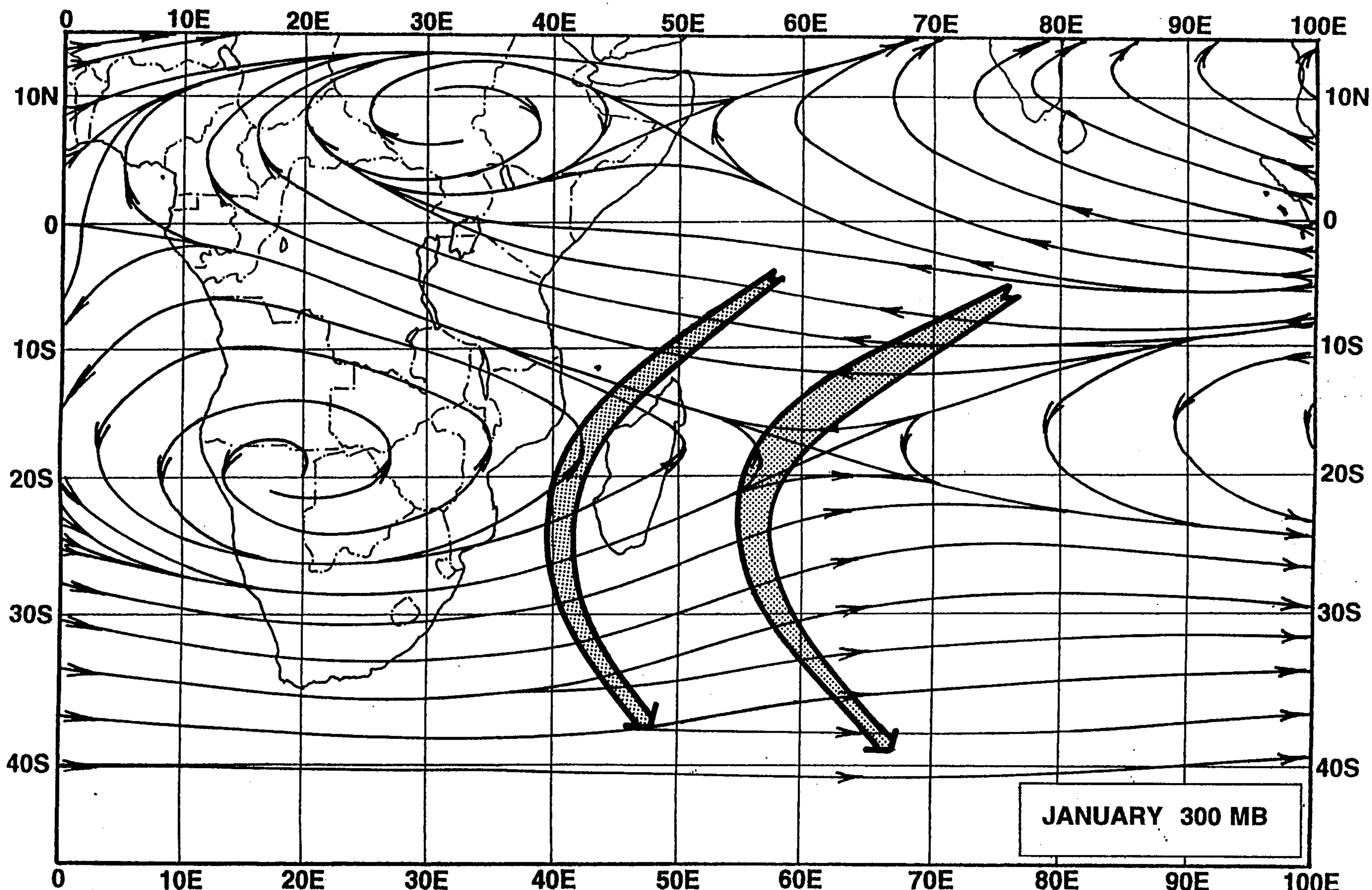


Figure D-26. January 300 mb streamlines and preferred tropical cyclone tracks for the Southwest Indian Ocean. Streamlines adapted from Sadler, 1975. Tropical cyclone tracks adapted from Crutcher and Quayle, 1974.

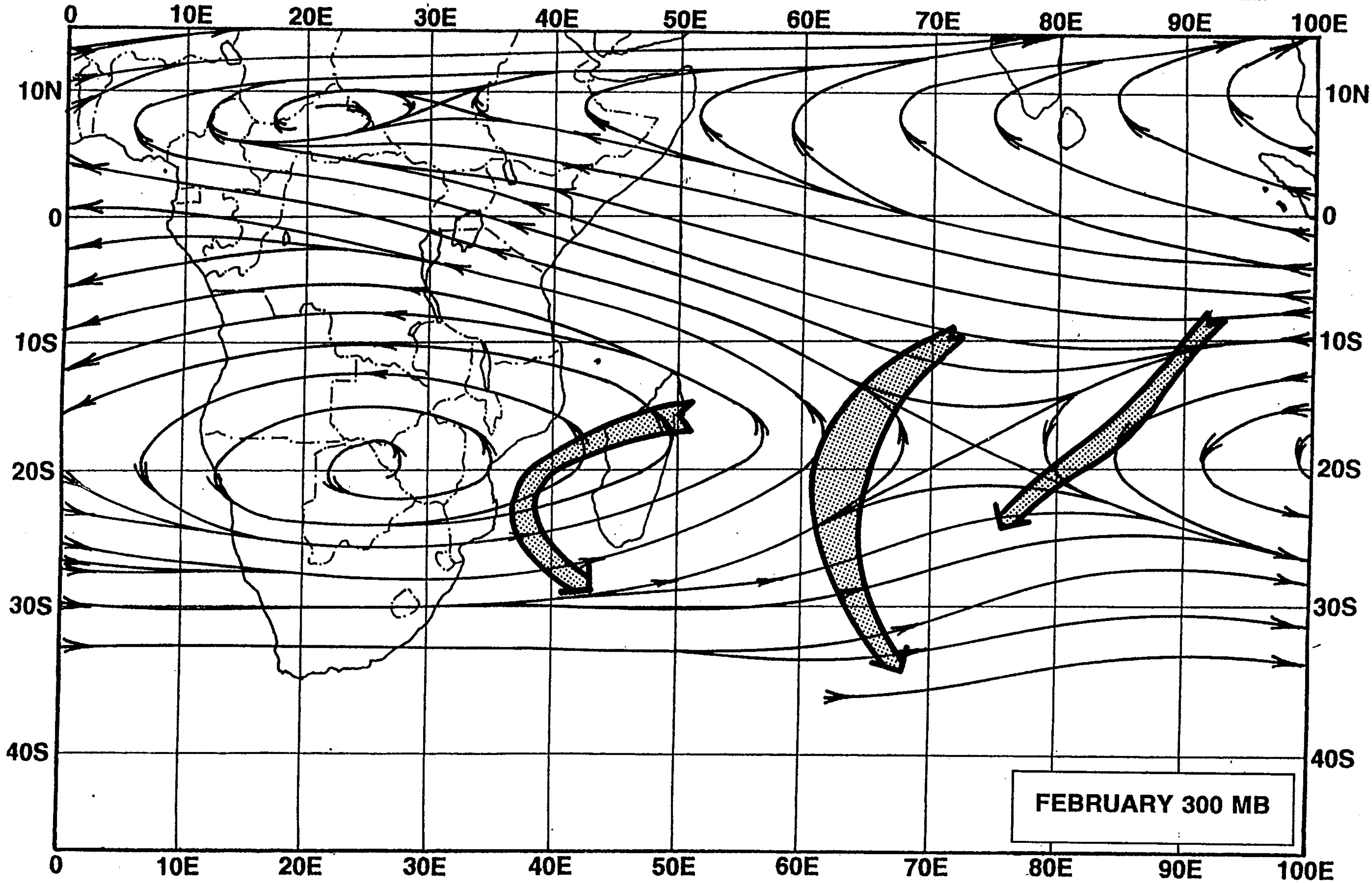


Figure D-27. February 300 mb streamlines and preferred tropical cyclone tracks for the Southwest Indian Ocean. Streamlines adapted from Sadler, 1975. Tropical cyclone tracks adapted from Crutcher and Quayle, 1974.

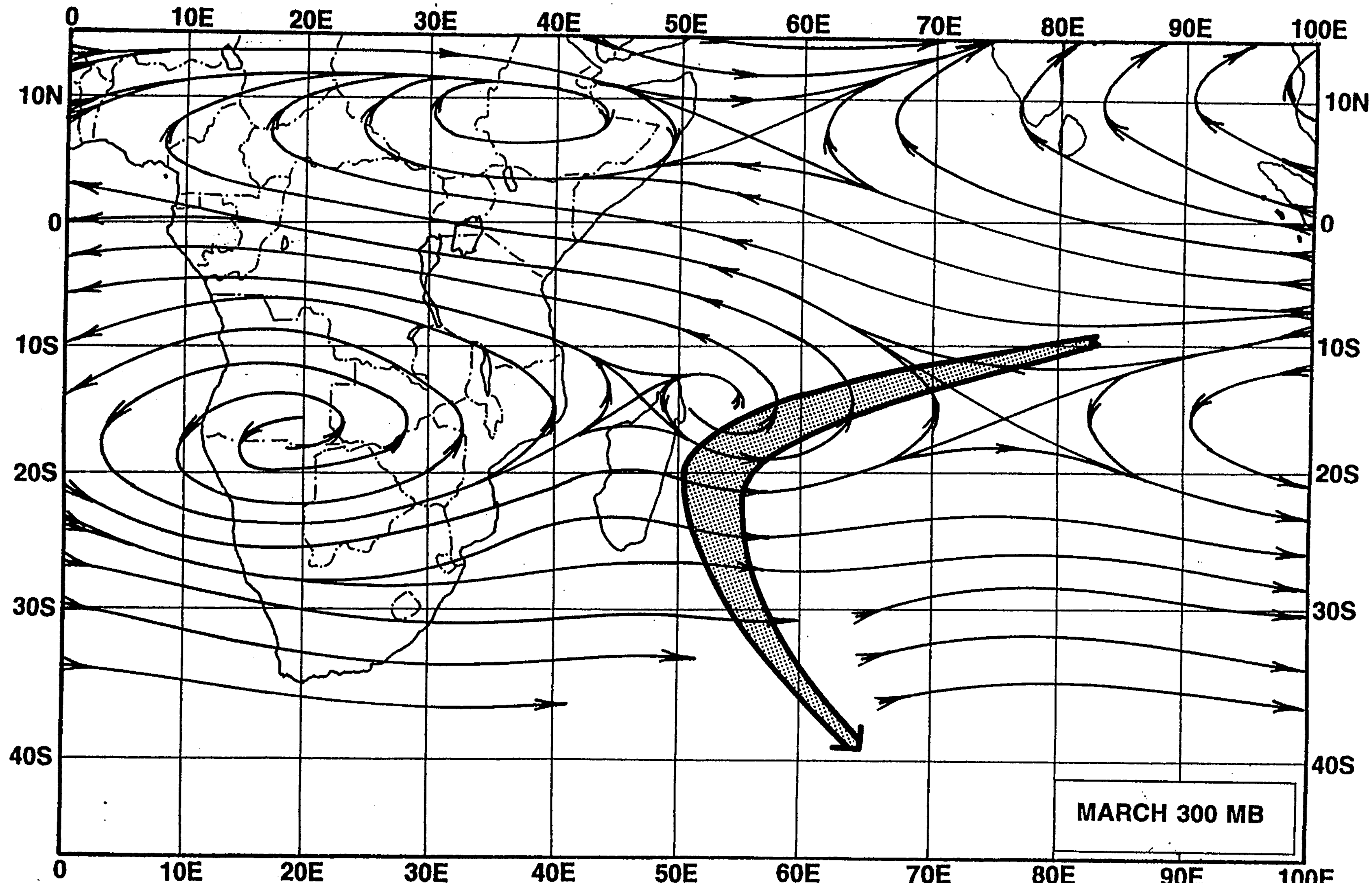


Figure D-28. March 300 mb streamlines and preferred tropical cyclone tracks for the Southwest Indian Ocean. Streamlines adapted from Sadler, 1975. Tropical cyclone tracks adapted from Crutcher and Quayle, 1974.

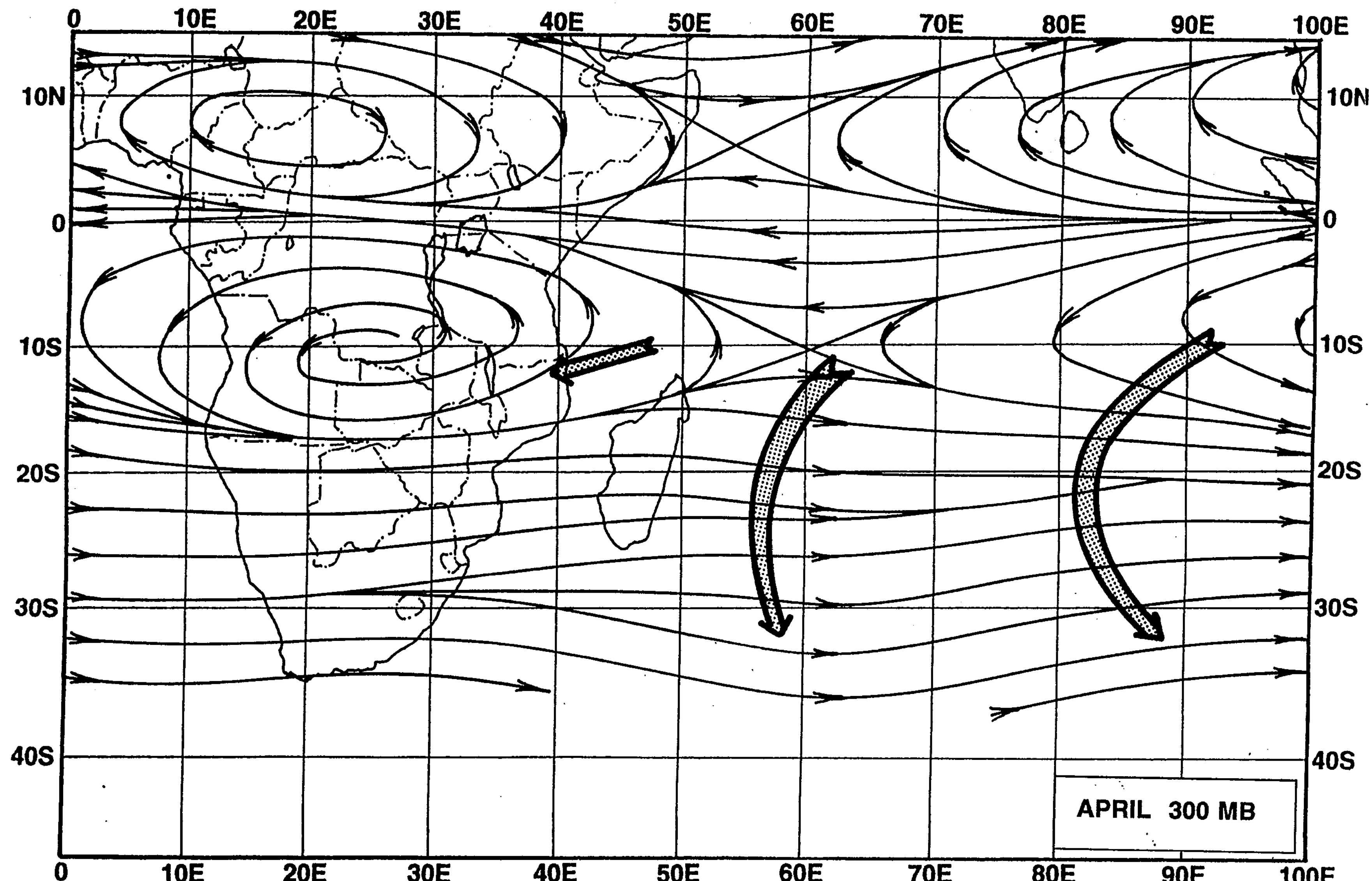


Figure D-29. April 300 mb streamlines and preferred tropical cyclone tracks for the Southwest Indian Ocean. Streamlines adapted from Sadler, 1975. Tropical cyclone tracks adapted from Crutcher and Quayle, 1974.

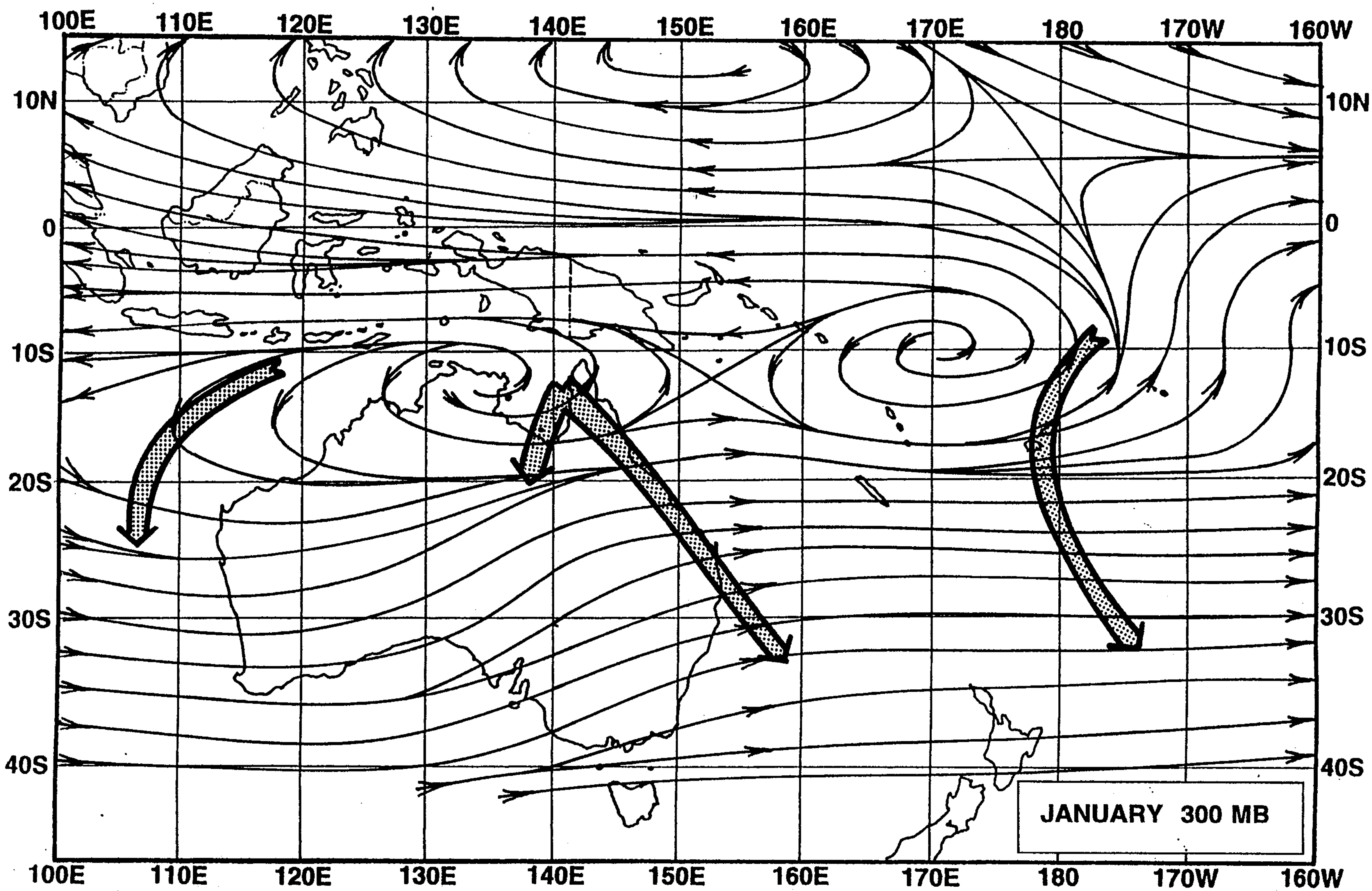


Figure D-30. January 300 mb streamlines and preferred tropical cyclone tracks for the Southeast Indian Ocean, South Pacific Ocean and Australia. Streamlines adapted from Sadler, 1975. Tropical cyclone tracks adapted from Crutcher and Quayle, 1974.

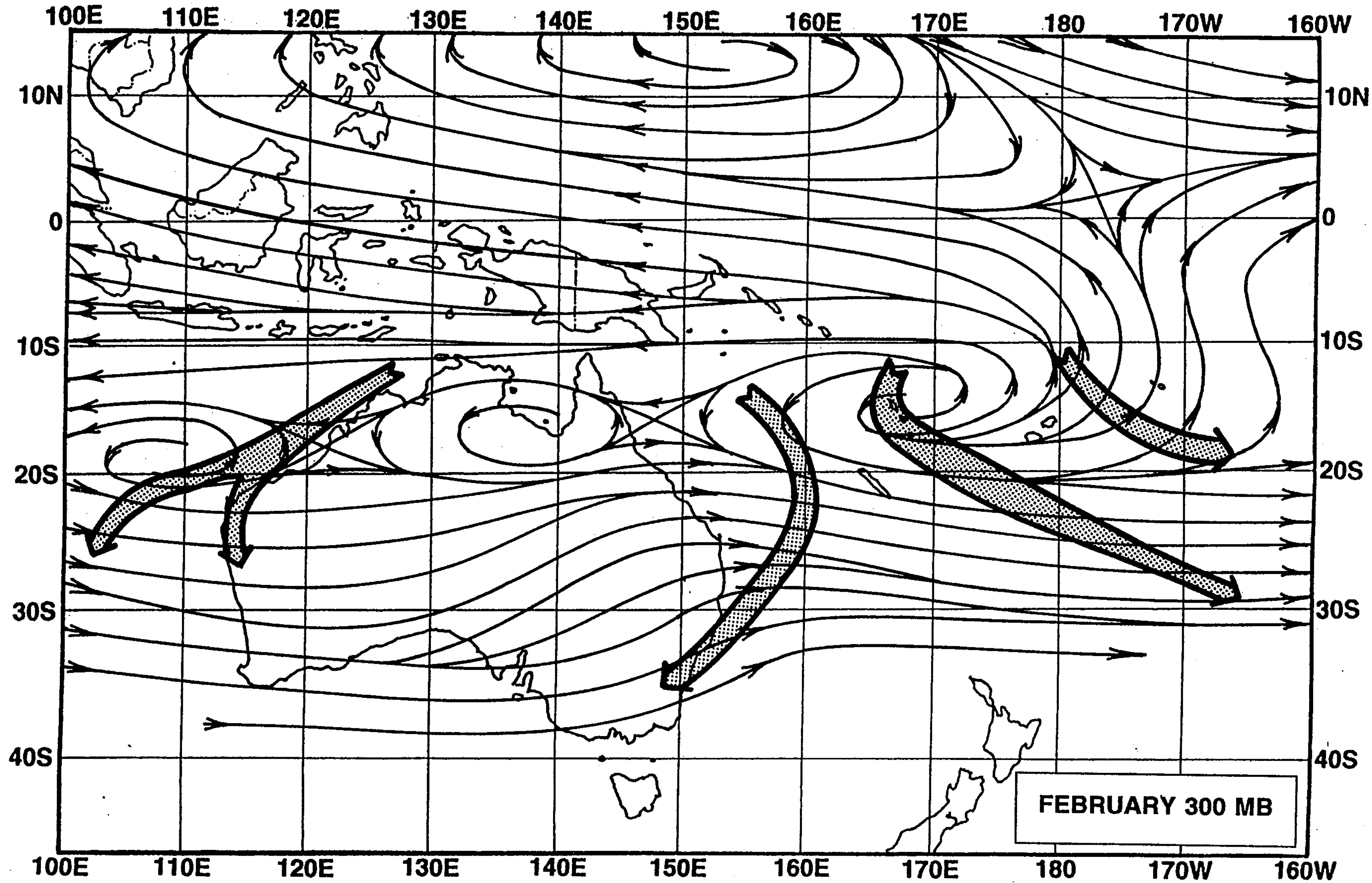


Figure D-31. February 300 mb streamlines and preferred tropical cyclone tracks for the Southeast Indian Ocean, South Pacific Ocean and Australia. Streamlines adapted from Sadler, 1975. Tropical cyclone tracks adapted from Crutcher and Quayle, 1974.

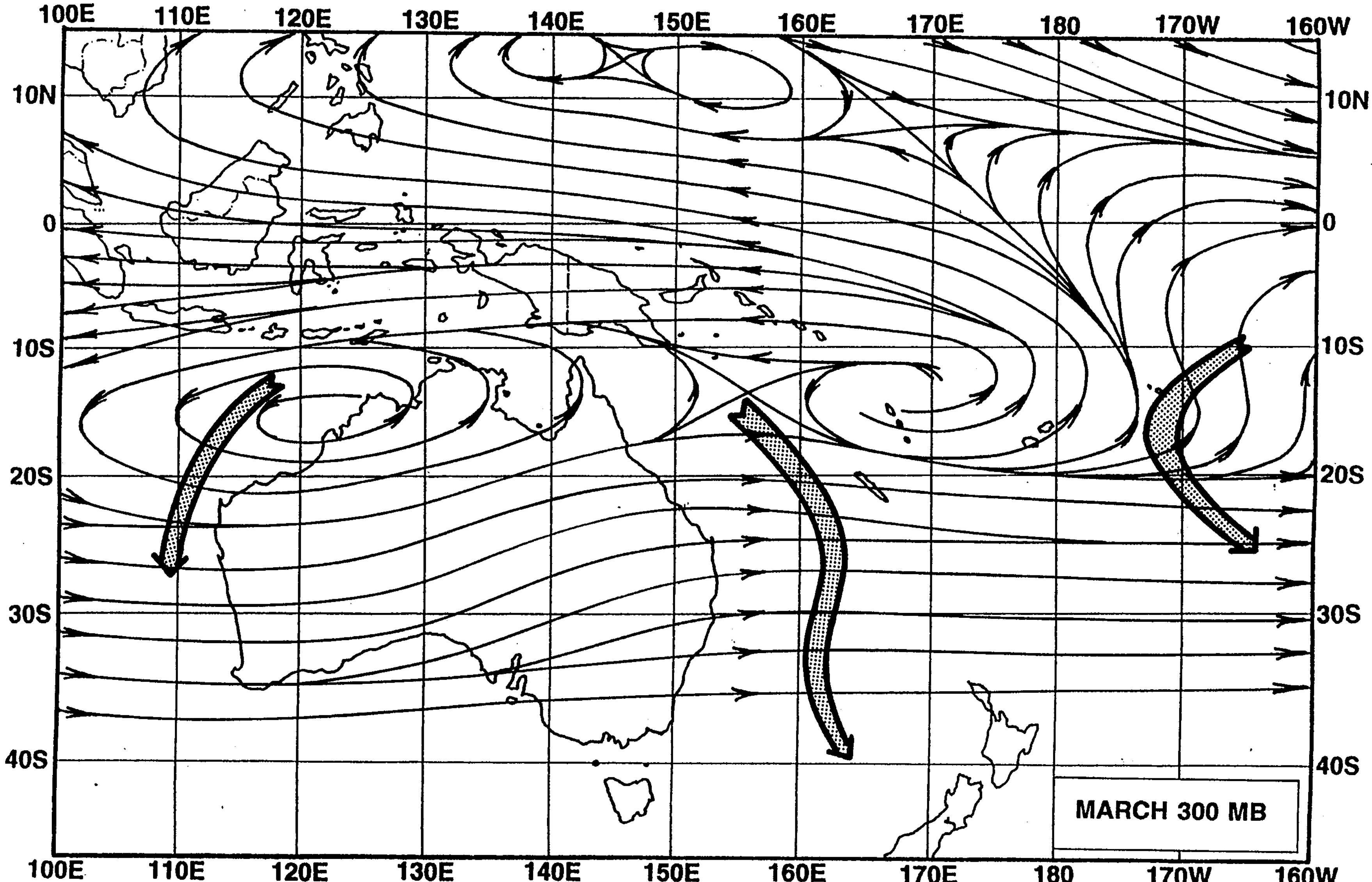


Figure D-32. March 300 mb streamlines and preferred tropical cyclone tracks for the Southeast Indian Ocean, South Pacific Ocean and Australia. Streamlines adapted from Sadler, 1975. Tropical cyclone tracks adapted from Crutcher and Quayle, 1974.

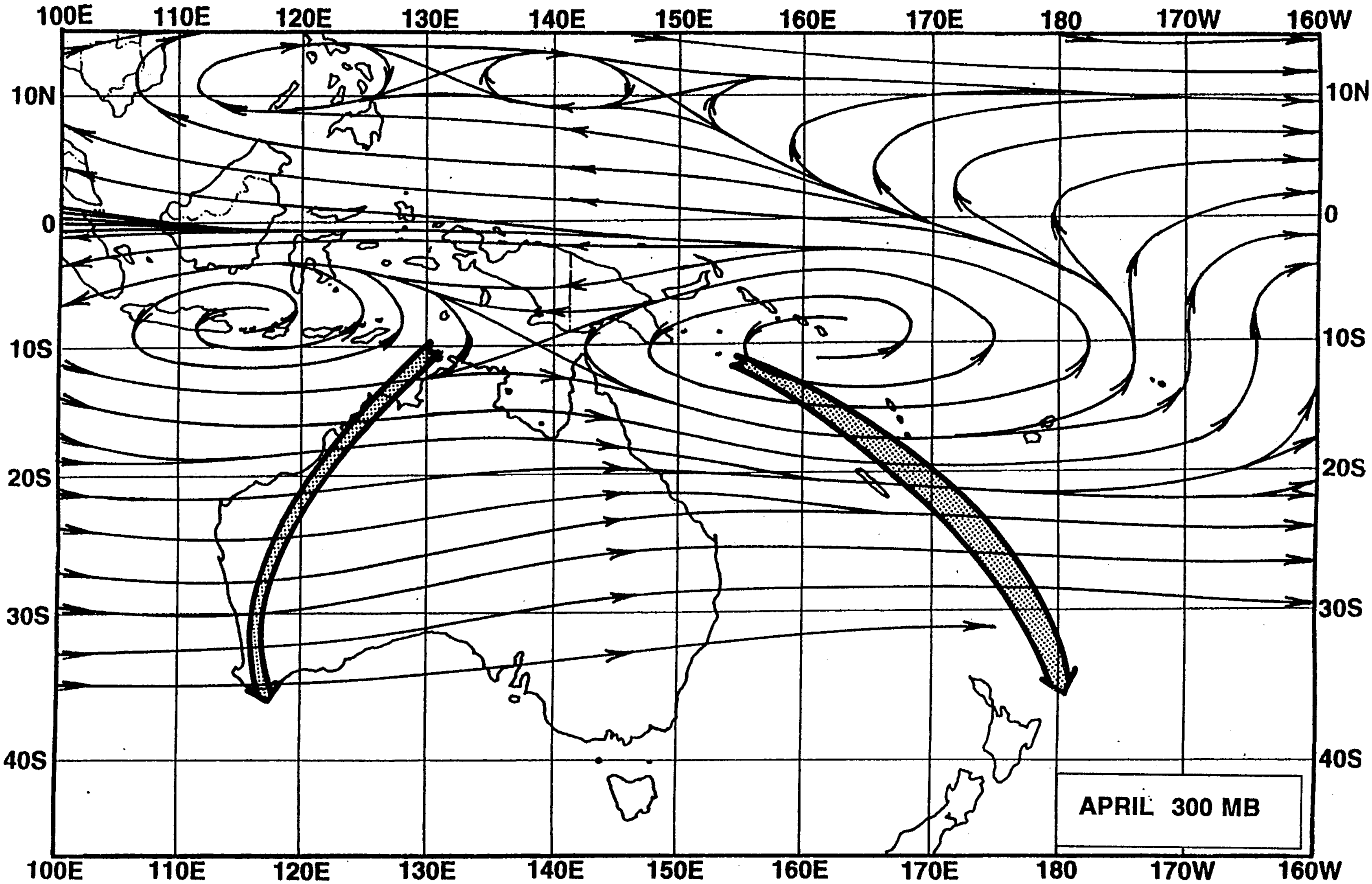


Figure D-33. April 300 mb streamlines and preferred tropical cyclone tracks for the Southeast Indian Ocean, South Pacific Ocean and Australia. Streamlines adapted from Sadler, 1975. Tropical cyclone tracks adapted from Crutcher and Quayle, 1974.

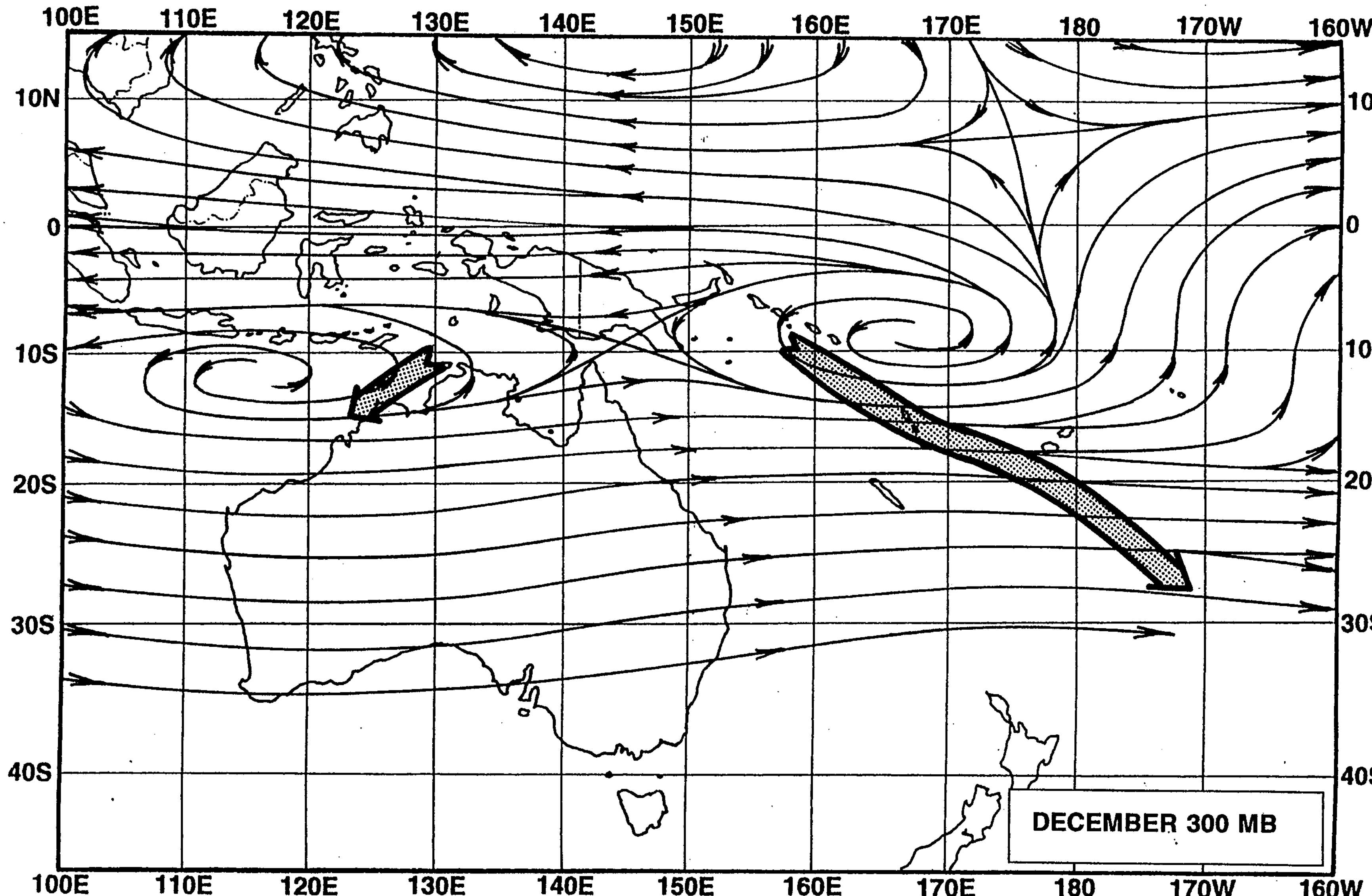


Figure D-34. December 300 mb streamlines and preferred tropical cyclone tracks for the Southeast Indian Ocean, South Pacific Ocean and Australia. Streamlines adapted from Sadler, 1975. Tropical cyclone tracks adapted from Crutcher and Quayle, 1974.