NPS-MR-98-002

NAVAL POSTGRADUATE SCHOOL
Monterey, California

Condensed and Updated Version of the Systematic Approach Meteorological Knowledge Base Western North Pacific

by

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December 1997

Prepared for: Office of Naval Research, Code 322MM, Arlington, VA 22217
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This report was prepared for the Joint Typhoon Warning Center (JWTC) at the Naval Pacific Meteorology and Oceanography Center (NPMOC) West, Guam and for the Alternate JTWC at NPMOC, Pearl Harbor, Hawaii. Funding was provided by the Office of Naval Research Marine Meteorology Program.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	December 1997	Interin 1/97 - 12/97

4. TITLE AND SUBTITLE
Condensed and Updated Version of the Systematic Approach Meteorological Knowledge Base -- Western North Pacific

5. FUNDING NUMBERS
N0001498WR30011

6. AUTHOR(S)
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
Code 322 MM
800 N. Quincy St.
Arlington, VA 22217-5000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
The views expressed in this report are those of the authors and do not reflect the official policy or position of the Department of Defense.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for Public Release; Distribution Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The meteorological knowledge base for the Systematic and Integrated Approach to Tropical Cyclone Track Forecasting proposed by Carr and Elsberry has evolved as additional research has been completed. This Systematic Approach has been applied in the eastern and central North Pacific, and in the Southern Hemisphere, a number of conceptual models have been refined and new terminology has been adopted to reflect global applicability. As a knowledge-based expert system is being developed, it was convenient to condense and update the meteorological knowledge base for the western North Pacific. Thus, the material is presented with text on the left page and the corresponding figure on the facing page as it will appear on the computer screen.

14. SUBJECT TERMS
Tropical cyclone track forecasting
Tropical cyclone motion

15. NUMBER OF PAGES

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	

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Acknowledgments. This research has been sponsored by the Office of Naval research Marine Meteorology Program, with additional matching funds from the Naval Postgraduate School. The authors gratefully acknowledge the crucial assistance and many valuable contributions made by personnel at the Naval Pacific Meteorology and Oceanography Center West Guam/Joint Typhoon Warning Center and the Naval Pacific Meteorology and Oceanography Center Pearl Harbor, Hawaii. Appreciation is extended for their support of this research and for making available personnel and facilities at NPMOC West Guam/JTWC during the development of this research. NOGAPS analyses were provided by the Fleet Numerical Meteorology and Oceanography Center, and modeling computations by the authors were made at the Naval Postgraduate School Church Computer Center. The manuscript was expertly typed by Mrs. Penny Jones.

INTRODUCTION

The original documentation of the Systematic Approach to Tropical Cyclone Track Forecasting (hereafter the Systematic Approach) was in a Naval Postgraduate School (NPS) Technical Report (Carr and Elsberry 1994). This lengthy report (273 pages) provided an overview of the Systematic Approach and a detailed development of the meteorological knowledge base with many examples of analyses, tracks, and satellite imagery. This was followed by a second NPS Technical Report (Carr et *al.* 1995) that provided a five-year climatology of the tropical cyclone (TC) environment structure for the western North Pacific region and a test of whether these synoptic classifications could be recognized by novices to the Systematic Approach. Based on this test and the preparation of the climatology, certain refinements were introduced. Concurrently, two M.S. theses were completed that applied the Systematic Approach to the eastern and Central Pacific (White 1995) and the Atlantic (Kent 1995). Recently, the meteorological knowledge base for the eastern and central Pacific has been extended by Boothe (1997), and adapted to South Hemisphere TCs by Bannister *et al.* (1997). These applications to other basins indicated the possibility of a general applicability, so that some names were changed to allow global application. Another M.S. thesis (Webb 1996) provided quantitative estimates of the degree of forecast difficulty, and demonstrated the official error variations, in different synoptic patterns.

Scientific journal documentation of various elements of the Systematic Approach meteorological knowledge base that have resulted from ongoing basic research by the Systematic Approach developers presently consists of: (i) Carr and Elsberry (1995), which addresses the phenomenon of monsoon gyre-TC interaction; (ii) Carr and Elsberry (1997), which addresses TC outer wind structure, TC propagation, and environmental modification by the TC; (iii) Carr et *al.* (1997), which proposes and documents the existence of multiple modes of binary TC interaction; and (iv) Carr and Elsberry (1998), which develops objective criteria for detecting, and distinguishing among, the different modes of TC interaction identified by Carr and Elsberry (1997).

The purpose of this report is to update and bring together in a more condensed form the Systematic Approach meteorological knowledge base for the western North Pacific. This documentation is based on eight years (1989-96), during which the basic concepts are found to apply in nearly all cases. Because this report will be incorporated in an expert system, the format is one of text on odd-numbered pages and a figure or other supporting information on the even-numbered pages as they will appear on a computer screen. Selected tracks in these case studies are given in Appendix A. All numerical analyses used here in case study illustrations are at 500 mb. Cross-references are given so that the reader can refer to earlier pages for clarification. Hopefully, this updated and condensed version will provide a useful reference guide for application of the Systematic Approach.

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White, S. R., 1995: Systematic and integrated approach to tropical cyclone track forecasting in the eastern and central North Pacific. M. S. Thesis, Naval Postgraduate School, Monterey, CA 93943, 79 pp.

GENERAL TOPICS

Topic: KEY TC MOTION CONCEPTS

The Systematic Approach meteorological knowledge base is based on three key concepts of tropical cyclone (TC) motion:

(a) ENVIRONMENTAL STEERING: To a first approximation, the TC vortex is advected by the large-scale environmental flow (i.e., the TC moves as a "cork in the stream");

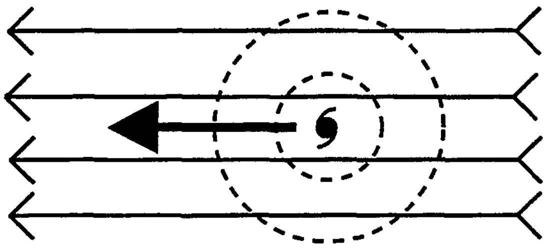
(b) TC PROPAGATION: The motion vector of TCs usually departs in a minor, and not insignificant, way from the large-scale environment steering vector.

(c) TC-ENVIRONMENT INTERACTION: In certain situations, the circulation of the TC interacts with the environment in such a way as to alter significantly the structure of the environment, and thus modifies the steering vector that is the first-order effect on the motion of the TC.

Cross references:
Environment Structure p. 19-52
Beta-effect Propagation p. 57
TC-Environment Transformations p. 57-115

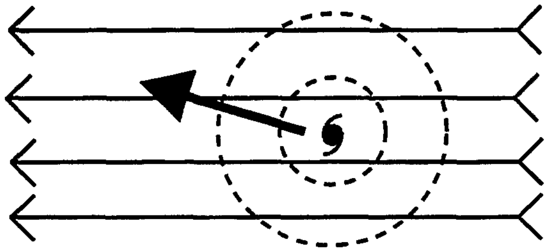
KEY TC MOTION CONCEPTS

(a)



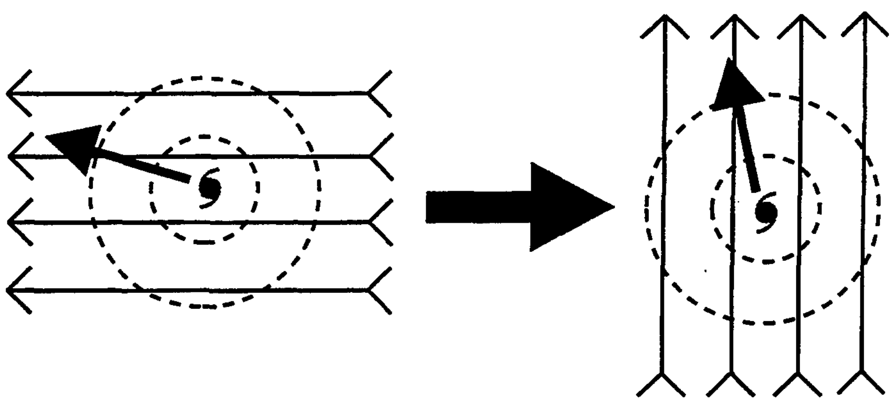
ENVIRONMENT
STEERING

(b)



ENVIRONMENT
STEERING
+
TROPICAL CYCLONE
PROPAGATION

(c)



CHANGE TO ENVIRONMENT STEERING
(i.e., structure)
DUE TO
INTERACTION OF TC CIRCULATION
WITH THE ENVIRONMENT

GENERAL TOPICS

Topic: GENERAL KNOWLEDGE BASE FRAMEWORK

Based on the three fundamental motion concepts on page 3, the meteorological knowledge base is comprised of three main components:

(a) ENVIRONMENT STRUCTURE, which is defined in terms of a large-scale synoptic PATTERN and two or more synoptic REGIONs within the pattern that tend to produce characteristic directions and speeds of the steering flow for a TC.

(b) TC STRUCTURE, which consists of an INTENSITY that is based on the maximum wind speed near the center of the TC, and a SIZE that is based on some measure of the extent of the cyclonic wind component in the lower troposphere.

(c) TRANSITIONAL MECHANISMS, which act to change the structure of the environment (pattern/region), and fall into two categories:

(1) TC-ENVIRONMENT TRANSFORMATIONS, which are processes by which the TC and the environment may interact, to change the environmental structure (pattern/region), and thus the direction/speed of the associated steering flow. In addition, TC-environment transformations may result in a change to the TC structure.

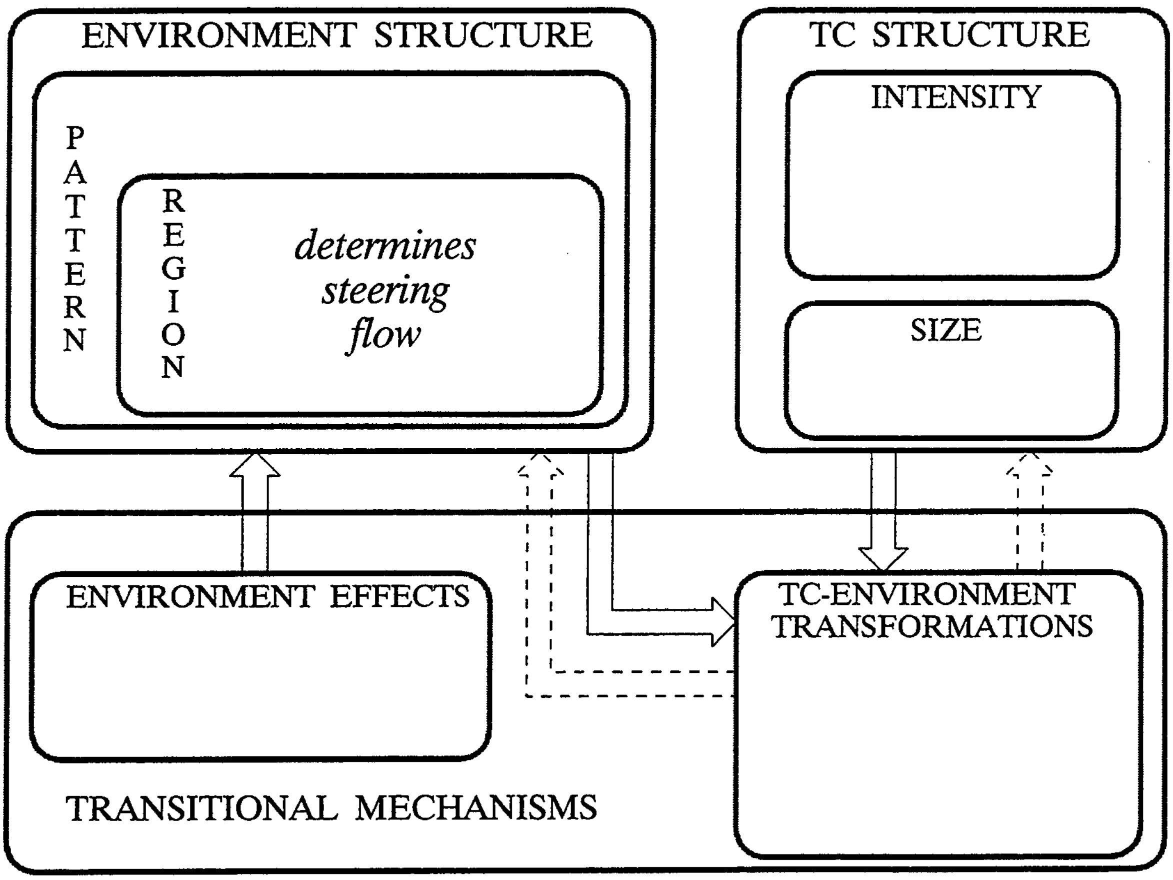
(2) ENVIRONMENT EFFECTS, which also result in changes to the structure of the environment (pattern/region) surrounding the TC, but that do not depend on, or are largely independent of, the presence of the TC.

Most of the entries in this basic framework depend on the TC basin because different environments exist. In this case, the entries for the western North Pacific TCs will be given below.

Cross references:

Western Pacific examples
- Environment Structure p. 19-56
- TC Structure p. 13-16
- Transitional Mechanisms
  - TC-Environment Transformations, p. 57-116
  - Environment Effects p. 117-142

METEOROLOGICAL KNOWLEDGE BASE



GENERAL TOPICS

Topic: WESTERN NORTH PACIFIC KNOWLEDGE BASE

ENVIRONMENT STRUCTURE in the western North Pacific is defined by four synoptic pattern classifications, and one of six region classifications. The pattern/region combinations listed below have been found to be adequate to classify nearly all environment structures in the western North Pacific:

PATTERN	REGION OPTIONS
S	EW, DR, WR, MW
P	PO, MW
G	PO, DR, MW
M	PF, EF

The GYRE PATTERN is virtually unique to the western North Pacific. The other patterns occur in other basins, but with different frequencies of occurrence than for the western North Pacific.

The TC INTENSITY classifications have the customary meanings, and the SIZE classifications will be defined later in terms on the magnitude of the beta-effect propagation. Although the intensity and size classifications are applicable to all basins (replacing typhoon with hurricane), the frequency of intensity and size classifications varies from basin to basin.

Of the TRANSITIONAL MECHANISMS, only those involving a monsoon gyre (MG) are unique to the western North Pacific. The frequency of occurrence of the others varies widely from basin to basin.

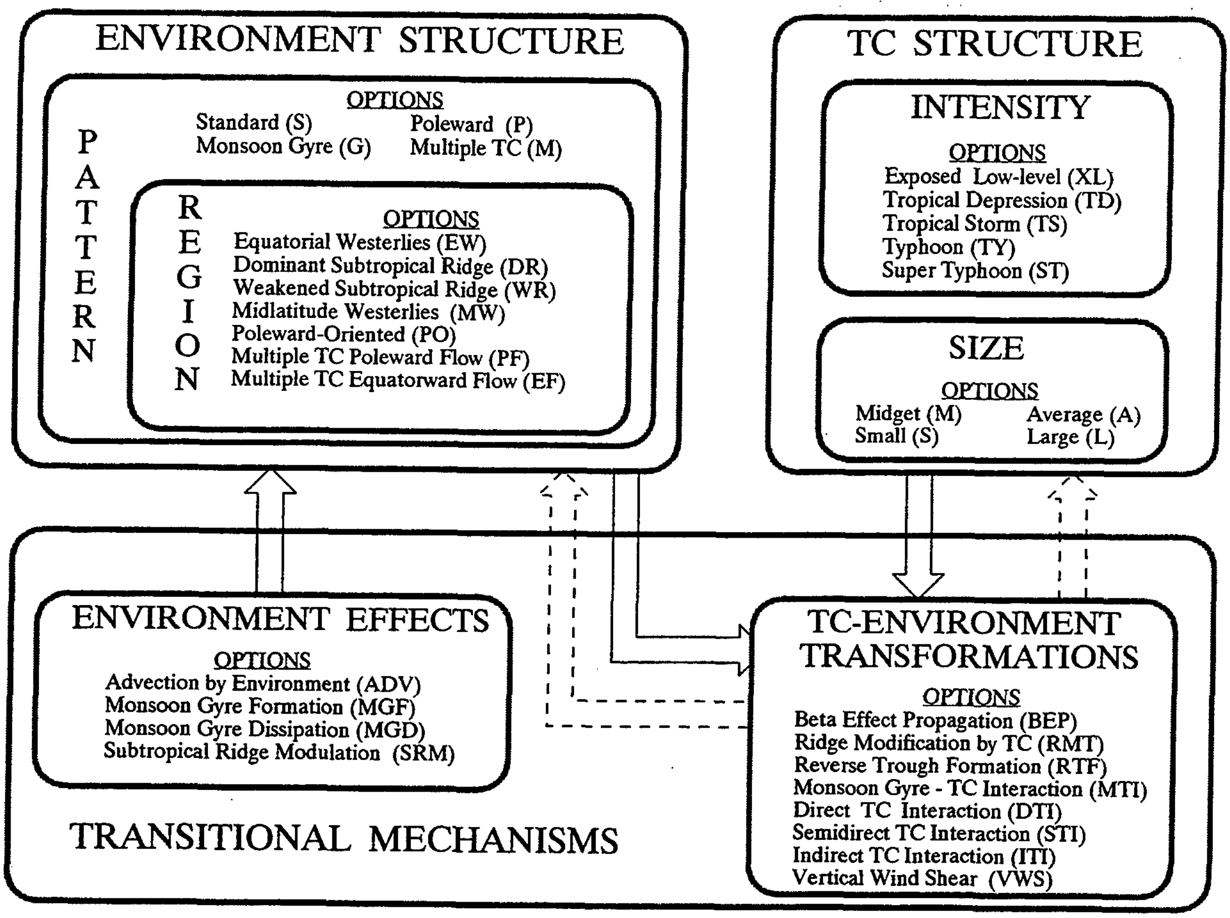
Cross-references:

Western North Pacific examples

S/DR p. 19-24
S/WR p. 19-24
S/MW p. 19-24
P/PO p. 29-34
P/MW p. 29-34
G/PO p. 39-44
G/DR p. 39-44
G/MW p. 39-44
M/PF p. 47-52
M/EF p. 47-52

TC Intensity p. 13
TC Size p. 15

WESTERN NORTH PACIFIC METEOROLOGICAL KNOWLEDGE BASE



Topic: DIAGNOSING ENVIRONMENTAL STEERING DIRECTION

As defined in the key motion concepts (p. 4), the environmental steering has the TC circulation removed. A qualitative estimate of the environmental steering direction is possible from operational dynamical model streamline/isotach analysis. Based on the schematic on the facing page, the superposition of a symmetric TC circulation and a large-scale environment flow will produce:

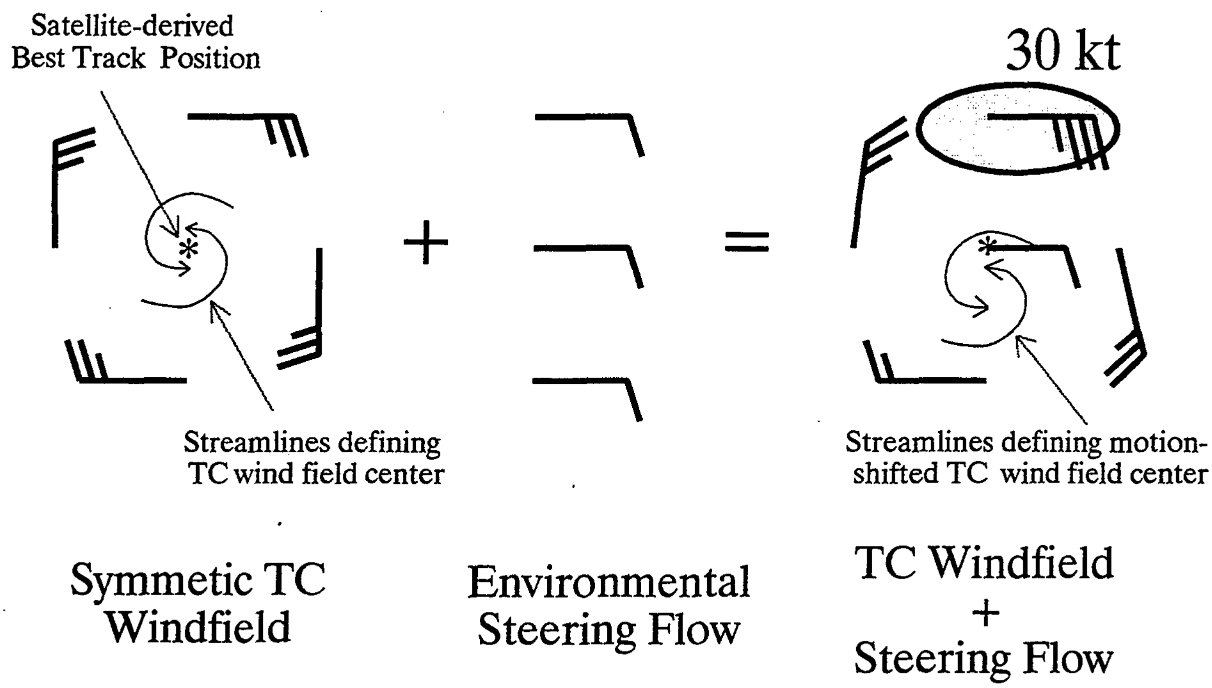
(a) a wind maximum to the right (Northern Hemisphere) of the direction of the environmental steering flow; and

(b) a displacement of the analyzed wind circulation center to the left of the vorticity center on which a satellite fix is based. The magnitude of the center displacement in intense TCs is usually not noticeable on a synoptic scale due to the small size of the radius of maximum winds. In a global model analysis, the center displacement may be up to several degrees latitude depending on the radius of maximum winds of the TC vortex in the numerical model analysis.

In a consistent numerical analysis, the locations of the TC wind circulation center, satellite-derived position, and isotach maximum should be aligned along a line perpendicular to the direction of the steering flow. Thus, the orientation of this line on a streamline/isotach analysis at the steering level (e.g., 500 mb) may be used to infer the direction of the steering flow at the location of the TC. Since the various synnoptic pattern/region combinations have characteristic directions of steering, the direction of steering diagnosed via the above procedure may assist the forecaster in assigning the correct synoptic pattern/region to a particular situation.

If these three positions are not aligned, then an error exists in the numerical analysis, or in the satellite-derived position, or in both (see next page).

MOVING TC WINDFIELD CONCEPTUAL MODEL



Topic: DIAGNOSING ENVIRONMENTAL STEERING DIRECTION (cont)

The NOGAPS streamline/isotach analysis in panel a on page 12 illustrates a consistent co-linear relationship among the positions of the satellite-derived position (asterisk), the model-analyzed wind circulation center to the left, and the model-analyzed isotach maximum to the right. In this case, the orientation of the three positions implies that the environmental steering direction is toward the northeast. This direction is consistent with the recent 12-h translation direction of the TC (arrow) when the propagation effect is included.

By contrast, the analysis in panel b has an inconsistent relationship among the three positions, which indicate that either:

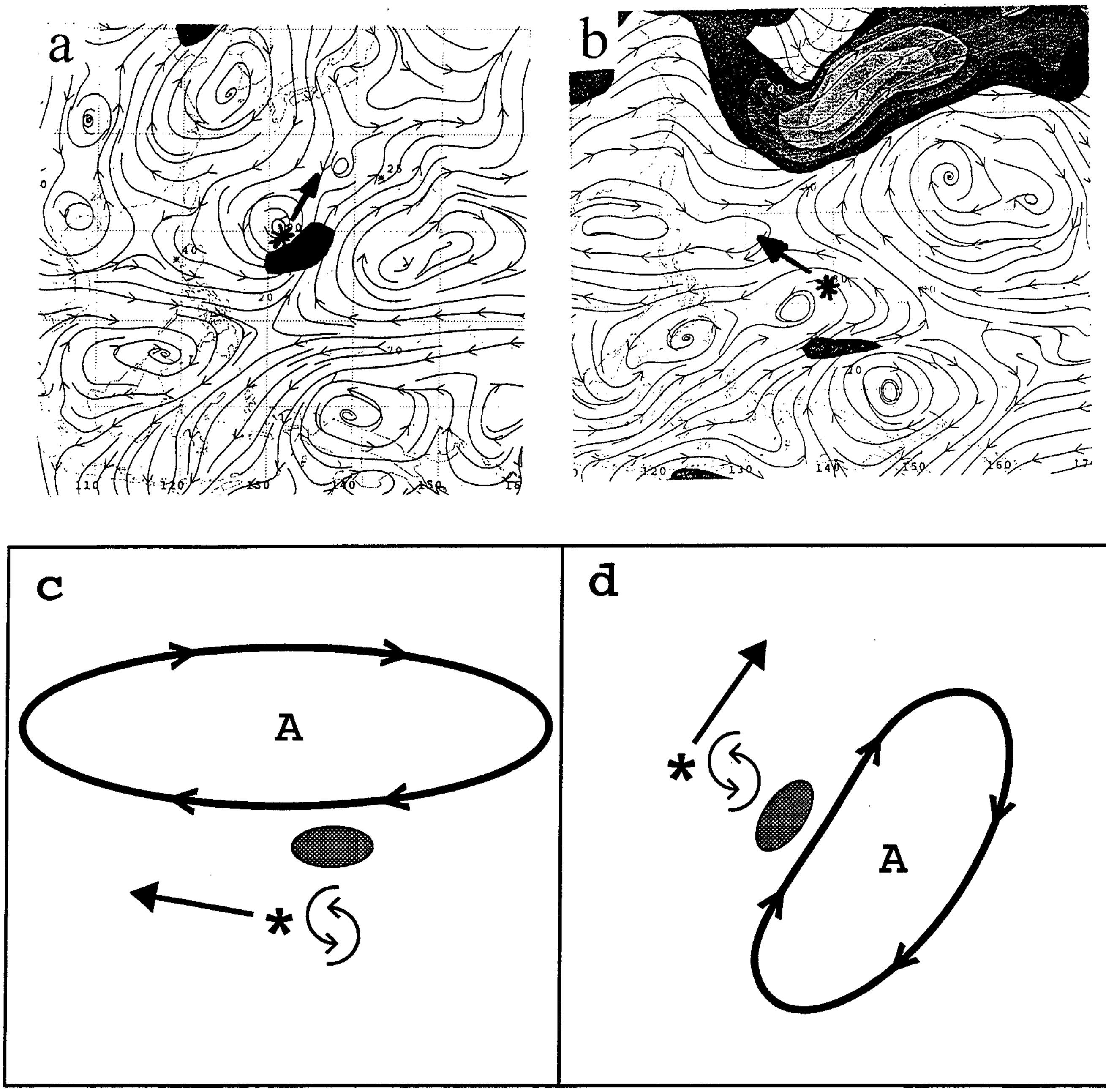
(a) the northwestward environmental steering direction suggested by the NOGAPS analysis (isotach maximum to southeast of wind circulation center) is in error; or
(b) the satellite-derived position (asterisk) is in error.

Notice that the recent translation direction of the TC (arrow) in the right panel disagrees with the steering direction inferred from NOGAPS streamline/isotach maximum. This strongly sugggests that the NOGAPS analysis is error because the position of the isotach maximum to the southeast would imply a storm translation to the northeast in this case.

Another analysis inconsistency may occur even if the steering direction inferred from the maximum isotach position in the NOGAPS analysis approximately agrees with the actual TC translation direction. In these cases, the warning position valid at the analysis time does not lie along the line connecting the wind circulation center and the maximum isotach position in the NOGAPS analysis. Two hypothetical examples are shown in panels c and d on p. 12. In these cases, either the warning position or the wind circulation center in the NOGAPS analysis is incorrect. In panel c, the warning position may be to the left and in advance of the actual position, or the wind circulation center is to the right and behind a proper location. In panel d, the warning position is behind and to the left of the actual position, or the wind circulation center is in advance and to the right of its correct location. Whether the error arises from the warning position or is in the wind circulation center may be discriminated by considering whether:

(a) the systematic TC wind observations have (or have not) been entered in NOGAPS;
(b) a large Position Code Number (PCN) for the satellite fixes would suggest that the warning position might be in error; or
(c) a sudden, large shift in the warning position (i.e., a major relocation) has been made as a result of an unexpected change in cloud structure or receipt of the first visible imagery of the day. Following such relocations, the NOGAPS wind circulation center may reflect a blending of the previous and new positions for one or two analysis cycles.

NOGAPS ANALYSIS/TC POSITIONING ERROR DETECTION



TC STRUCTURE DEFINITIONS

Topic: TC INTENSITY

The intensity of a TC is used here to define the depth of the steering layer, or equivalently the pressure level of the steering that has been found to best conform to the observed motion of the TC. From a quantitative perspective, steering averaged over some layer depth has been shown to correlate more closely with TC motion. However, the mid-layer pressure will be used here to determine the level of the NOGAPS streamline/isotach analysis from which a qualitative determination of the pattern/region/transitional mechanism is to be made. The table at right associates a TC intensity range to the best steering level.

In cases for which the TC intensity is expected to remain in the same intensity category throughout the forecast period, use the steering level shown in the table at right.

Generally, it will not be practical to use a different steering level at each forecast interval for which a pattern/region/transitional mechanism assessment must be made. When significant intensification (weakening) of a weak (intense) TC is expected, a compromise level of 500 mb may be used.

TC INTENSITY CLASSIFICATIONS

INTENSITY CATEGORY		MAXIMUM WIND SPEED RANGE (kt)	BEST STEERING LEVEL (mb)
Exposed Low-level	(XL)	(Note 1)	850
Tropical Depression	(TD)	25-30	700 (Note 2)
Tropical Storm	(TS)	35-60	700
Typhoon	(TY)	65-125	500
Super Typhoon	(ST)	130-180	400 (Note 3)

NOTES:

1. Exposed low-level (XL) is not an officially recognized term. In cases of sudden onset of vertical wind shear, the convective cloud mass that maintains the high wind speeds near the center of the TC can separate so rapidly that the resulting XL can have wind speeds exceeding 65 kt for short periods (hours). However, the maximum wind speed in a XL is typically less than typhoon intensity. Thus, a TC designated XL for the purposes of the Systematic Approach (assigning steering level) is assigned either a TD or TS intensity.

2. This steering level applies only to TCs that have a solid coupling between the wind field and the convective cloud mass (i.e., not separating with time).

3. Since insufficient data are probably available to calculate accurately the steering flow variations between 400 mb and 500 mb, the 500 mb charts may be usually substituted for the 400 mb. With increasing availability of satellite water vapor winds to define the winds in the 400-100 mb layer, this substitution may not be justified.

TC STRUCTURE DEFINITIONS

Topic: TC SIZE

For the purposes of the Systematic Approach, the size of a TC is defined based on the expected beta-effect propagation (BEP) speed, and also is qualitatively associated with the potential of the TC circulation to modify the structure of the environment (i.e., change the pattern/region) via interaction with the environment. The four size definitions that associate beta-effect propagation speed, size, and propensity to modify the environment are shown at right. Notice that each TC size is associated with a TC propagation speed range and a capacity to modify the structure of the environment.

NOTE: Environment modification potential depends on the relative sizes of the TC circulation and the subtropical ridge circulation providing easterly steering. Thus, an average TC could have significant environment modification potential if the subtropical ridge circulation to the north has a small horizontal scale. Conversely, a large TC may have only moderate environment modification potential if the subtropical ridge circulation to the north is very large.

Cross-reference:

Beta-effect Propagation p. 57

TC SIZE MODELS

TC SIZE RANGE	PROPAGATION SPEED (kt (m/s))	POTENTIAL TO CAUSE ENVIRONMENT MODIFICATION
Midget (M)	0.0 - 0.9 (0.0 - 0.45)	negligible
Small (S)	1.0 - 1.9 (0.5 - 0.95)	minimal
Average (A)	2.0 - 3.9 (1.0 - 1.95)	moderate
Large (L)	4.0 & up (2.0 & up)	considerable

Topic: TC SIZE (cont.)

ANGULAR MOMENTUM TC WIND PROFILE

Barotropic theory and modelling have shown that the beta-effect propagation (BEP) speed depends on the outer wind strength of the TC circulation. As shown in the figure to the right, the Systematic Approach uses a TC wind distribution model based on a frictionally-adjusted conservation of absolute angular momentum that specifies outer wind strength in terms of two parameters:

(a) the radius of zero symmetric cyclonic tangential wind at 850 mb (R_0850), which is known as the "extent" of the TC;

(b) the value of the Coriolis parameter (as determined by the TC latitude), which determines the rate at which the tangential wind speed increases as radius decreases (slope of the outer wind profile); and

(c) the exponential factor X, which has a value less than 1.0 (0.4 used here) to account for loss of absolute angular momentum due to friction.

As result, the outer tangential wind strength can be increased (decreased) not only by increasing (decreasing) R_0850 at a constant latitude, but also by increasing (decreasing) latitude at a constant R_0850.

Since R_0850 cannot be measured directly, it must be estimated by:

(1) using available wind data to estimate the average radius of some non-zero wind speed (e.g., radius of 25, 30, 35, or 40 kt) at 850 mb and using the tangential wind distribution model to calculate the corresponding R_0850 (e.g., see nomograms at lower right); or

(2) assuming that the overall extent of the TC low-level cloud pattern in satellite imagery is roughly representative of R_0850.

Because neither of these size estimates will be precise, the R_0850 and f_0 values are used to define a BEP speed in one of four broad categorizations (see previous page).

Cross-reference:

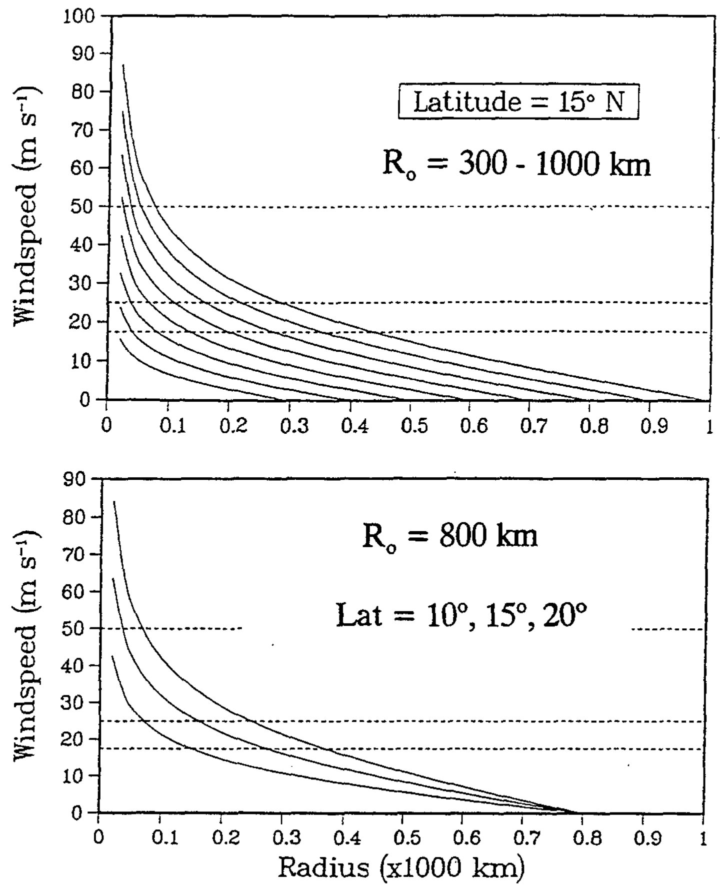
Beta-effect Propagation p. 57

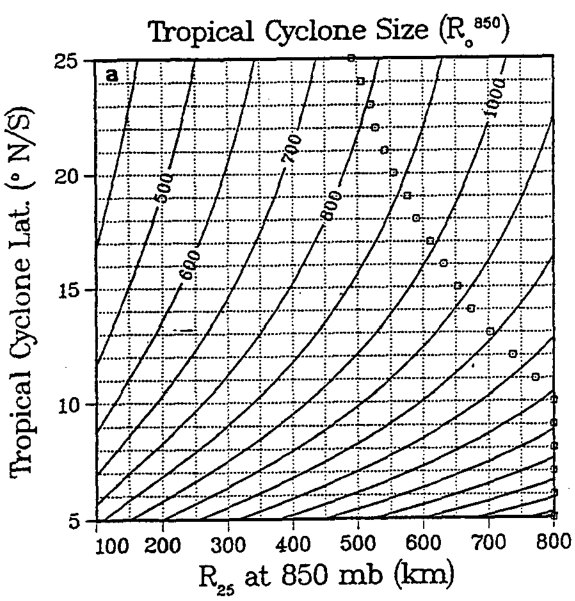
ANGULAR MOMENTUM-BASED TC WIND DISTRIBUTION MODEL

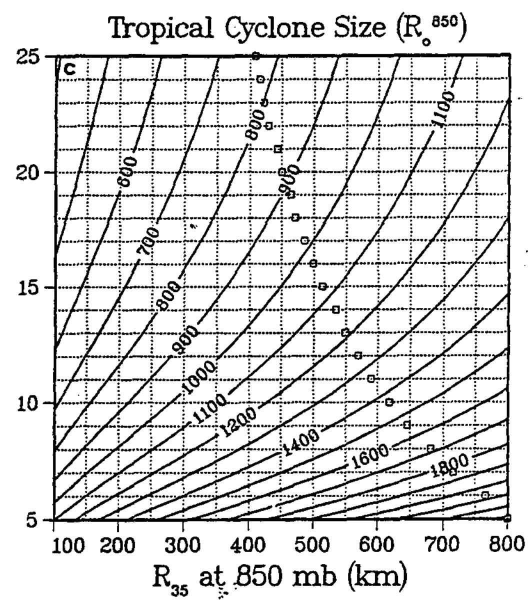
$$v(r) = \frac{M}{r^X} - \frac{1}{2} f_o r$$

$$M = \frac{1}{2} f_o \left(R_o^p\right)^{1+X}$$

$$v(R_o^p) = 0$$







ENVIRONMENT STRUCTURE DEFINITIONS

Topic: STANDARD (S) PATTERN

PATTERN/REGIONS DESCRIPTION

At the steering level of the TC, the key environment feature that defines a pattern classification of STANDARD (S) is one or more roughly zonally oriented subtropical ridge (STR) anticyclones. In the vicinity of the TC, the STR may be either unbroken or divided into two cells by an evolving (deepening/filling/moving) midlatitude trough. (NOTES: A midlatitude trough-related break in the STR is an example of SUBTROPICAL RIDGE MODULATION (SRM), which is summarized later. When the equatorial trough is displaced more than about 8° lat. from the Equator, which is then called a monsoon trough, the cross-equatorial flow will lead to equatorial westerly winds. While rare in the western North Pacific, a tropical cyclone may form in the cyclonic shear of the equatorial westerlies and first move eastward.)

The synoptic REGIONS of the S Pattern are:

(a) EQUATORIAL WESTERLIES (EW), which is in the area of equatorial westerlies equatorward of the monsoon trough.

(b) DOMINANT RIDGE (DR), which encompasses the area of tropical easterlies (typical speeds of 10-15 kt) equatorward of the STR axis, except near a break in the STR.

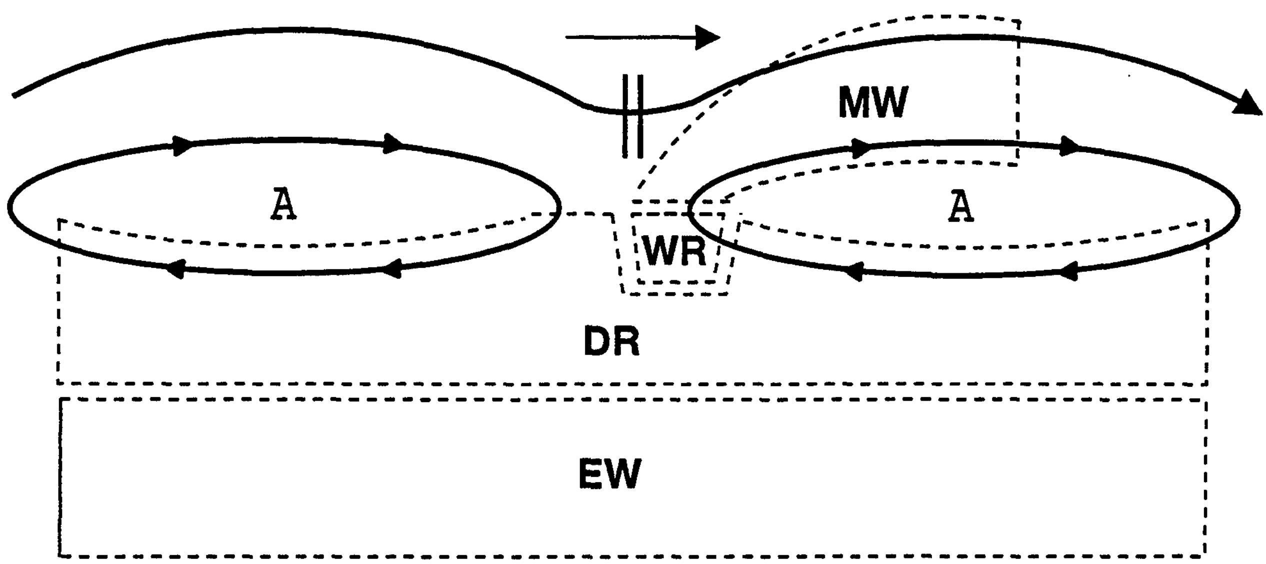
(c) WEAKENED RIDGE (WR), which encompasses the area of weaker southeasterly winds in the vicinity of a break in the STR.

(d) MIDLATITUDE WESTERLIES (MW), which encompasses the area of eastward and poleward steering that extends eastward from a break in the STR.

Cross-reference:

Subtropical Ridge Modulation p. 115

STANDARD (S) PATTERN



-------- Region boundaries

ENVIRONMENT STRUCTURE DEFINITIONS

Topic: STANDARD (S) PATTERN (cont)

CHARACTERISTIC TC LOCATIONS AND TRACKS

Representative TC positions in each Synoptic REGION of a S Pattern are shown at right. The following considerations apply to a single TC (other considerations apply if multiple TCs are present, as will be discussed below) in each region:

(a) In the EW region, the isotach maximum (shaded elliptical region), which implies the direction of environmental steering, will be S to SE of the TC.
(b) In the DR region, the isotach maximum will be found NNW to NE of the TC depending on the orientation of the STR axis (sloping vs. zonal). As illustrated for the easternmost TC, a ridge (peripheral anticyclone) may be located SE of large western North Pacific TCs. If the peripheral anticyclone becomes strong enough to shift the isotach maximum to an E to SE position, and the TC is moving strongly poleward (say > 315 deg), then the pattern/region classification is actually P/PO (see below).
(c) In the WR region, the isotach maximum will be oriented from NE to E of the TC depending on the location of the TC in the region.
(d) In the MW region, the isotach maximum will be oriented from E to SSE of the TC depending on the location of the TC in the region, and the amplitude of the associated midlatitude trough.

If the S Pattern persists, a TC may follow any one of three characteristic tracks indicated by the numbers:

(1) a persistently westward STRAIGHT track in the DR region that may also have a small to moderate poleward component for average to large sizes of the TC;
(2) a RECURVATURE track, in which the TC changes direction from a westward track in the DR region to a more poleward track as it enters a trough-induced break in the STR (WR region) and then has an accelerating track poleward and eastward in the MW region after the TC passes the latitude of the STR axis; or
(3) a STAIR-STEP track, in which the TC moves toward, or even into, the midlatitude trough-induced break in the STR, but rather than recurving then turns toward the SW and returns to the tropics in the DR region.

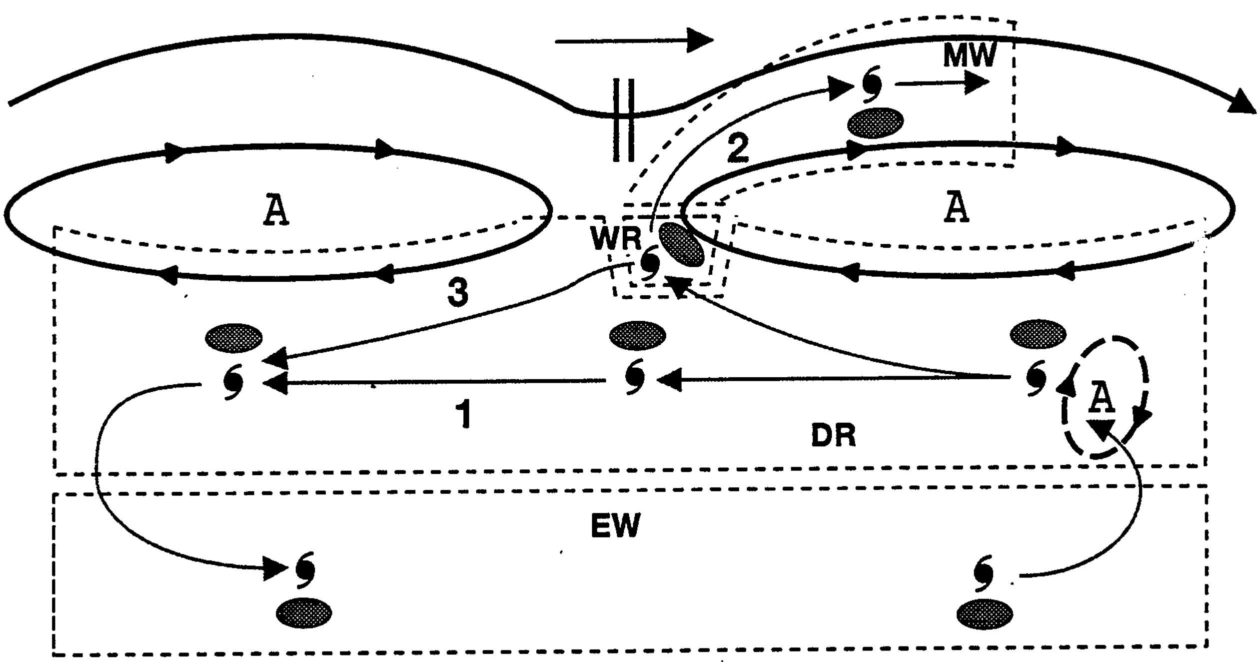
NOTES: At the bifurcation point between characteristic tracks 2 and 3, only subtle variations in TC position, STR structure, and midlatitude trough behavior may alter whether the TC "stair-steps" or "recurves." For the rare TC in the EW region, the motion will be eastward.

Cross-references:

P/PO pattern/region p. 29

Multiple TC pattern p. 47

STANDARD (S) PATTERN
CHARACTERISTIC TRACKS



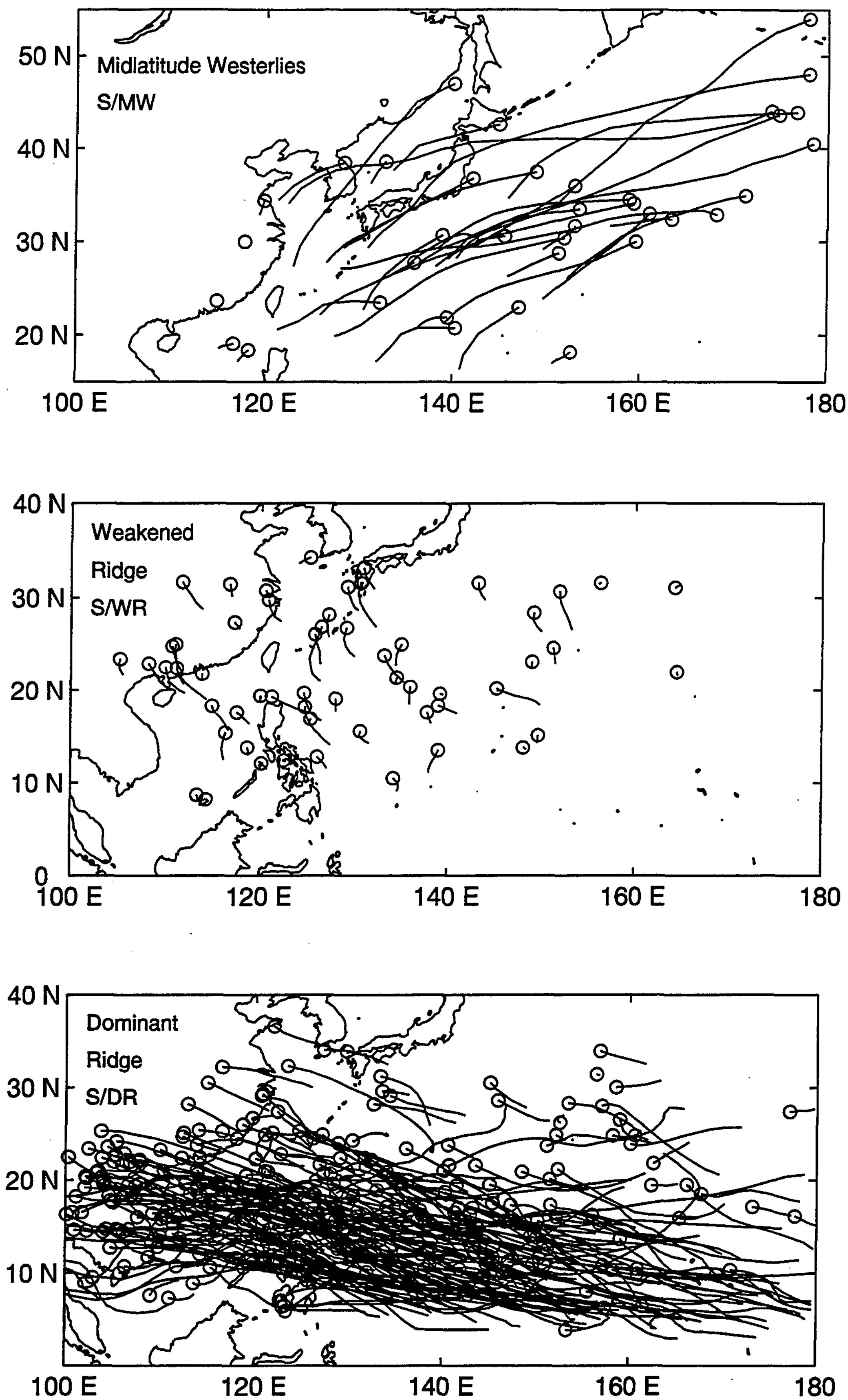
-------- Region boundaries
Isotach maximum
Characteristic track

ENVIRONMENT STRUCTURE DEFINITIONS

Topic: STANDARD (S) PATTERN (cont)

ACTUAL TRACKS

The tracks of TCs in the western North Pacific during 1989-1996 while in the Standard (S) synoptic pattern are shown on the right. Notice the long, generally west-northwestward tracks in the Dominant Ridge (DR) synoptic region, although some segments are south of west. Track segments in the Weakened Ridge (WR) synoptic region are generally poleward and are short because the TC does not remain in this region for very long. Poleward and eastward tracks are found in the Midlatitude Westerlies (MW) synoptic region.


50 N
40 N
30 N
20 N
Midlatitude Westerlies
S/MW
100 E
120 E
140 E
160 E
180
40 N
30 N
20 N
10 N
0
Weakened
Ridge
S/WR
100 E
120 E
140 E
160 E
180
40 N
30 N
20 N
10 N
Dominant
Ridge
S/DR
100 E
120 E
140 E
160 E
180

ENVIRONMENT STRUCTURE DEFINITIONS

Topic: STANDARD (S) PATTERN (cont)

SCENARIO ILLUSTRATION: S/DR (Steady)

The NOGAPS streamline/isotach analysis series at right shows Typhoon Ed in a persistent S/DR environment. The track of Ed is given in the Appendix page A-2. Notice the following:

- on 11 September (panel a), even though the circulation of Ed is not represented well in the NOGAPS analysis, the easterly steering that is moving Ed westward is readily discernable. At the time Ed was only a 30-kt TD, and thus no synthetic TC winds had yet been incorporated into the NOGAPS data assimilation cycle.

- a closed wind circulation for Ed does appear on the 12th (panel b) since synthetic TC winds have been added to NOGAPS. Although no isotach maximum is visible, the displacement of the NOGAPS wind center to the south of the satellite-based position is consistent with easterly steering and westward TC motion.

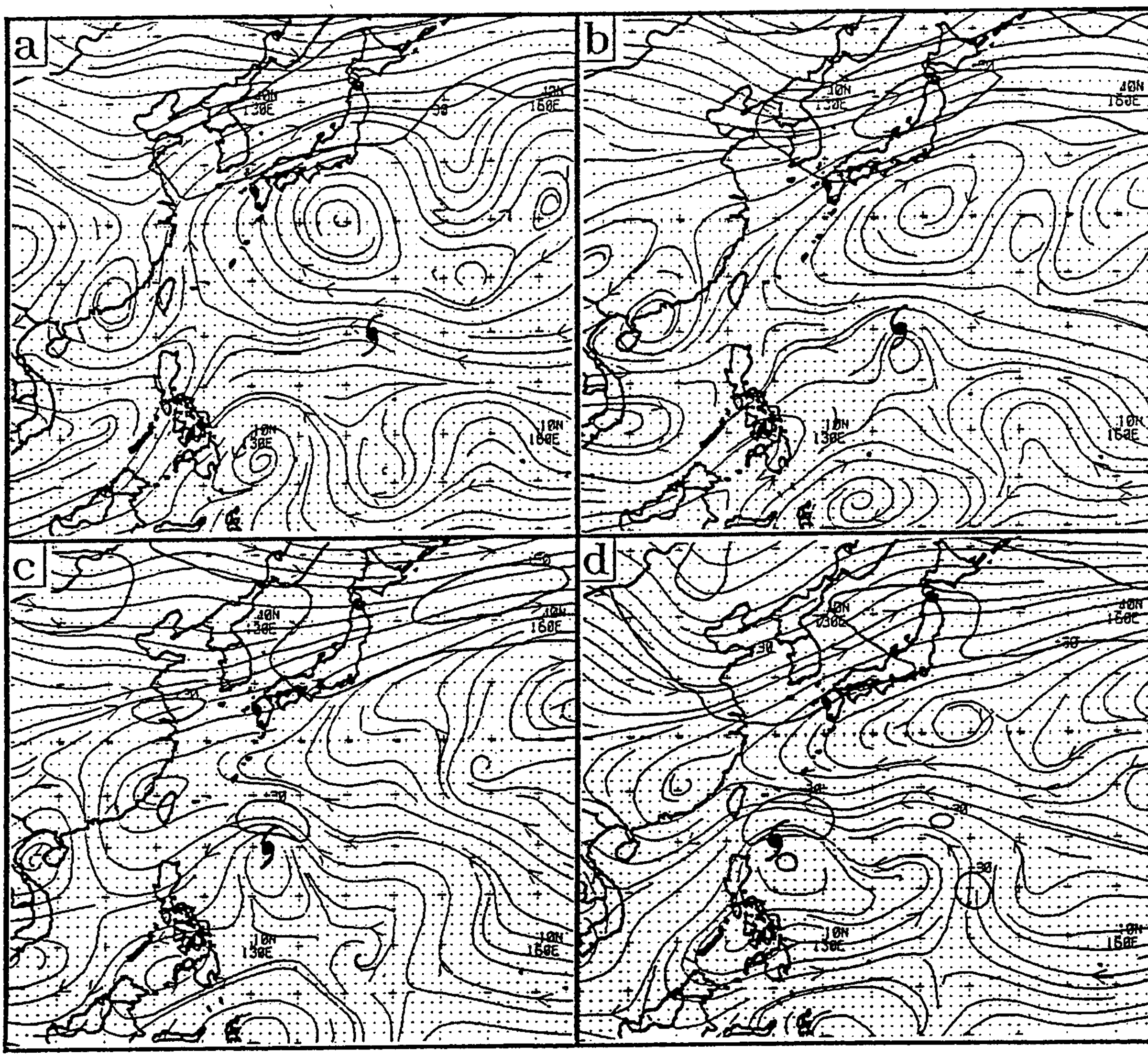
- on 13 and 14 September (panels c and d), a 30-kt isotach maximum appears to the north of the TC position as expected in a S/DR scenario.

Notice the large STR amplitude and zonal orientation on the 11th and 12th versus the WSW-ENE tilt of the STR axis on the 13th and 14th, which is consistent with the south of west displacements.

Cross-reference:

Diagnosing Environmental Steering Direction p. 9

Typhoon Ed
11-14 Sept 1990 (0000 UTC)
Persistent S/DR



ENVIRONMENT STRUCTURE DEFINITIONS

Topic: STANDARD (S) PATTERN (cont)

SCENARIO ILLUSTRATION: S/DR - S/WR Transition

The NOGAPS streamline/isotach analysis series at right shows Typhoon Hattie initially in a S/DR environment, and then a transition to a S/WR environment. The corresponding track of Hattie is in the Appendix page A-3. Notice that:

- on 3 October (panel a), the NOGAPS wind center, the Hattie position, and the NOGAPS isotach maximum are in a nearly north-south alignment that is consistent with a S/DR environment.

- on 4 October (panel b), the NOGAPS wind center, the Hattie position, and the NOGAPS isotach maximum are in an approximately NNE-SSW alignment that is consistent with a S/DR environment.

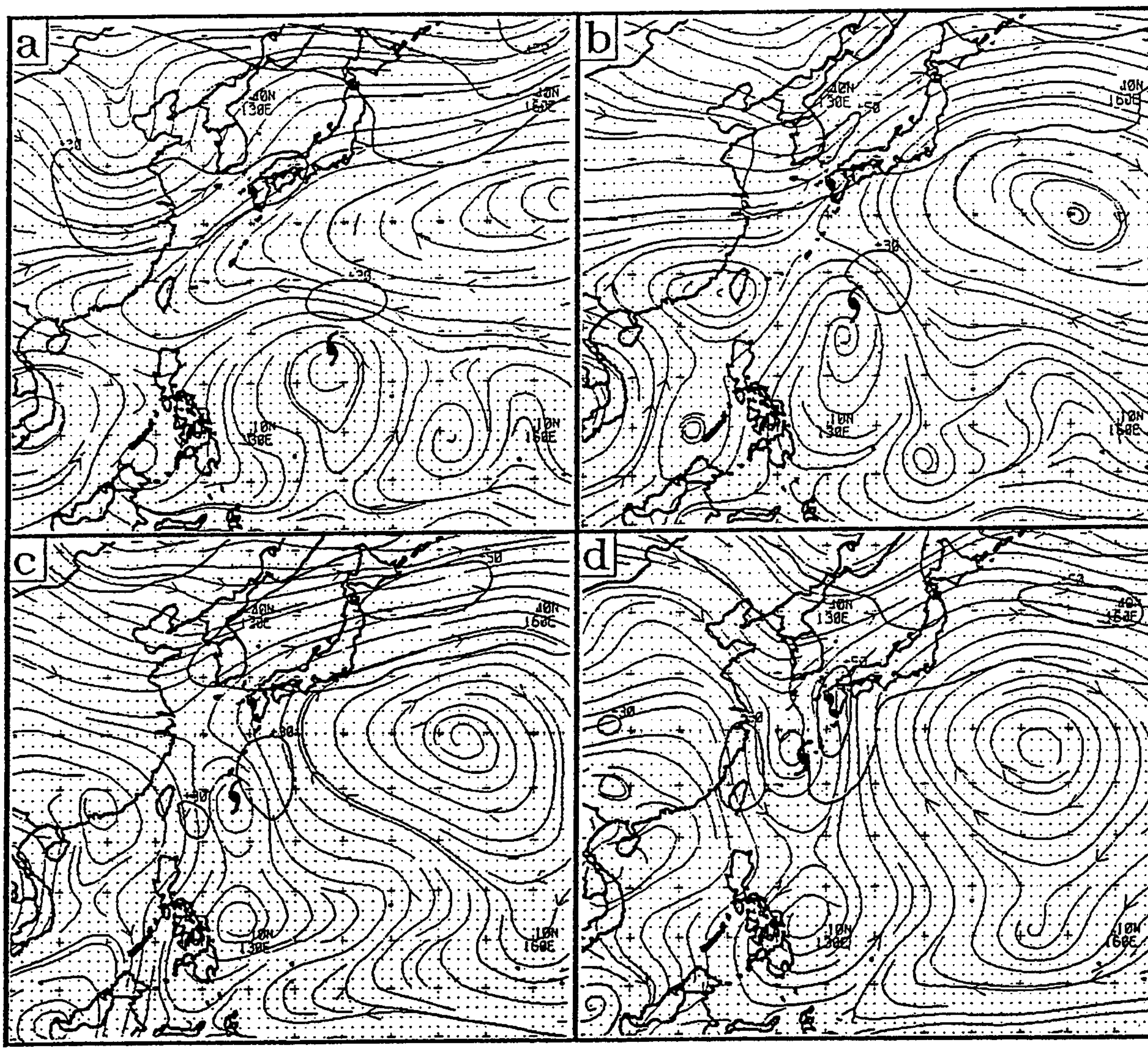
- on 5 October (panel c), the larger of the NOGAPS isotach maxima near Hattie has shifted to the northeast of the TC position (and the TC translation speed is slowing), which indicates a transition to S/WR is taking place.

- on 6 October (panel d), the largest isotach maximum is to the east, which indicates that Hattie is in an S/WR environment (about to recurve into the MW region). NOTE: If Hattie was analyzed to be in a P/PO environment (to be described below) vice S/WR, the isotach maximum would be to the southeast of the TC wind center in the NOGAPS analysis.

Cross-reference:

Diagnosing Environmental Steering Direction p. 9

Typhoon Hattie
3-6 Oct 1990 (0000 UTC)
S/DR - S/WR - (S/MW)



ENVIRONMENT STRUCTURE DEFINITIONS

Topic: POLEWARD (P) PATTERN

PATTERN/REGIONS DESCRIPTION

At the steering level of the TC, the key environment feature that defines a synoptic pattern classification of POLEWARD (P) is a ridge (peripheral anticyclone) to the east of the TC that:

(a) extends from the STR deep into the tropics and interrupts the tropical easterlies;

(b) usually has a SW-to-NE axis (Northern Hemisphere) orientation, although this orientation may vary from SSE-to-NNW to WSW-to-ENE in certain scenarios; and

(c) usually produces strongly poleward steering (with either a westward or eastward component) on its west and poleward side.

The poleward-oriented ridge feature may be associated with either a reverse-oriented monsoon trough, or may be generated through the Ridge Modification by a large TC (RMT) or Reverse Trough Formation (RTF) transitional mechanisms summarized later. (NOTE: There is usually, but not necessarily, a break in the STR to the NW of the poleward-oriented ridge feature.)

The synoptic REGIONS of the P pattern are:

(a) POLEWARD-ORIENTED (PO), which encompasses the area of poleward steering west of the ridge feature that identifies the pattern as P.

(b) MIDLATITUDE WESTERLIES (MW), which encompasses the area of eastward and poleward steering extending east from the break in the STR.

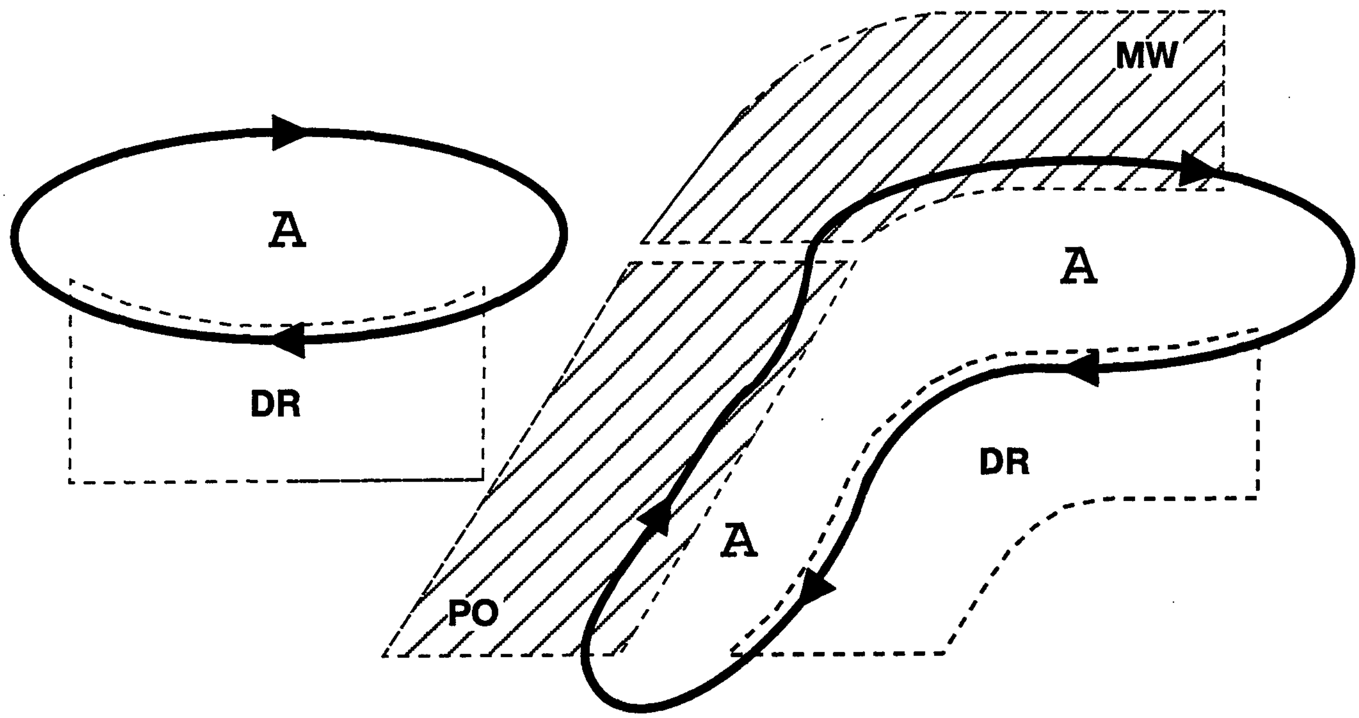
NOTE: Neither of the DR regions shown at right belong to the P pattern. Any TCs found in these regions are regarded as belonging to the S patterns that are adjacent to the P pattern.

Cross-references:

Ridge modification by a TC (RMT) p. 65

Reverse Trough formation (RTF) p. 73

POLEWARD (P) PATTERN



-------- Region boundaries

ENVIRONMENT STRUCTURE DEFINITIONS

Topic: POLEWARD (P) PATTERN (cont)

CHARACTERISTIC LOCATIONS AND TRACKS

Representative positions where TCs may be in each REGION of a P Pattern are shown at right. The following considerations apply in these regions:

(a) In the POLEWARD-ORIENTED (PO) region, the isotach maximum that indicates the direction of environmental steering will be positioned approximately between the TC and the peripheral anticyclone to the east. NOTE: An accurate NOGAPS analysis that has the isotach maximum position more between the TC and the STR to the north, so that the easterly steering of the STR is actually "dominating" the motion of the TC, then the pattern/region classification would actually be S/DR (see S Pattern summary). There is usually no break in the STR to the north of the TC when this situation occurs.

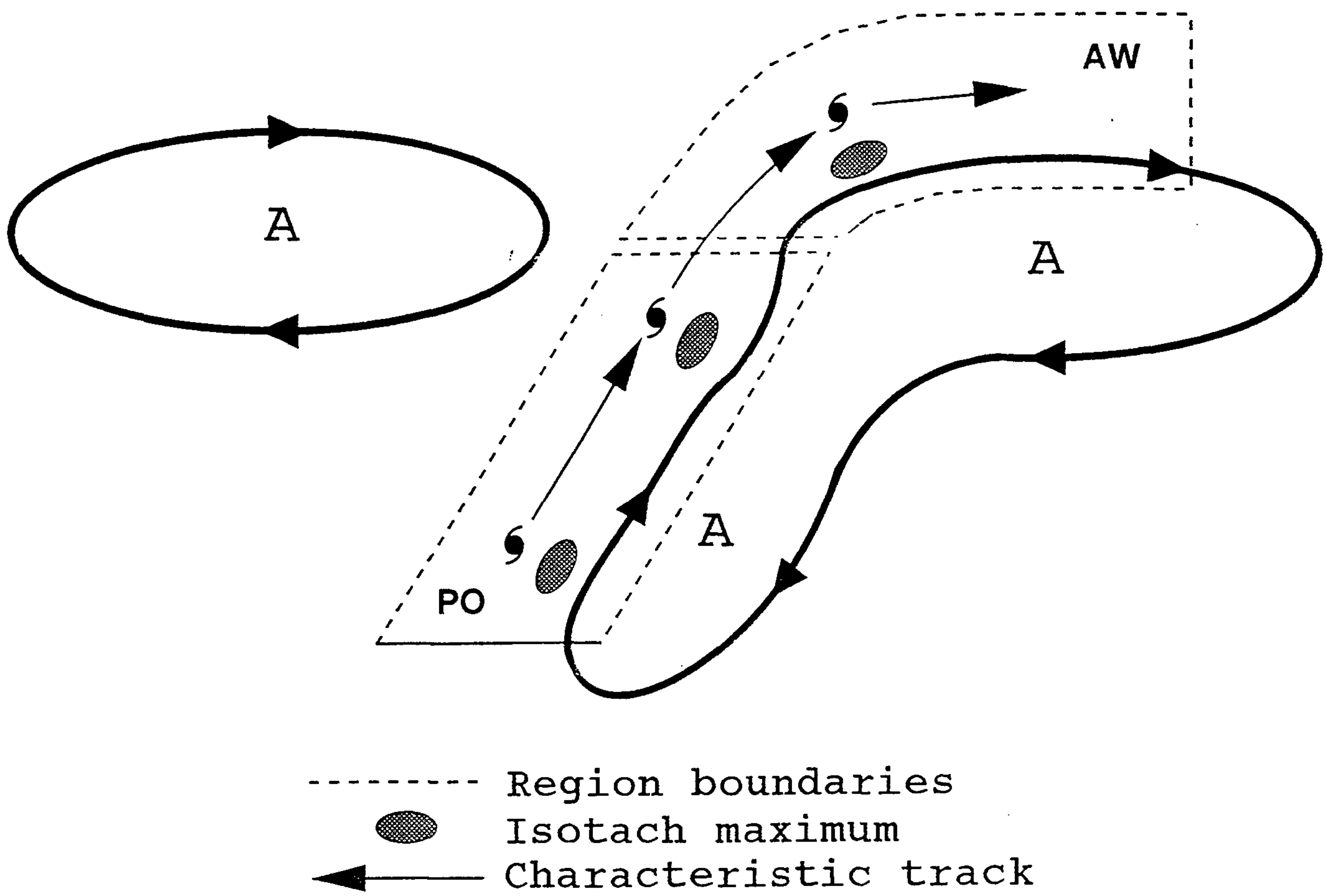
(b) In the MW region, the motion-related isotach maximum will be from E to SE of the TC depending on the location of the TC in the region, and the orientation/shape of the peripheral anticyclone to the east and south of the TC.

If the P pattern persists, a TC can follow only the one characteristic track shown at right. Thus, a TC in a "persistent" P pattern must eventually enter the midlatitudes. That is, no track bifurcation point exists as in the S pattern where subtle variations in TC position, STR structure, and trough behavior can determine whether the TC "stair-steps" or "recurves." However, the STR may strengthen (perhaps in response to passage of a midlatitude ridge) poleward of the TC and cause a return to the S/DR pattern/region with a westward track.

Cross references:

Diagnosing Environmental Steering Direction p. 9
Standard pattern p. 19

POLEWARD (P) PATTERN CHARACTERISTIC TRACKS



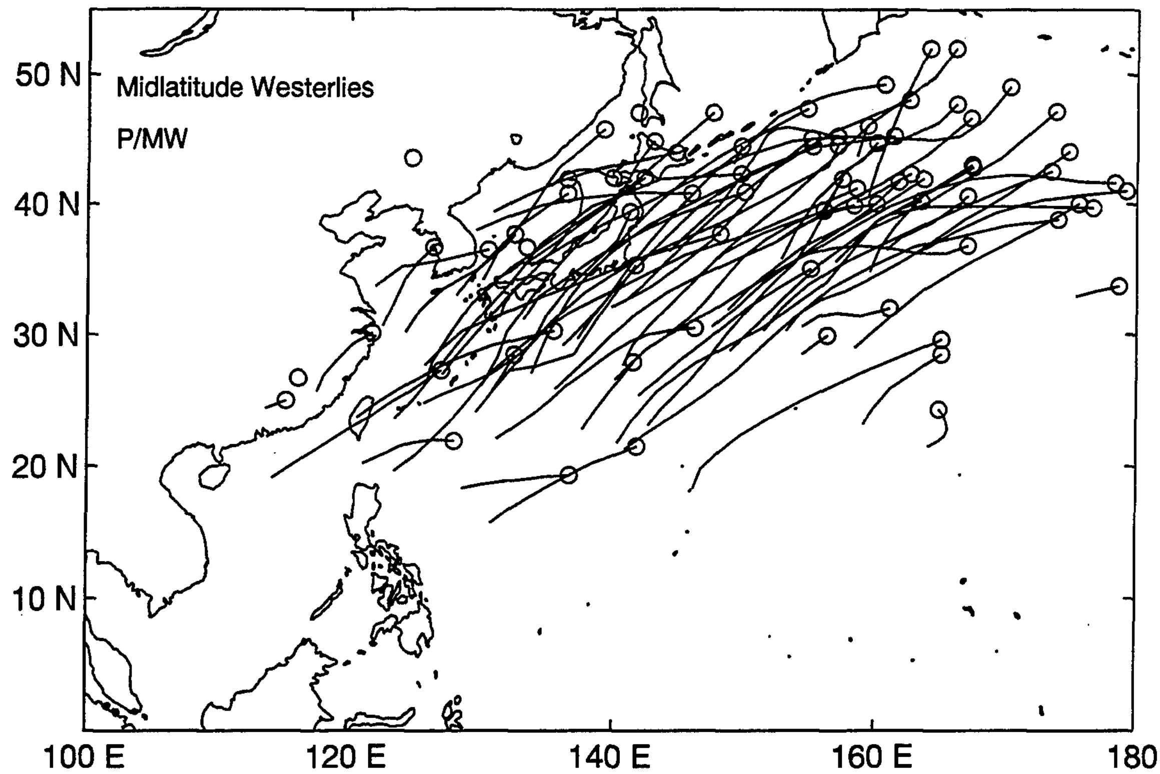
Topic: POLEWARD (P) PATTERN (cont)

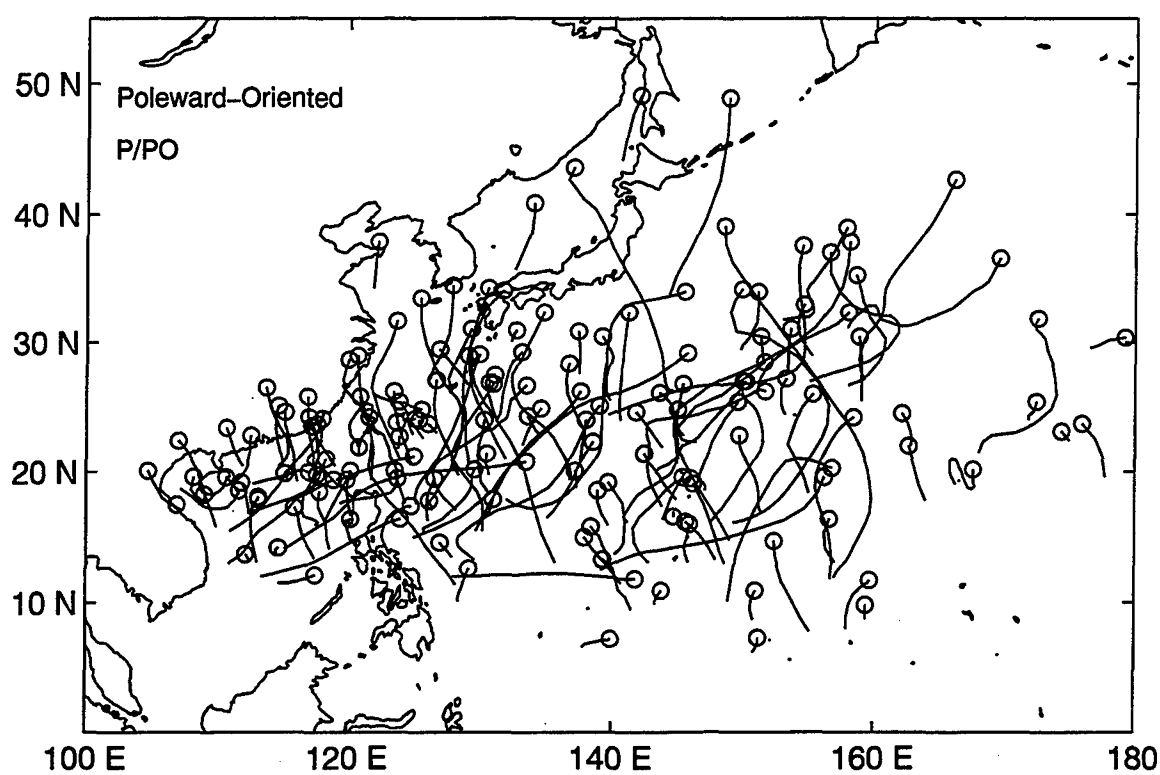
ACTUAL TRACKS

The tracks of TCs in the western North Pacific during 1989 - 1996 while in the Poleward (P) synoptic pattern are shown to the right. Whereas the tracks are generally poleward in the Poleward-Oriented (PO) synoptic region, a large variety of track directions and lengths exist. Although the TC tracks in the Midlatitude Westerlies (MW) synoptic region are generally toward the northeast, an eastward track is found in many cases. The more poleward orientation of the P/MW tracks than for the Standard (S) /MW tracks is consistent with the presence of the peripheral anticyclone to the east. Since the peripheral anticyclone may be enhanced by a large TC, a cell in the peripheral anticyclone may translate poleward with the TC, which favors a continued poleward track. If the influence of the peripheral anticyclone diminishes, the TC track will be dominated by westerly steering and turn eastward.

Cross references:

Standard (S) Pattern, Actual Tracks pp. 23-24


50 N
40 N
30 N
20 N
10 N
Midlatitude Westerlies
P/MW
100 E
120 E
140 E
160 E
180


50 N
40 N
30 N
20 N
10 N
Poleward-Oriented
P/PO
100 E
120 E
140 E
160 E
180

ENVIRONMENT STRUCTURE DEFINITIONS

Topic: POLEWARD (P) PATTERN (cont)

SCENARIO ILLUSTRATION: P/PO (steady)

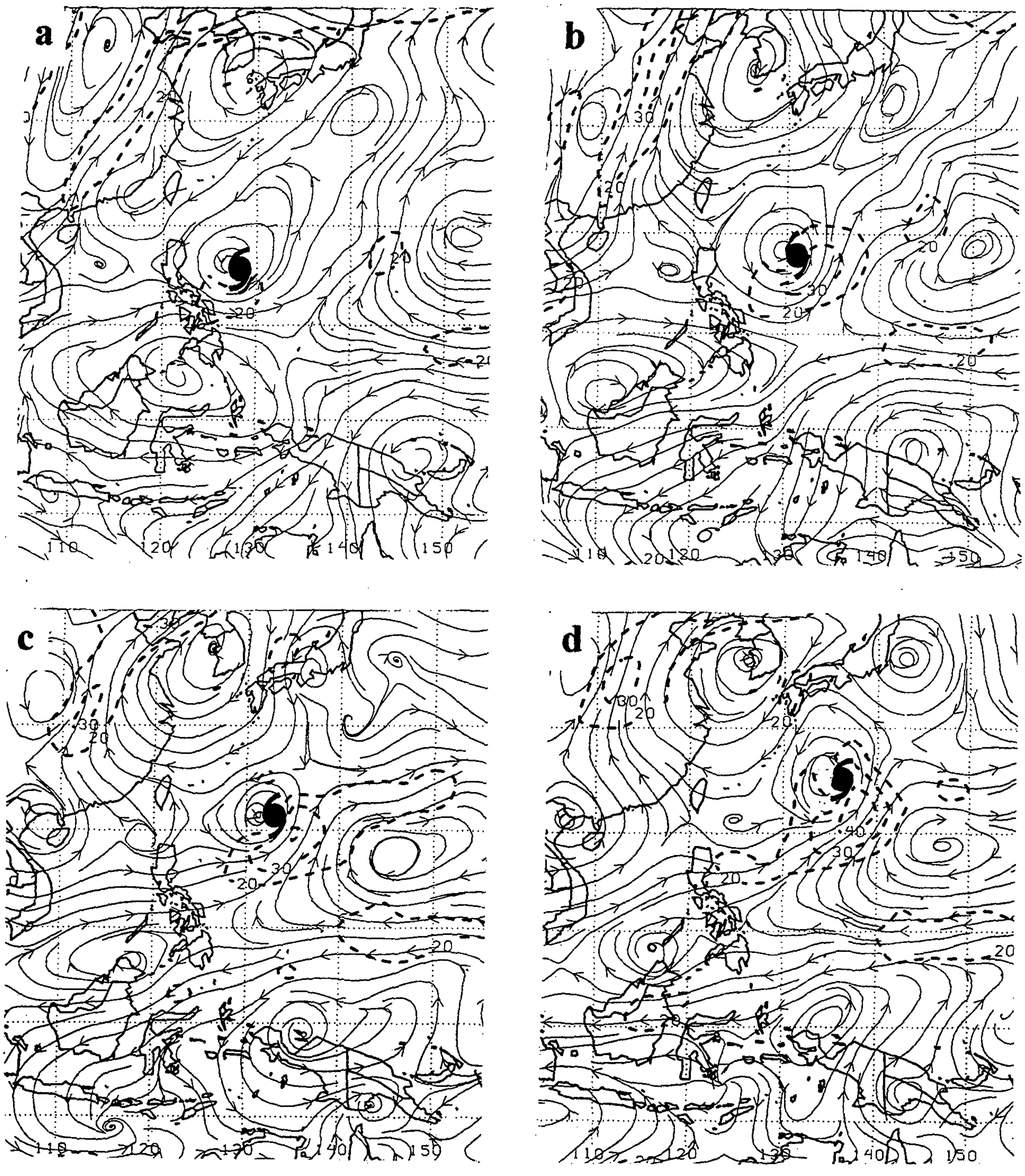
The NOGAPS analysis series at right shows Super Typhoon Walt in a persistent P/PO environment and the track is given on page A-4 in the Appendix.. Notice that in each analysis:

- the NOGAPS TC wind center, the satellite-based TC position, and the NOGAPS isotach maximum have a NW-SE orientation, which is an indication of the southwesterly steeering expected in a P/PO region, and which agrees with the observed steady poleward motion of the TC.

Cross-reference:

Diagnosing Environmental Steering Direction p. 9

Super Typhoon Walt
17-20 July 1994 (0000 UTC)
Persistent P/PO



ENVIRONMENTAL STRUCTURE DEFINITIONS

Topic: GYRE (G) PATTERN

SATELLITE IMAGERY OF MONSOON GYRE (MG)

At the steering level of the TC, the key environment feature that defines a synoptic pattern classification of GYRE (G) is a particularly large and deep circulation known as a MONSOON GYRE (MG).

An example of the evolving cloud pattern associated with the development of the MG and Tropical Storm Val during September 1992 is shown at right. The track of Val is given on page A-5. Notice that:

- on 22 September (panel c), the MG center is at about 10°N, 160°E, and the FISH HOOK pattern of convection that wraps around the east side of the MG first becomes evident.

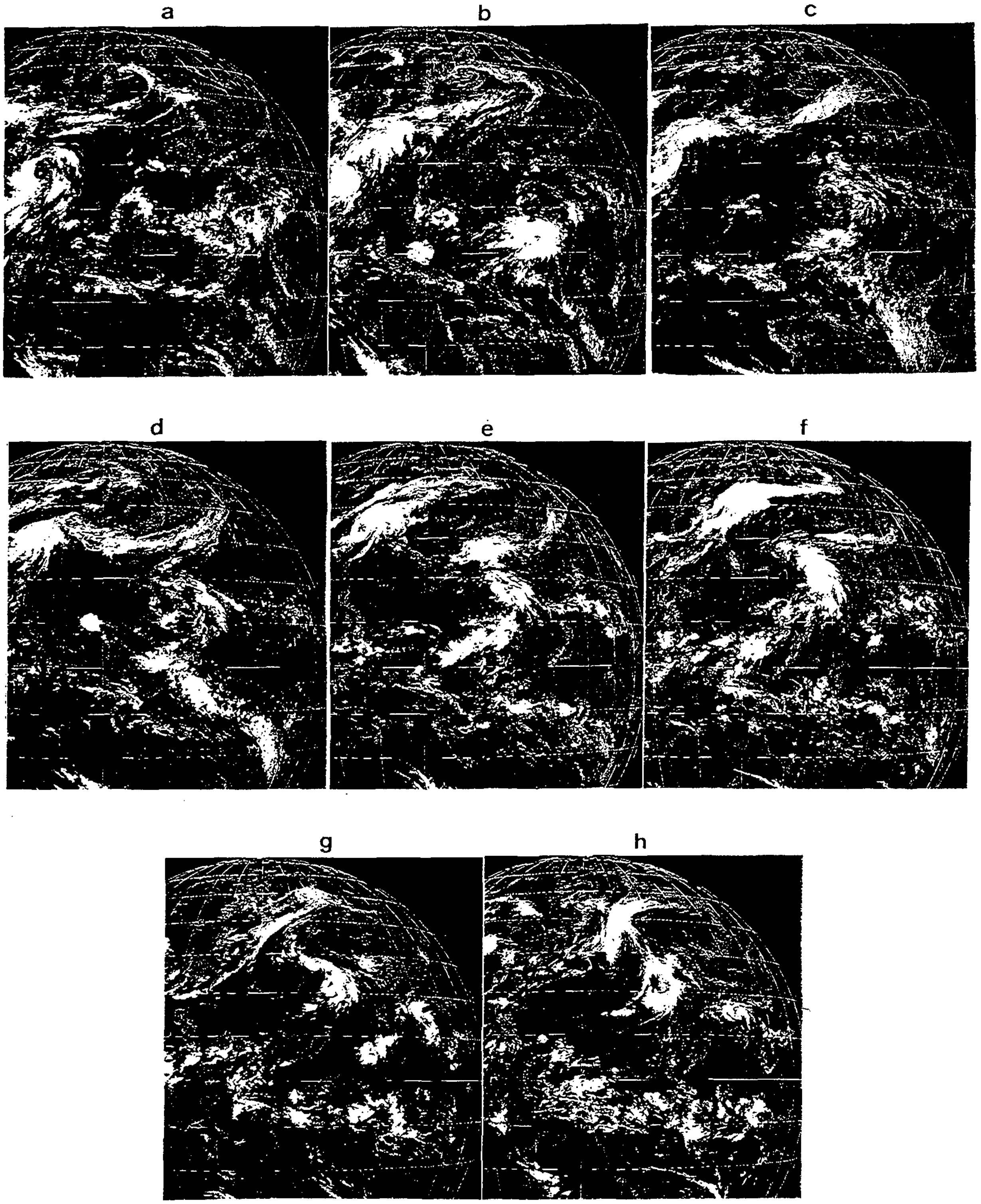
- on 23 September (panel d), the small, organized convection that will become Val is evident at about 15°N, 162°E.

- on 27 September (panel h), the center of the MG is evident as a swirl of cumulus cloud lines at about 27°N, 147°E. Val is farther north at about 34°N, 151°E.

- from 23 - 27 September, the MG translates from about 10°N, 160°E to about 27°N, 147°E, which is equivalent to about 12 kt. Thus, the MG in this example translates at a speed that is commensurate with typical TC translation speeds. Although the motion of MGs is typically westward and poleward, it may be significantly slower than in the Val case.

WARNING!!: Because the circulation of a MG may be poorly resolved in operational numerical analyses, and because numerical models can falsely generate MG-like circulations, it is IMPERATIVE that the presence of a MG be confirmed using SATELLITE IMAGERY to identify the characteristic FISH HOOK convection pattern that typically wraps around the east side of the MG, and occasionally wraps all the way around the MG.

20 - 27 September 1992 (0300 UTC)



ENVIRONMENT STRUCTURE DEFINITIONS

Topic: GYRE (G) PATTERN (cont)

PATTERN/REGIONS DESCRIPTION

In a G synoptic pattern, the MG is usually between a zonally-oriented STR anticyclone to the NW and a meridionally-oriented anticyclone on its eastern periphery, which resembles (because it is dynamically related to) the peripheral anticyclone east and south of a large TC in a P pattern. Owing to the similar appearance of these peripheral anticyclones, a G (P) pattern can be confused with a P (G) pattern, unless satellite imagery and data (if available) are used to establish independently whether or not a MG circulation is present.

The synoptic REGIONS of the G pattern are:

(a) POLEWARD-ORIENTED (PO), which encompasses the area of poleward steering between the MG and the peripheral anticyclone to the east.

(b) MIDLATITUDE WESTERLIES (MW), which encompasses the area of eastward and poleward steering that extends east from the break in the STR.

(c) DOMINANT RIDGE (DR), which encompasses the area of westward, and often slightly equatorward, steering between the MG and the STR anticyclone to the NW.

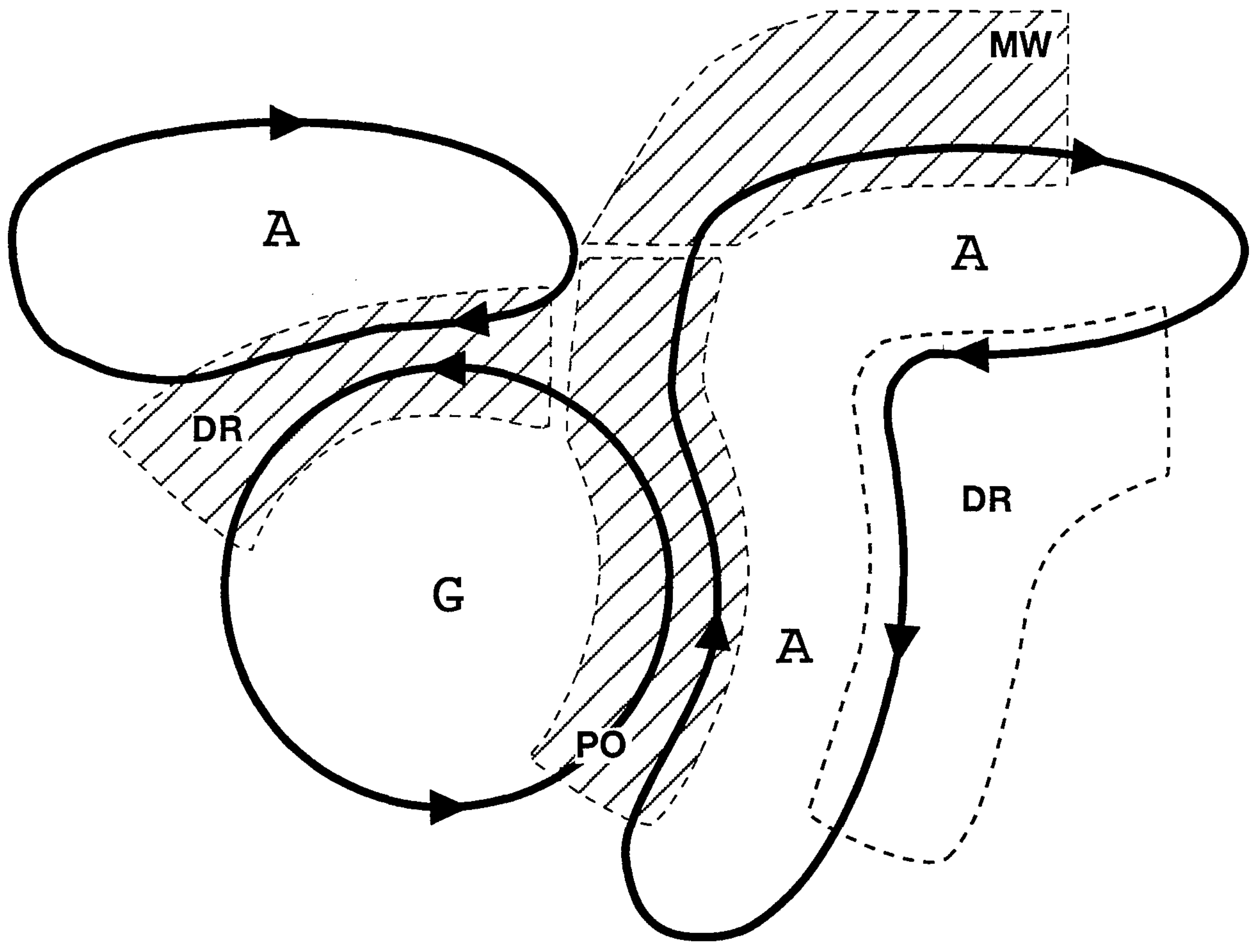
NOTE: The DR region to the east of the MG does not belong to the G pattern. A TC in this DR region is regarded as belonging to a S pattern that is adjacent to the G pattern.

Cross-references:

Poleward (P) Patterns/Regions Description p. 29

Standard (S) Pattern p. 19

GYRE (G) PATTERN



G Monsoon gyre center
-------- Region boundaries

Topic: GYRE (G) PATTERN (cont)

CHARACTERISTIC TC LOCATIONS AND TRACKS

Representative positions where a TC may be located in each synoptic REGION of a G pattern are shown at right. The following considerations apply in each region:

(a) In the PO synoptic region, the isotach maximum that indicates the direction of environmental steering will be positioned approximately between the TC and the peripheral anticyclone circulation to the east of the MG.

(b) In the Midlatitude Westerlies (MW) region, the motion-related isotach maximum will be oriented from E to SE of the TC depending on the location of the TC in the region, and the orientation/shape of the STR circulation to the east and south of the TC.

(c) In the Dominant Ridge (DR) region, the isotach maximum that indicates the direction of environmental steering will be approximately between the TC and the STR circulation to the northwest of the MG.

If the G Pattern persists, and the TC does not undergo an interaction with the MG known as Monsoon-TC Interaction (MTI) (see separate summary), a TC can follow one of two characteristic tracks:

(1) a sinuous "recurvature" type track in which the TC is advected around the east side of the MG, through the break in the STR, and into the midlatitude westerlies. This track is more likely for TCs that form or proceed around the MG at a comparatively large distance from the MG center.

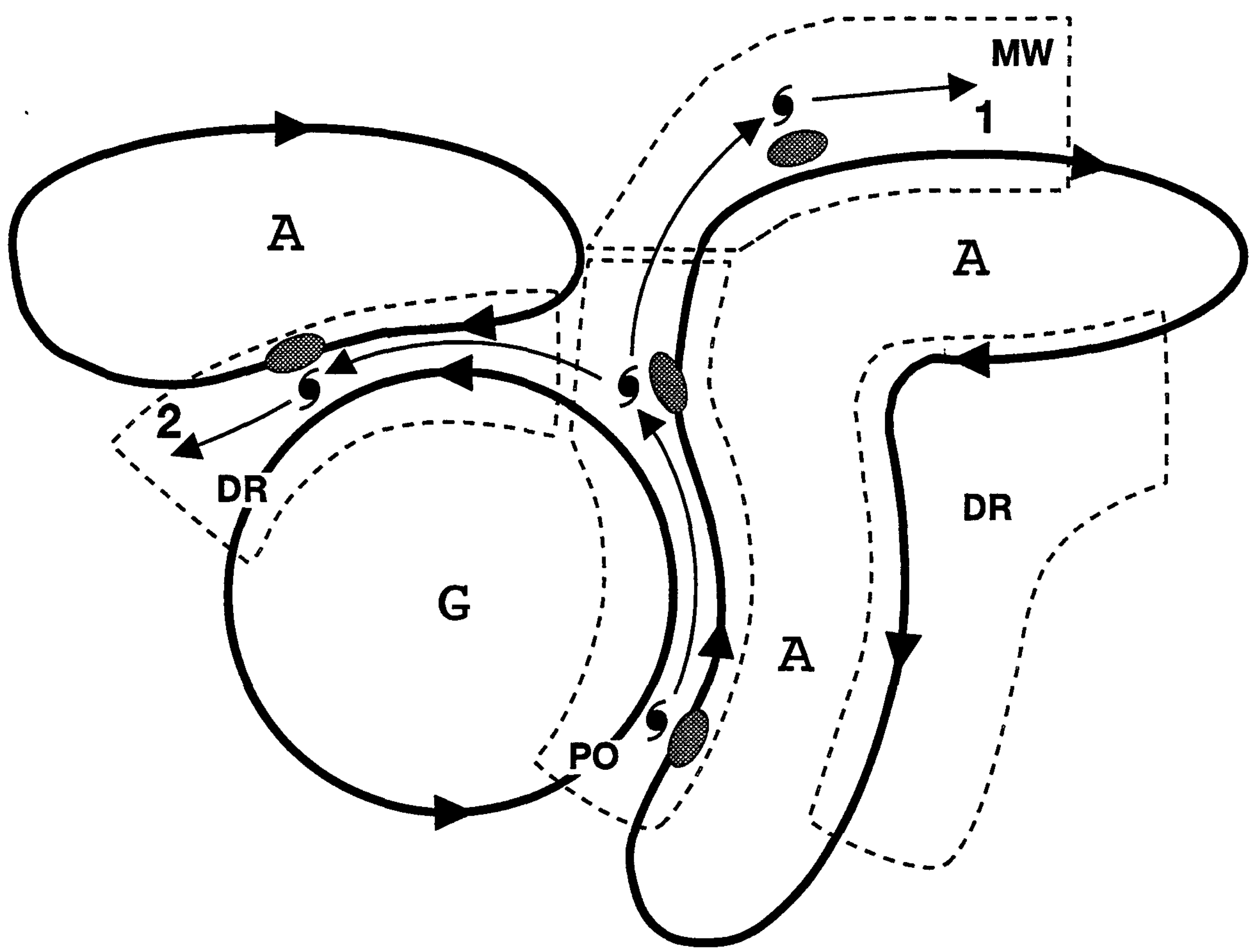
(2) a cyclonically curved track in which the TC is advected around the east side of the MG and into the easterly steering of the DR region to the N or NW of the MG. This track is more likely for TCs that form and proceed around the MG at a comparatively small distance from the MG center.

NOTE: The characteristic TC tracks at right are relative to the center of the MG so that the actual track will be similar to these characteristic tracks only if the MG circulation is quasi-stationary. Since MGs often move westward and poleward at significant speeds (5-15 kt) as they evolve, the actual track of the TC will be a vector sum of the steering provided by the MG and the translation velocity of the MG center.

Cross-reference:

Diagnosing Environmental Steering Direction p. 9
Monsoon-TC Interaction (MTI) p. 79

GYRE (G) PATTERN CHARACTERISTIC TRACKS

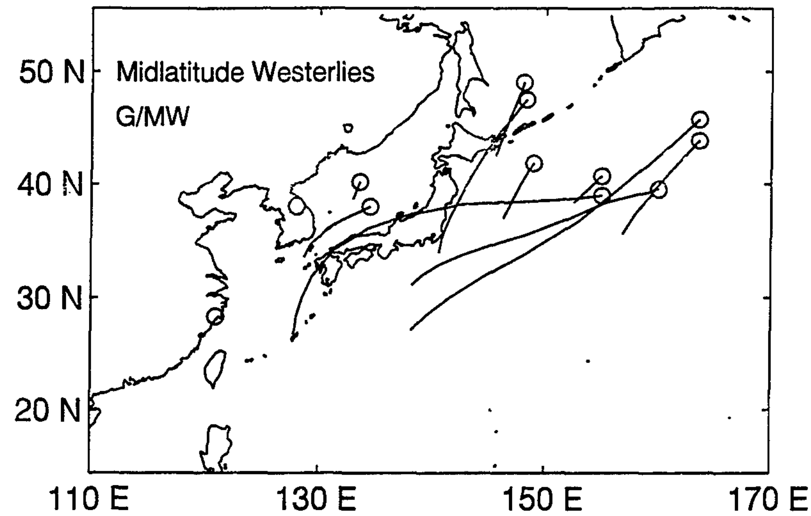


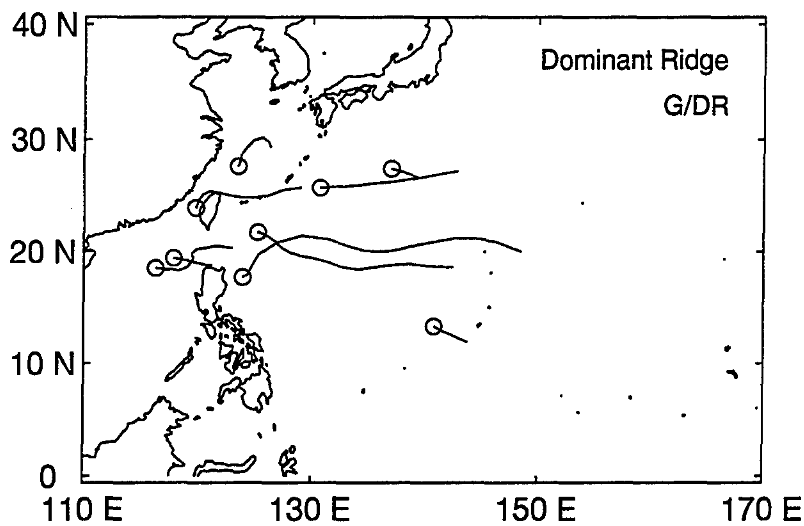
G Monsoon gyre center
-------- Region boundaries
Isotach maximum
Characteristic tracks relative to gyre center

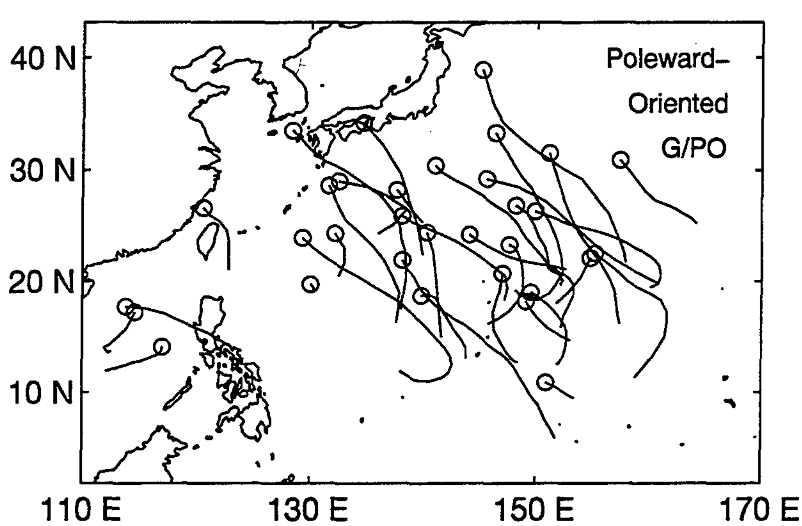
Topic: GYRE (G) PATTERN (cont)

ACTUAL TRACKS

In the 1989-1996 sample of western North Pacific TCs, the Gyre (G) synoptic pattern was relatively rare. Some years had no Gyre patterns. One characteristic of the tracks in the Poleward-Oriented (PO) synoptic region is a cyclonic turning. Some TCs first move toward the east after forming in the southeast quadrant of the MG, and then curve poleward around the eastern side. A bifurcation point exists between tracks 1 and 2 in the schematic on the previous page. Those TCs that continue toward the pole into the Midlatitude Westerlies (MW) synoptic region (track 1) have a variety of track directions and lengths. Those TCs that move into the Dominant Ridge (DR) synoptic region (track 2) have generally westward tracks, and may even be south of west if the TC motion is being advected by the MG western quadrant circulation.


Midlatitude Westerlies
G/MW
50 N
40 N
30 N
20 N
110 E
130 E
150 E
170 E


Dominant Ridge
G/DR
40 N
30 N
20 N
10 N
0
110 E
130 E
150 E
170 E


Poleward-
Oriented
G/PO
40 N
30 N
20 N
10 N
110 E
130 E
150 E
170 E

ENVIRONMENT STRUCTURE DEFINITIONS

Topic: MONSOON GYRE (G) PATTERN (cont)

SCENARIO ILLUSTRATION: G/PO - G/MW Transition

The NOGAPS analysis series at right shows Tropical Storm Val initially in a G/PO environment, and then a transition to a G/MW. Recall that the track of Val is on page A-5. Notice that:

- on 25 and 26 September (panels b and c), the NOGAPS analyses clearly indicate a distinct MG wind center about 10 deg. long. to the west of the TC position.

- from 24 to 26 September, the MG moves as fast as Val, which keeps the TC in almost the same location within the PO region.

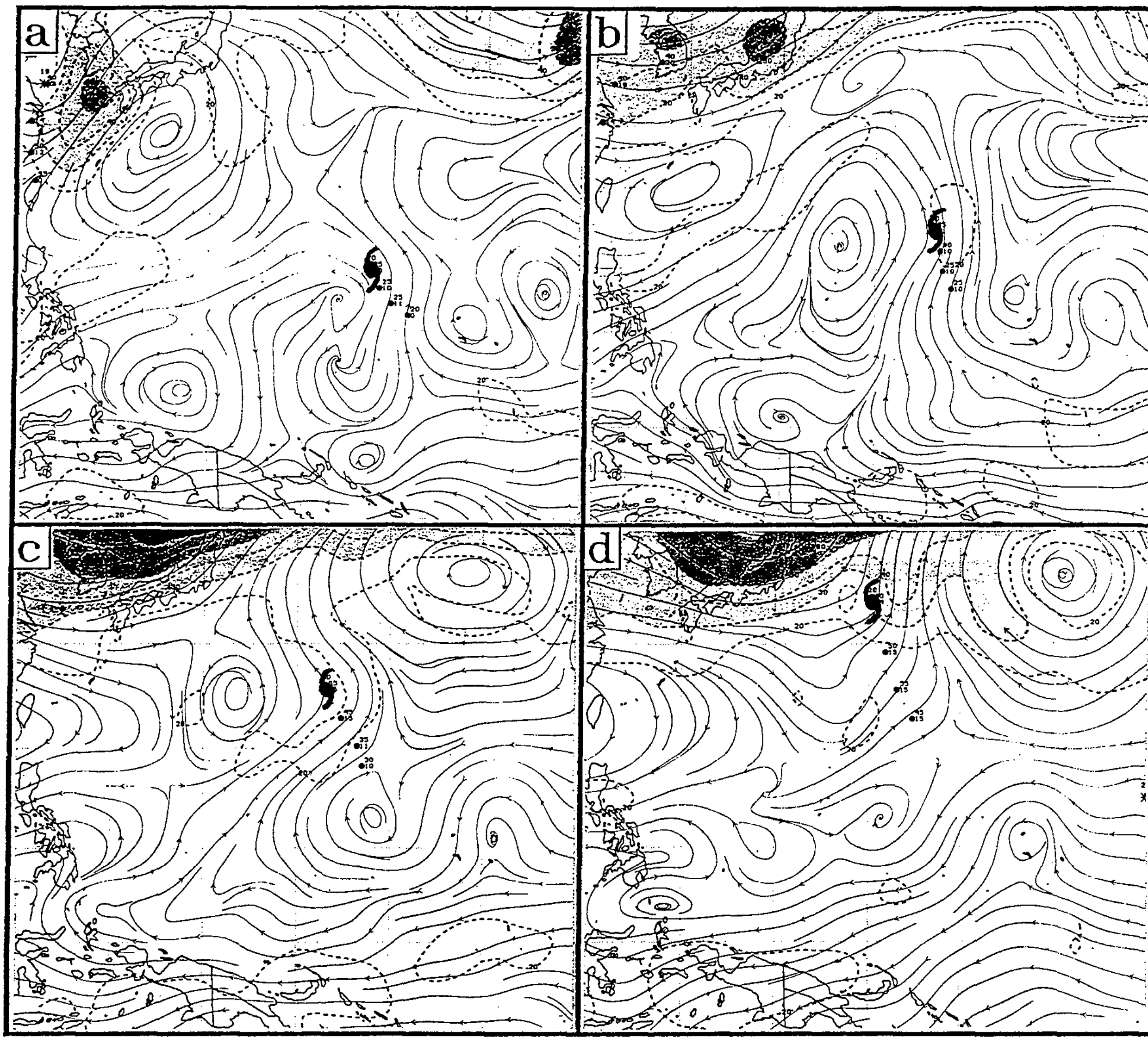
- on 27 September (panel d), Val is in a transition from the PO region to the MW region.

- on 27 September, the NOGAPS analysis does not have a closed center for the MG. Nevertheless, the location of the MG can be readily discerned from the satellite image (see p. 38 above).

Cross-reference:

Satellite Imagery of Monsoon Gyre (MG) p. 38

Tropical Storm Val
24-27 Sep 1992 (0000 UTC)
G/PO - G/MW



ENVIRONMENT STRUCTURE DEFINITIONS

Topic: MULTIPLE (M) TC PATTERN

PATTERN/REGIONS DESCRIPTIONS

At the steering level of the TCs, the following relationships exist among adjacent environment circulations for a pattern classification of MULTIPLE (M):

(a) a large break must exist in the STR in the vicinity of the two TCs;

(b) the two TCs must be oriented approximately east-west; and

(c) the two TCs must be far enough apart to preclude significant direct interaction (mutual advection), but close enough to preclude the presence/development of ridging between them (typically greater than 10 deg. long., but less than about 20° long.); and

(d) the average latitude of the two TCs must be sufficiently close to the latitude of the STR axis (no more than about 10° lat. equatorward or 5° lat. poleward), so that

(1) a POLEWARD FLOW (PF) synoptic region is created in the region of the eastern TC as a result of the pressure gradient between the western TC and the STR circulation to the east; and

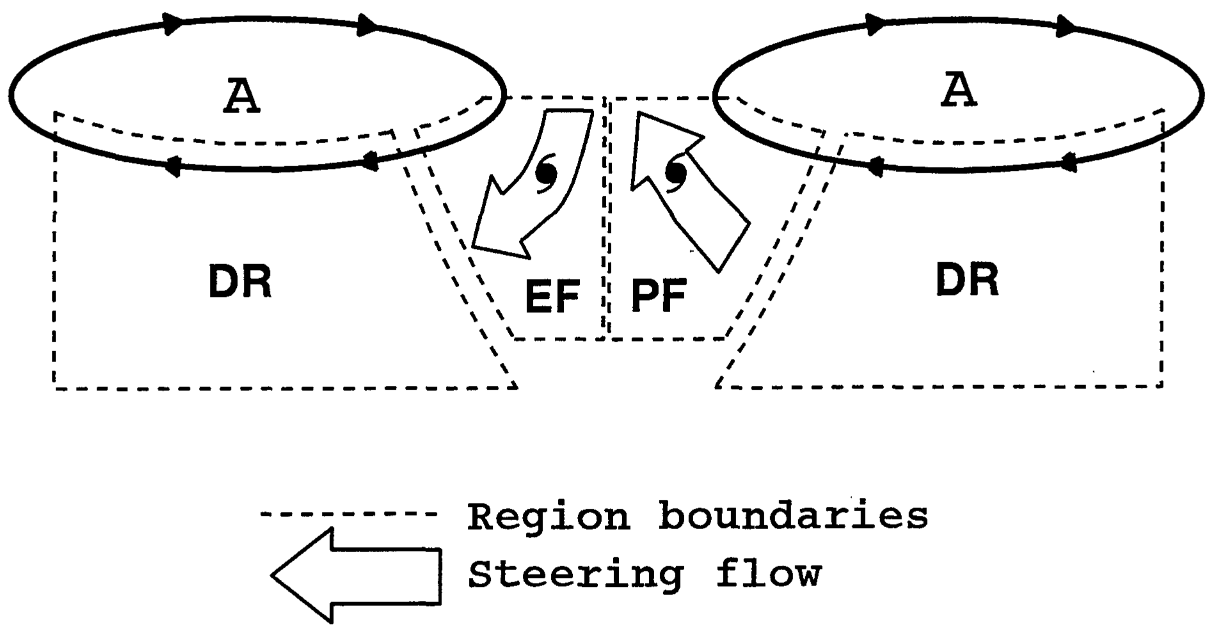
(2) an EQUATORWARD FLOW (EF) synoptic region is created in the region of the western TC as a result of the pressure gradient between the eastern TC and the STR circulation to the west.

NOTE: In the Systematic Approach, the formation of a M pattern and the occurrence of Semidirect TC Interaction (STI) are somewhat synonymous. This overlap makes sense since, for the purposes of determining the steering flow affecting the TC of interest, another TC in the vicinity constitutes part of the "environment." When the location of the other TC relative to the TC of interest and the subtropical ridge satisfy certain requirements, a M pattern is formed as the TCs interact in a semidirect fashion. Another way to view the connection between the M pattern and STI is that the M pattern is the environment structure that results from the effect of STI. See the section on STI for a complete description of the associated STI transitional mechanism.

Cross-reference:

Semidirect TC Interaction (STI) p. 97

MULTIPLE (M) PATTERN



Topic: M PATTERN (cont)

CHARACTERISTIC TC LOCATIONS AND TRACKS

Representative positions where TCs may be in each synoptic REGION of the M pattern are shown at right. The following considerations apply to each region:

(a) In the PF region, the isotach maximum that indicates the direction of environmental steering will be positioned approximately between the TC and the STR feature to the east.

(b) In the EF region, the isotach maximum that indicates the direction of environmental steering will be positioned approximately between the TC and the STR feature to the west. NOTE: The isotach orientation and the direction of motion of the western TC may show only rough agreement, owing to the large difference between the direction of steering in the EF region and the northwestward direction of TC Beta-Effect Propagation.

If the M pattern persists, the characteristic track:

(a) of the western TC in the EF region is typically a slow west-southward drift, but may be westward or even slightly poleward of west depending on whether or not the meridional component of the equatorward steering is larger or smaller than the meridional component of the TC beta-effect propagation; and

(b) of the eastern TC in the PF region is a non-decelerating 10-15 kt movement past the axis of the STR, in contrast to a recurving TC that would typically slow near the axis.

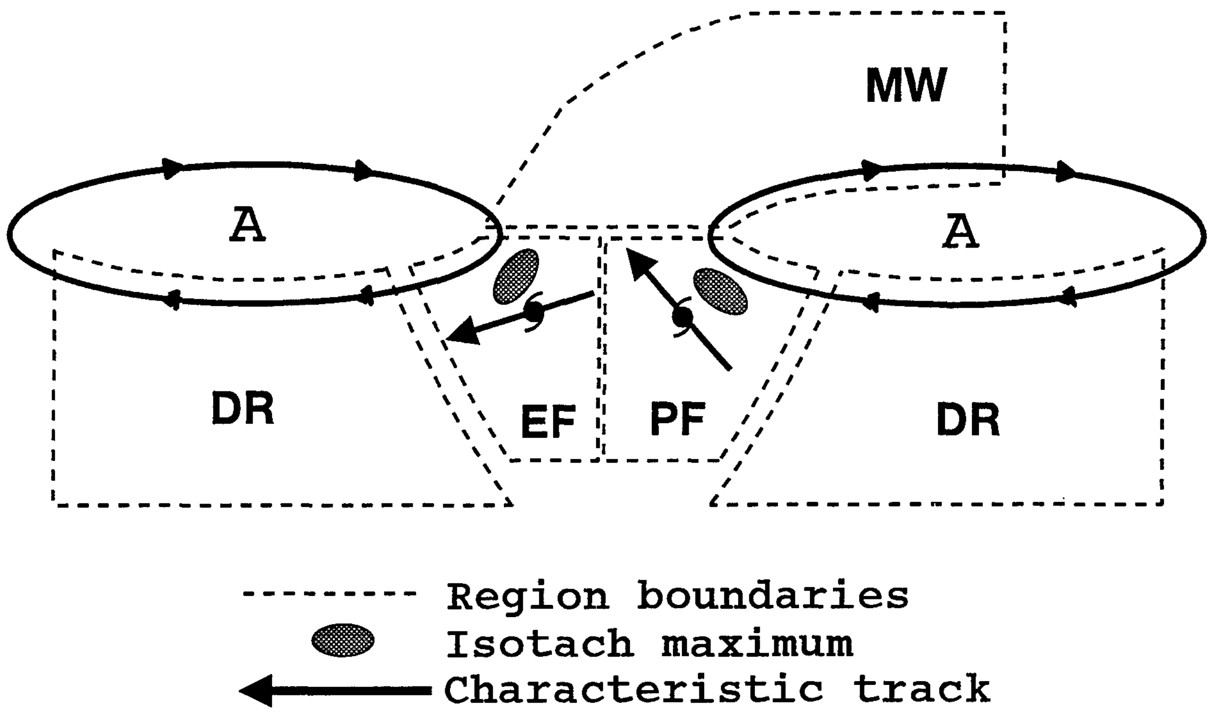
NOTE: The entry/exit of the western TC into/out of the EF region need not occur simultaneously with the entry/exit of the eastern TC into/out of the PF region.

Cross-references:

Diagnosing Environmental Steering Direction p. 9

Beta-Effect Propagation p. 57

MULTIPLE (M) PATTERN CHARACTERISTIC TRACKS

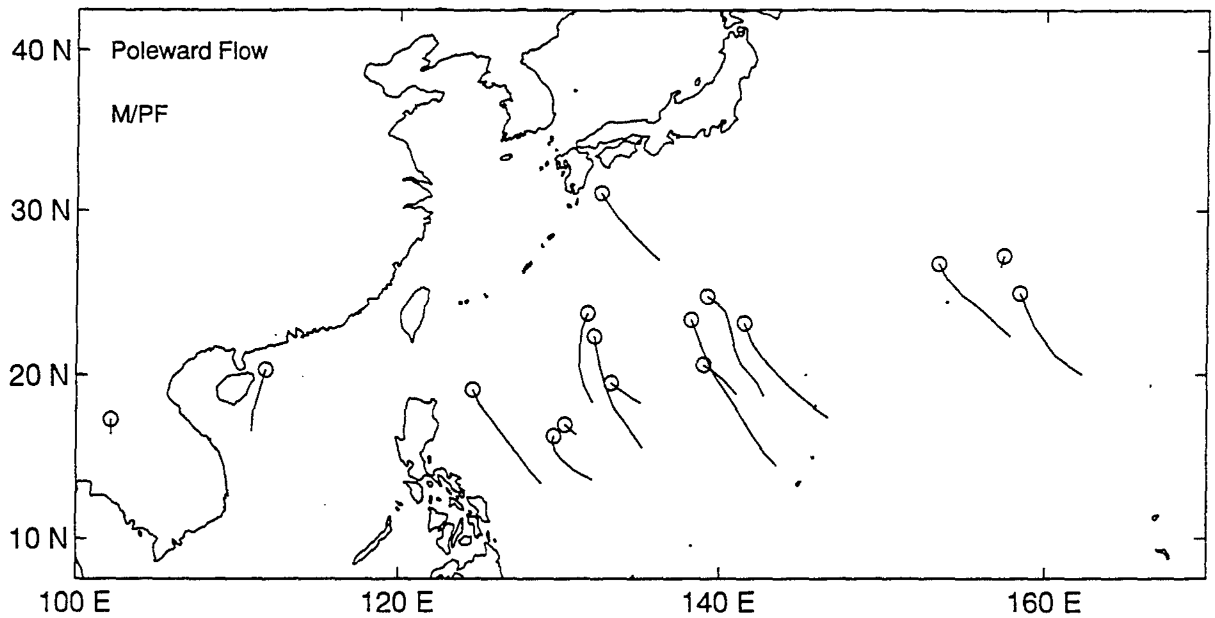


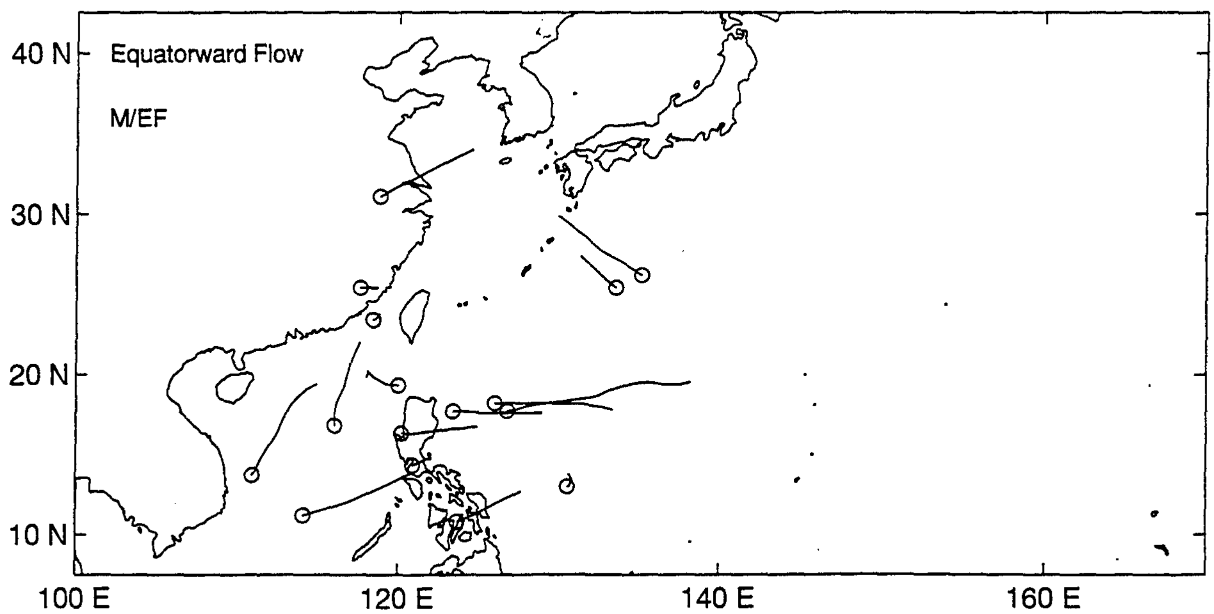
ENVIRONMENT STRUCTURE DEFINITIONS

Topic: MULTIPLE TC (M) PATTERN (cont)

ACTUAL TRACKS

The tracks of TCs in the western North Pacific during 1989-1996 while in the Multiple (M) TC synoptic pattern are shown on the right. In the Poleward Flow (PF) synoptic region, the TC tracks are toward the north-northwest. Although not obvious in this diagram, the TCs do not slow down as they approach the STR. In the Equatorward Flow (EF) synoptic region, the TC tracks are generally westward with an equatorward component. One exception south of Japan has a southeastward direction because it is the western TC with the eastern TC to the northeast and the STR cell is well to the southwest.


40 N
30 N
20 N
10 N
100 E
120 E
140 E
160 E
Poleward Flow
M/PF


40 N
30 N
20 N
10 N
100 E
120 E
140 E
160 E
Equatorward Flow
M/EF

ENVIRONMENT STRUCTURE DEFINITIONS

PATTERN CLIMATOLOGY

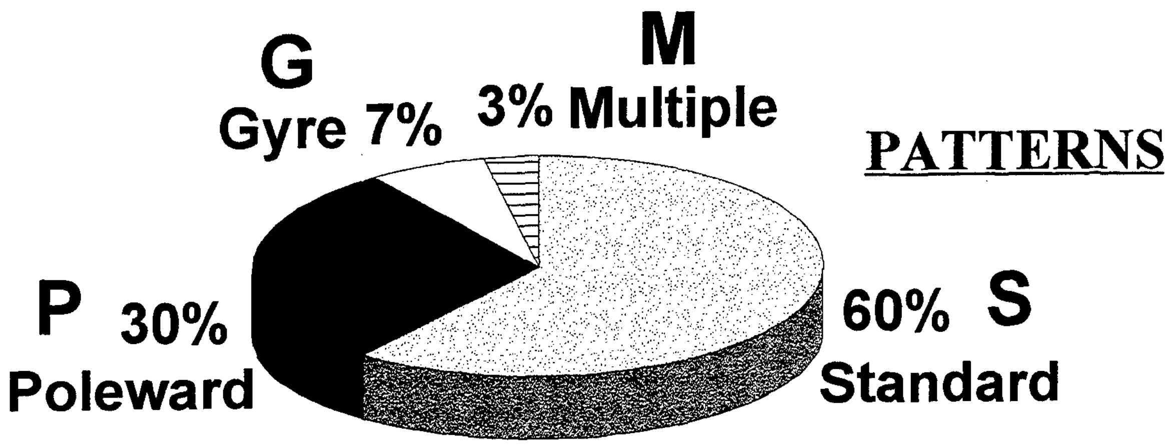
A total of 4017 characterizations were made of the synoptic patterns relative to western North Pacific tropical cyclones each 12 h during 1989-1996. The Standard (S) pattern was involved in 60% of these characterizations. Another frequent pattern with 30% of the cases is the Poleward (P) pattern, so that 90% of all cases will occur in these two patterns. The Gyre (G) pattern occurred in 7% of the cases, even though no G patterns occurred in some years. Finally, the specific criteria for a Multiple (M) TC synoptic pattern are so restrictive, and these conditions are highly transient, that only 3% of the cases fall in the M pattern.

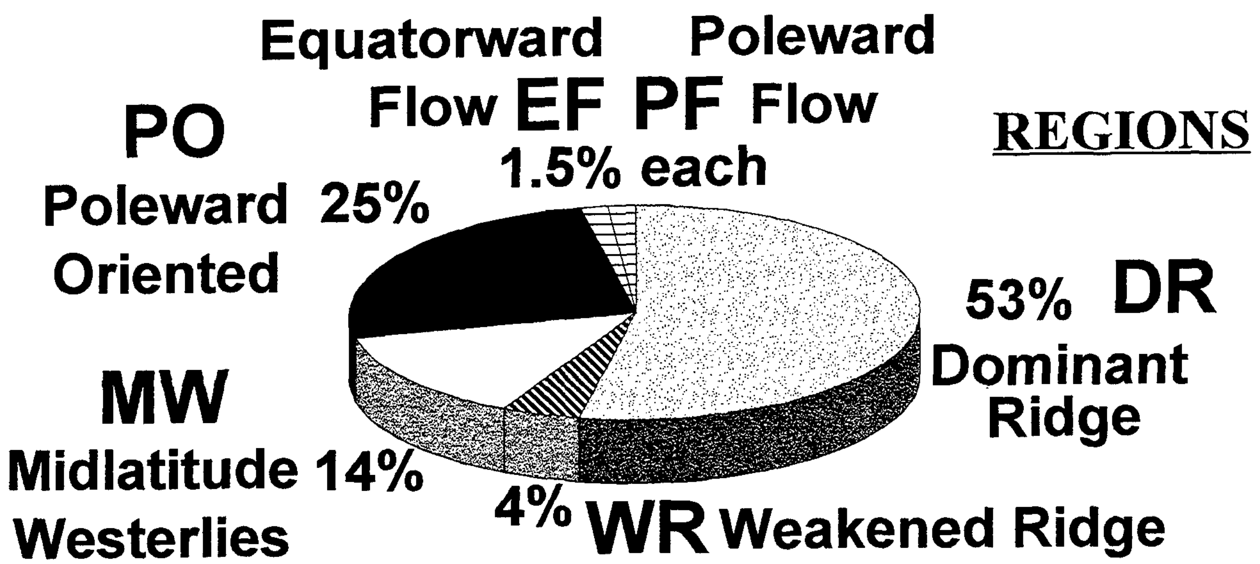
REGION CLIMATOLOGY

The most common (53%) synoptic region is the Dominant Ridge (DR), which may occur in the S and G patterns. A Poleward-Oriented (PO) region is the next most common (25%) occurrence, as it may occur in both the P and G patterns. An Midlatitude Westerlies (MW) region may be found in the S, P, and G patterns, and 14% of all cases are in the MW region. Finally, the Equatorward Flow (EF) and Poleward Flow (PF) regions occur only in the M pattern, and about 1.5% of the 4017 cases during 1989-1996 are found in the EF and PF regions.

Cross-references:

Standard (S) Pattern	p. 19
Poleward (P) Pattern	p. 29
Gyre (G) Pattern	p. 37
Multiple (M) Pattern	p. 47

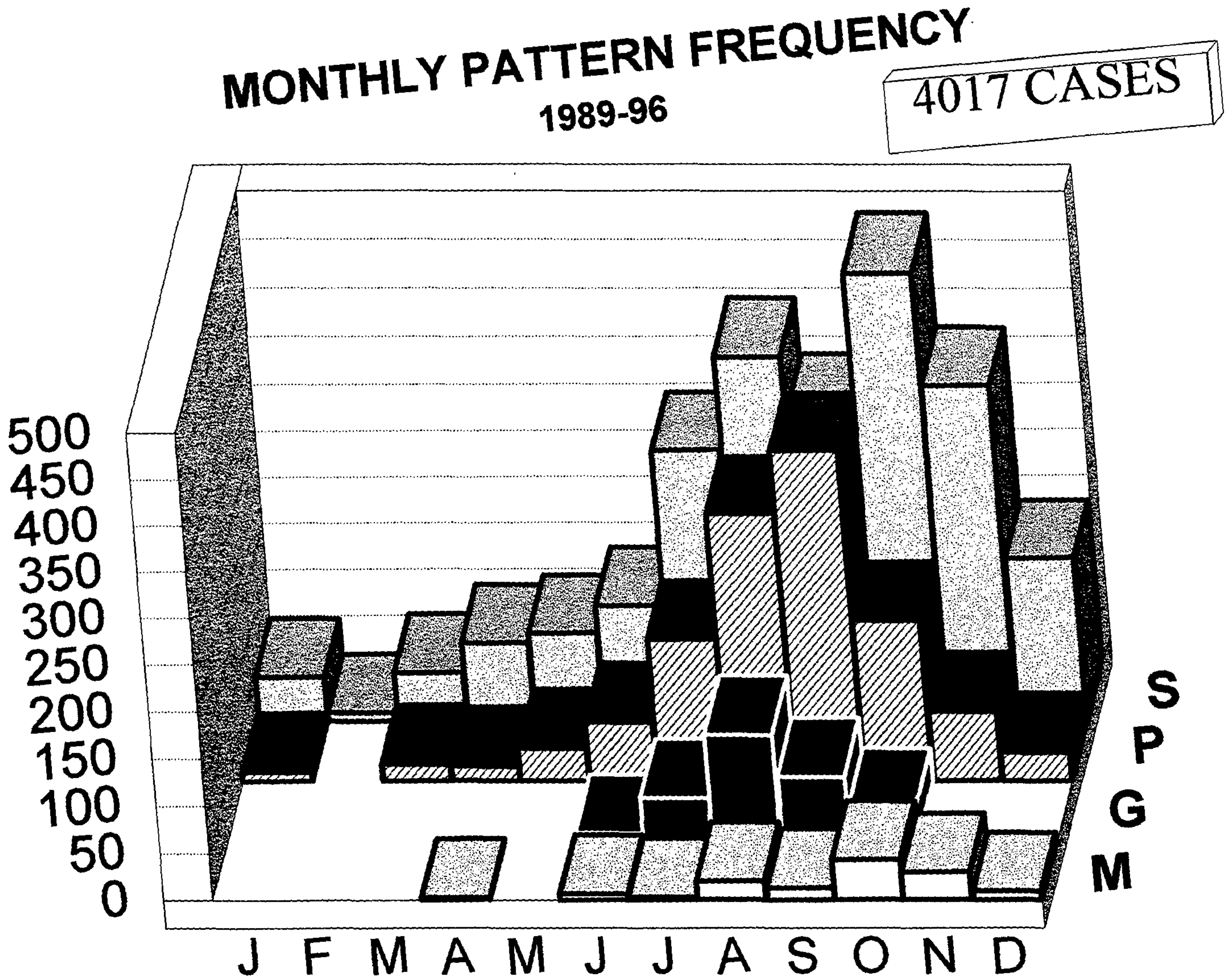

G
Gyre 7%
M
3% Multiple
PATTERNS
P 30%
Poleward
60% S
Standard


Equatorward
Flow EF
PF Flow
Poleward
1.5% each
REGIONS
PO
Poleward 25%
Oriented
53% DR
Dominant
Ridge
MW
Midlatitude 14%
Westerlies
4% WR Weakened Ridge

ENVIRONMENT STRUCTURE DEFINITIONS

SEASONAL VARIATIONS IN SYNOPTIC PATTERNS

Although a TC may occur in any month in the western North Pacific region, the highest frequency is during July to December. The Standard (S) and the Poleward (P) synoptic patterns have roughly the same monthly frequency distributions as the overall total occurrence of TCs, although the S pattern has a relative minimum in September. However, the Gyre (G) and Multiple (M) TC patterns tend to be confined to the June-November and June-December periods, respectively. The JTWC forecaster should be aware of the seasonality of these synoptic patterns.



MONTHLY PATTERN FREQUENCY
1989-96
4017 CASES
500
450
400
350
300
250
200
150
100
50
0
J F M A M J J A S O N D
S
P
G
M

Topic: BETA-EFFECT PROPAGATION (BEP)

DESCRIPTION

Based on observational studies, the motion of TCs differs from environmental steering by up to a few meters per second. The difference is called propagation and usually has a westward and poleward direction.

Barotropic modelling studies indicate that one explanation for this propagation is a self-advection of the TC that results from a slight distortion of the cyclone windfield from axisymmetry, which is in turn a result of variation of the Coriolis parameter (approximated by beta). Thus, the nomenclature is Beta-Effect Propagation (BEP). If a non-divergent, barotropic numerical model is initialized with only the symmetric cyclonic wind profiles (see panel a) based on the angular momentum TC wind model (summarized above), then the tracks that result from BEP (no environmental flow) are generally to the west and poleward. Varying the cyclonic extent (R_o) values from 300 km to 1000 km with fixed f, or varying the latitude from 5° to 20°, with R_o = 800 km, leads to the following behavior:

(a) the speed of BEP depends directly on the extent R_o of the TC wind profile (panel b);

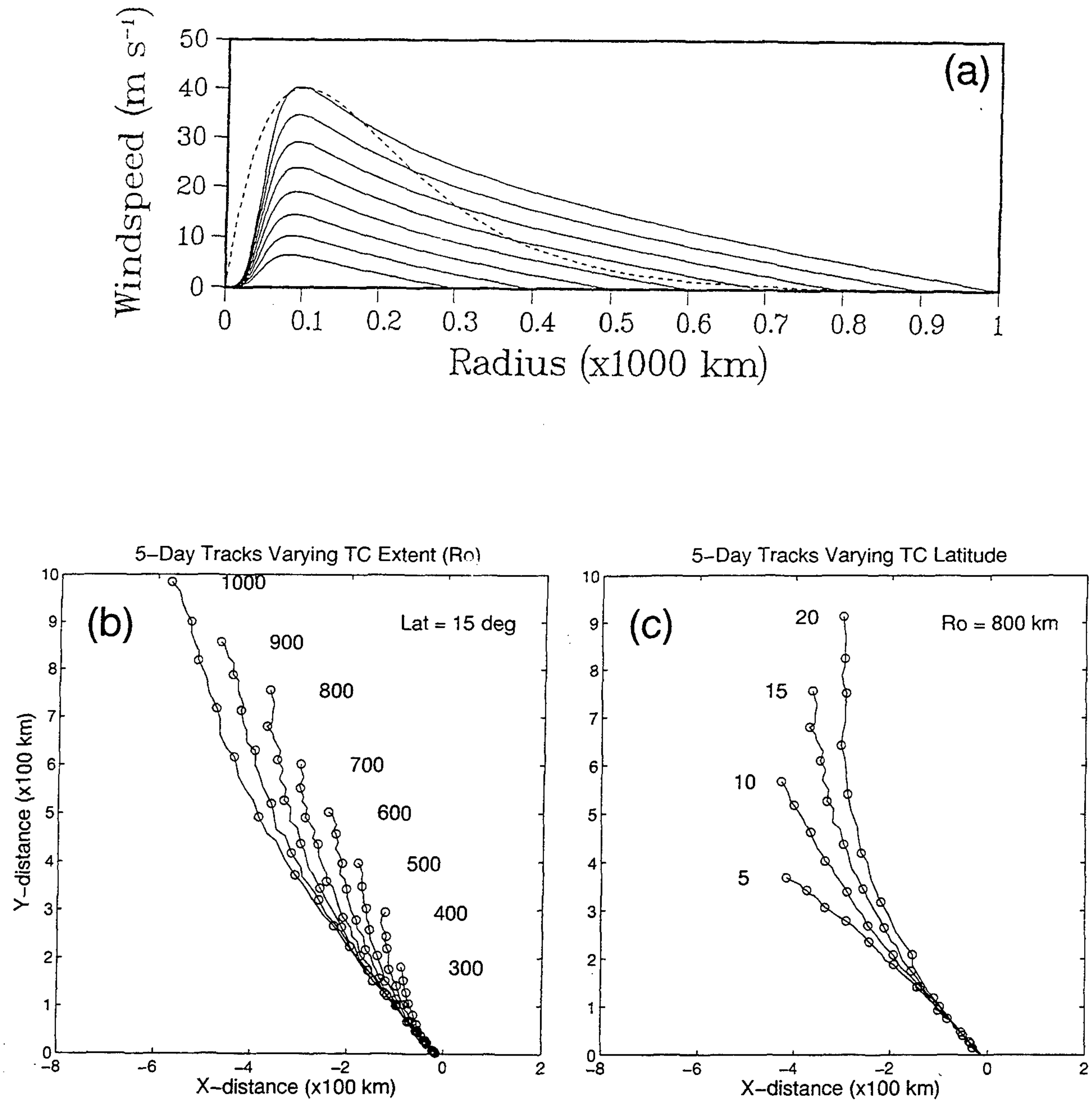
(b) the BEP speed depends directly on the latitude (panel c) used to compute the value of the Coriolis parameter in the TC wind profile, which affects the slope of the outer portion of the wind profile and thus the outer wind strength; and

(c) the BEP direction is initially toward 315° for all profiles. At longer forecast intervals (assuming unchanging conditions), the steady northwestward track turns more poleward for the TC wind profiles representing higher latitude TCs (panel c), or for larger TCs (panel b).

Cross-references:

Key TC Motion Concepts p. 3

TC Structure Definitions, Angular Momentum TC Wind Profile p. 17


(a)
Windspeed (m s^{-1})
Radius (x1000 km)
5–Day Tracks Varying TC Extent (Ro)
(b)
Lat = 15 deg
1000
900
800
700
600
500
400
300
Y–distance (x100 km)
X–distance (x100 km)
5–Day Tracks Varying TC Latitude
(c)
Ro = 800 km
20
15
10
5
X–distance (x100 km)

Topic: BETA-EFFECT PROPAGATION (BEP) (cont)

DESCRIPTION (cont)

Based on the maximum BEP speeds in the barotropic numerical model integrations shown on the previous page, the distribution of BEP speeds as a function of TC extent (R_0850) and latitude may be constructed (shown at right). Since TC size is defined in terms of BEP speed in the Systematic Approach, the four TC size categories may also be denoted on the diagram.

To use the diagram, find the point that corresponds to the latitude and R_0850 of the TC, and read off the BEP speed (in m/s) and TC size assignment. For example, a TC at latitude 15° with R_0850 = 800 km would have a BEP speed of 1.5 m/s and a size classification of AVERAGE.

NOTE: The diagram at right should only be used at latitudes equatorward of about 30°, where the dynamics of the large-scale tropical atmosphere are such that it is reasonable to use a barotropic model.

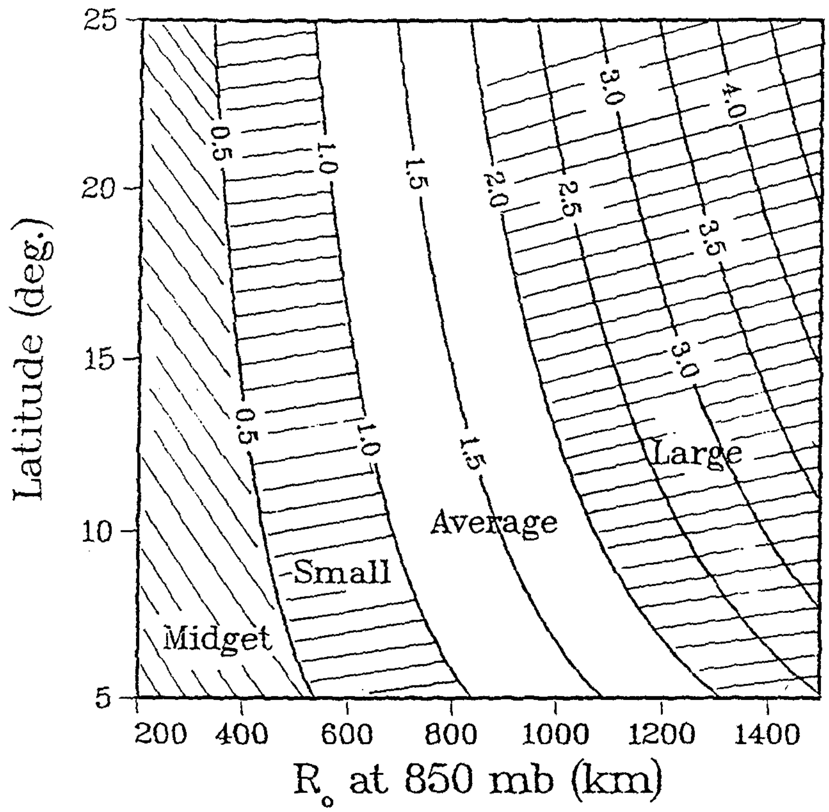
The BEP may cause a TC-Environment transformation by advecting the TC into another synoptic region within the same pattern, or contribute to a pattern transition via the peripheral anticyclone development.

Cross-references:

TC Structure Definitions, Angular Momentum TC Wind Profile p. 17

TC size p. 15

BEP Speed & TC Sizes



BEP Direction (315°-360°)

Topic: BETA-EFFECT PROPAGATION (BEP) (cont)

DESCRIPTION (cont)

At latitudes south of 30° in the western North Pacific, a TC is usually in the easterly 10-15 kt steering associated with the DR region of a S pattern. The diagrams at right show the departure of TC motion from a 5 m/s (10 kt) easterly steering flow that can be expected for BEP speeds from a SMALL, AVERAGE, or LARGE TC propagating at 0.5, 1.5, 2.5 m/s, respectively, and at a direction of 315° (panel a) or 360° (panel b).

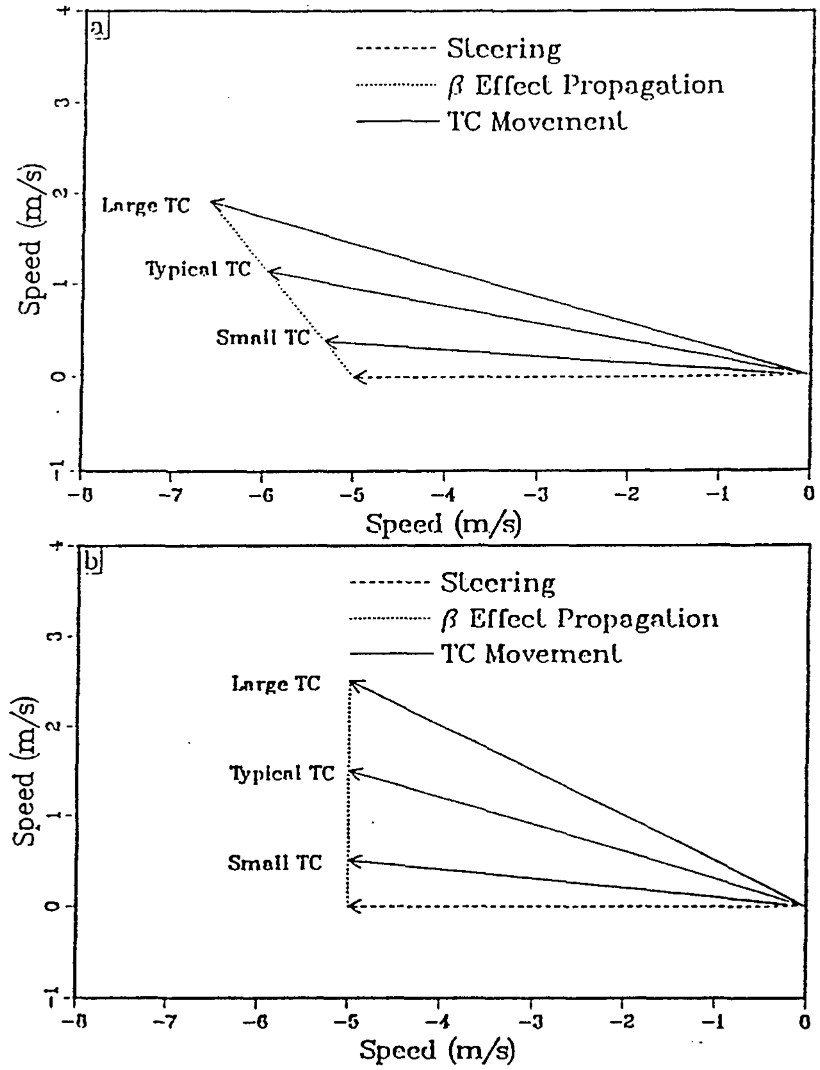
Whereas the motion of a SMALL TC departs very little (i.e., a cork in the stream) from the motion of the steering flow, the motion of an AVERAGE or LARGE TCs departs quite significantly. In addition, recall from the definition of the LARGE TC that it also has a considerable potential to alter the structure of its environment (i.e., induce an environment transition).

Cross-references:

Standard (S) Pattern p. 19

TC size p. 15

Conceptual Impact of Different TC Sizes



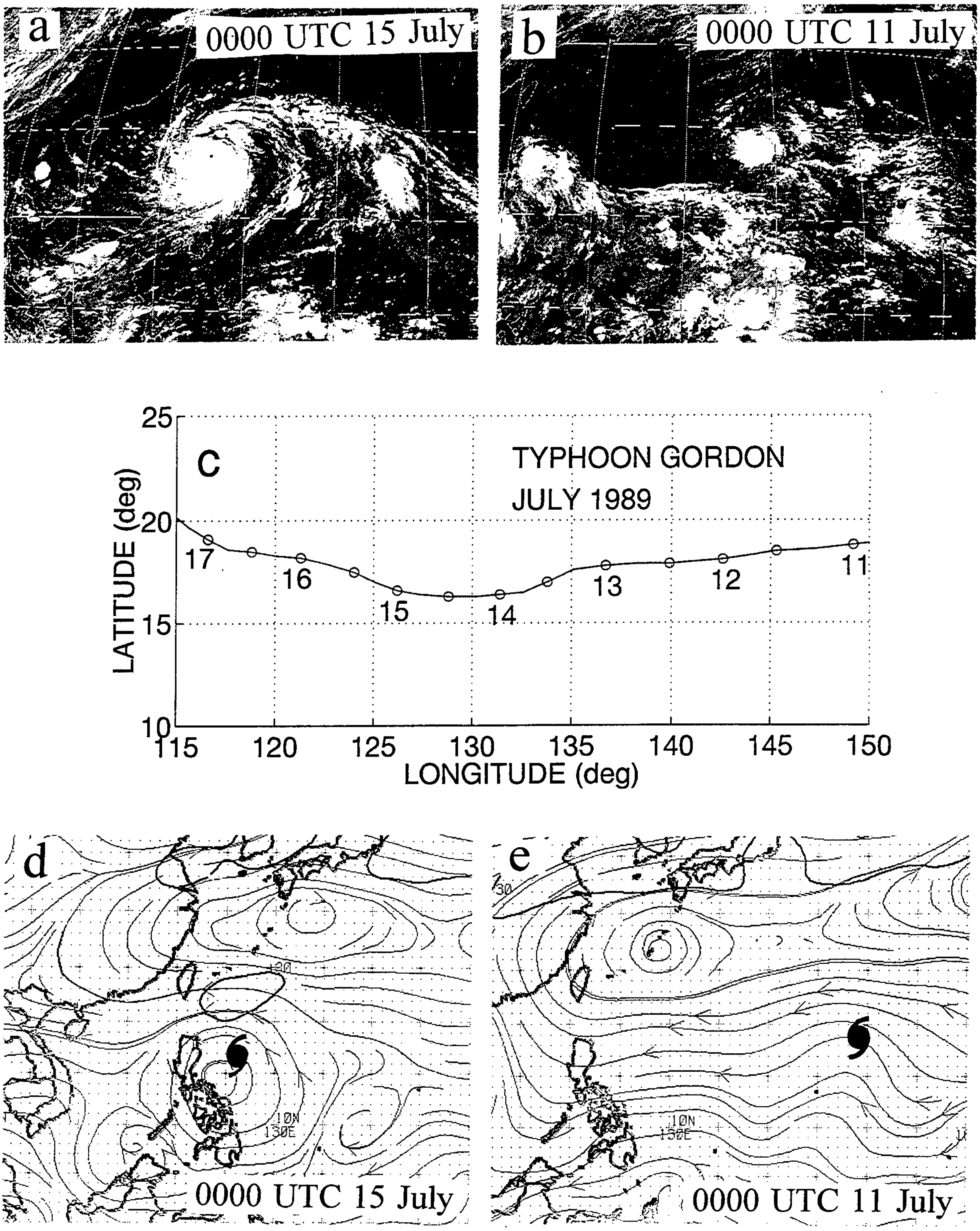
Topic: BETA-EFFECT PROPAGATION (BEP) (cont)

BEP SCENARIO ILLUSTRATION

The imagery and track of Super Typhoon Gordon shown at right provide strong evidence for the dependence of TC propagation on TC size.

At 0000 UTC 11 July 1989, satellite imagery (panel b) indicates that Gordon has a relatively small cyclonic circulation. At this time, Gordon is tracking WSW (panel c) in close conformity to the east-northeasterly steering (panel e) equatorward of a mid-level STR that had a similar axis slope.

At 0000 UTC 15 July 1989, satellite imagery indicates that the cyclonic circulation of Gordon has grown considerably during the past four days. Beginning on the 14th of July, the track of Gordon turned from WSW to WNW (panel c) despite the fact that the steering flow and STR axis orientation have remained essentially unchanged. This greater poleward (and westward) deflection of the TC track relative to the unchanged steering is attributed to the larger size of Gordon.


a
0000 UTC 15 July
b
0000 UTC 11 July
c
TYPHOON GORDON
JULY 1989
LATITUDE (deg)
LONGITUDE (deg)
25
20
15
10
115
120
125
130
135
140
145
150
17
16
15
14
13
12
11
d
0000 UTC 15 July
10N
130E
e
0000 UTC 11 July
10N
130E

Topic: RIDGE MODIFICATION BY A TC (RMT)

DESCRIPTION

According to barotropic modelling results, the beta effect (variation of Coriolis) not only results in a TC deflection relative to steering (i.e., propagation), but also causes the TC to radiate energy eastward and equatorward in the form of a Rossby wavetrain of alternating anticyclonic and cyclonic circulations. The horizontal scale and amplitude of these circulations depend on the outer wind strength of the TC as determined by the TC cyclonic extent (R_o) as shown in the model simulations of streamfunction (cyclonic, dashed; anticyclonic, solid) at right.

Based on barotropic modelling results, a TC of smaller radial extent produces a smaller/weaker wavetrain (panel a) than a more extensive TC (panel b) for the same latitude. If the TC radial extent is held constant, a TC at lower latitude produces a smaller/weaker wavetrain (panel c) than a TC at higher latitude (panel d). The anticyclone that forms on the periphery of the TC is the strongest feature of the wavetrain. This peripheral anticyclone forms in response to strong negative (anticyclonic) vorticity advection (NVA) that occurs in the southeastern portion of the TC circulation due to distortion of the TC windfield in association with the beta effect. Similarly, positive (cyclonic) vorticity advection (PVA) occurs poleward and somewhat westward of the TC.

The development of a vigorous peripheral anticyclone as in panels c and d leads to a poleward steering flow component across the TC to the west. This may lead to a synoptic pattern change for a large TC from S/DR to P/PO.

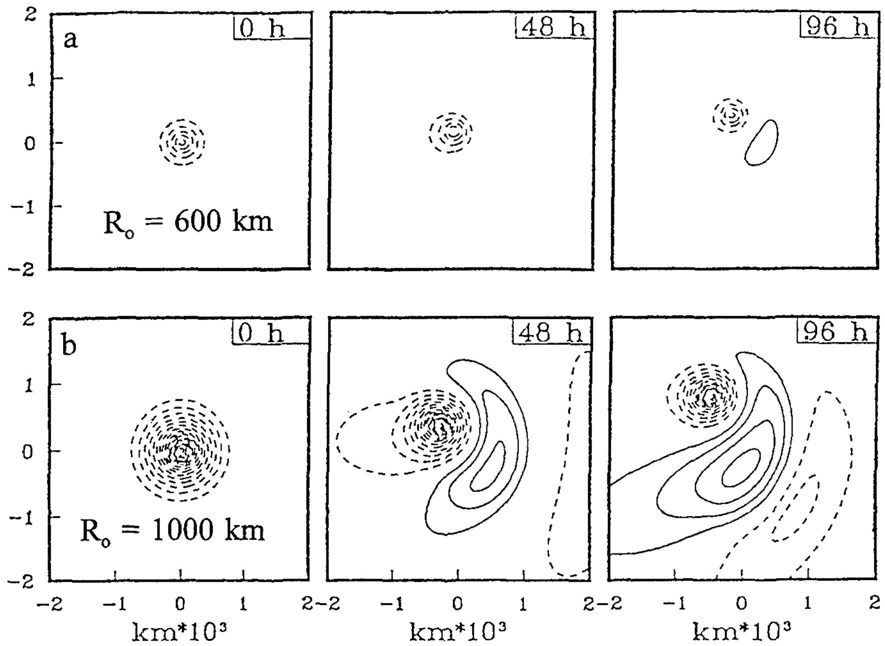
Cross-references:

TC size p. 15

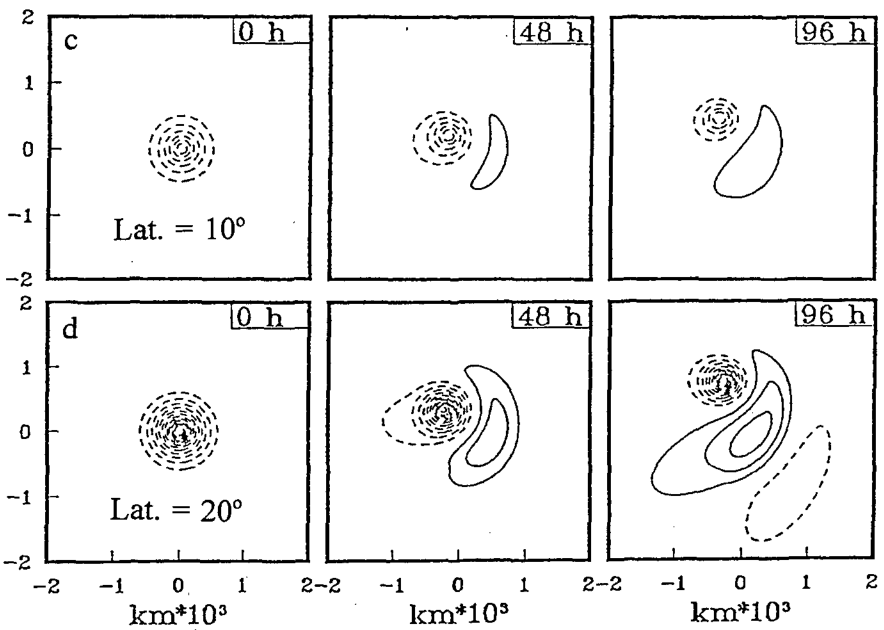
Angular Momentum TC Wind Profile p. 17

Standard (S) Pattern, Characteristic Locations and Tracks p. 21

Impact of TC Extent (R_o)
(Latitude = 15°)



Impact of TC Latitude
(R_o = 800 km)



Topic: RIDGE MODIFICATION BY A TC (RMT) (cont)

DESCRIPTION (cont)

Based on the barotropic modelling results on pp. 55-56, schematics to illustrate the RMT phenomenon are shown at right.

In panel (a), the peripheral anticyclone associated with a small TC is small compared to the scale of a typical subtropical ridge (STR) circulation. In addition, the PVA that occurs poleward of the small TC, which is a ridge-weakening effect, does little to alter the structure of the STR.

By contrast, a large TC in panel (b) has significant and extensive PVA on its poleward side, which, in combination with the TCs poleward propagation, can erode the STR sufficiently (even without the assistance of midlatitude wave activity) to separate or "break" the STR into two circulations. Concurrently, the large, building peripheral anticyclone to the southeast of the TC tends to join with the eastern portion of the broken subtropical ridge to form a single meridionally-oriented circulation that can advect the TC poleward and through the break in the STR.

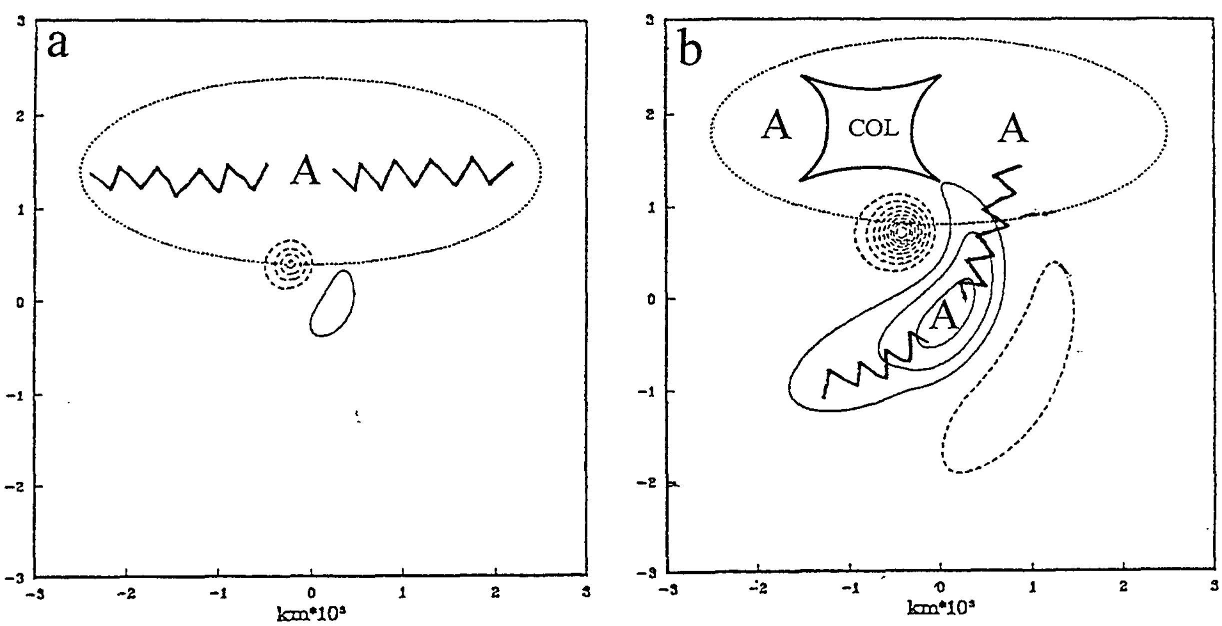
NOTE: It is the RELATIVE SIZE of the TC and its associated peripheral anticyclone in comparison with the amplitude of the STR that determines whether or not (or with what rapidity) the RMT process will result in a ridge-breaking event and a poleward turn by the TC. Thus, the relatively weak RMT process associated with a small TC might contribute to a "break" in the STR if the scale of the ridge (particularly north/south) is sufficiently small. Conversely, a large TC may have difficulty breaking through a ridge that is abnormally large.

Cross-references:

TC size p. 15

Beta-Effect Propagation p. 57

RIDGE MODIFICATION BY TC (RMT) CONCEPTUAL MODEL



Topic: RIDGE MODIFICATION BY A TC (RMT) (cont)

DESCRIPTION (cont)

The usual result of sufficiently strong RMT is to cause a transition in the TC-environment structure from a S/DR pattern/region combination (panel a) to a P/PO combination (panel b).

While the TC is still in the S pattern, the peripheral anticyclone develops until the structure of the environment begins to resemble a combination of both S/DR and P/PO, which makes it difficult to determine the pattern/region classification on the basis the circulation patterns in the streamline analysis alone. Use the recent motion of the TC, and the relative positions of the isotach maximum, the TC position, and the analyzed wind circulation center at the steering level to resolve the situation as on p. 9.

For example, the environment structure classification in panel (a) is still S/DR because the TC is moving more westward and poleward and the isotach maximum is to the north-northeast of the TC. By contrast, the environment structure in panel (b) is P/PO because the TC is moving more poleward than westward (and sometimes eastward) and the isotach maximum is to the southeast of the TC.

NOTE: The two TC translation directions shown in each panel indicate the expected impact of TC size. The translation directions that closely conform to the direction of environmental steering represent smaller TCs (i.e., negligible propagation), whereas the more poleward motion and more westward motion represent a larger TC in the S/DR and P/PO situation, respectively. Notice also that this implies that in general the track change associated with an S/DR to P/PO transition involving a small TC will be more severe (sharp) than for a larger TC. Such behavior has often actually been observed. For example (see appropriate ATCRs):

(a) in 1992, Typhoon Yvette (small) underwent a very sharp S/DR-P/PO track change.

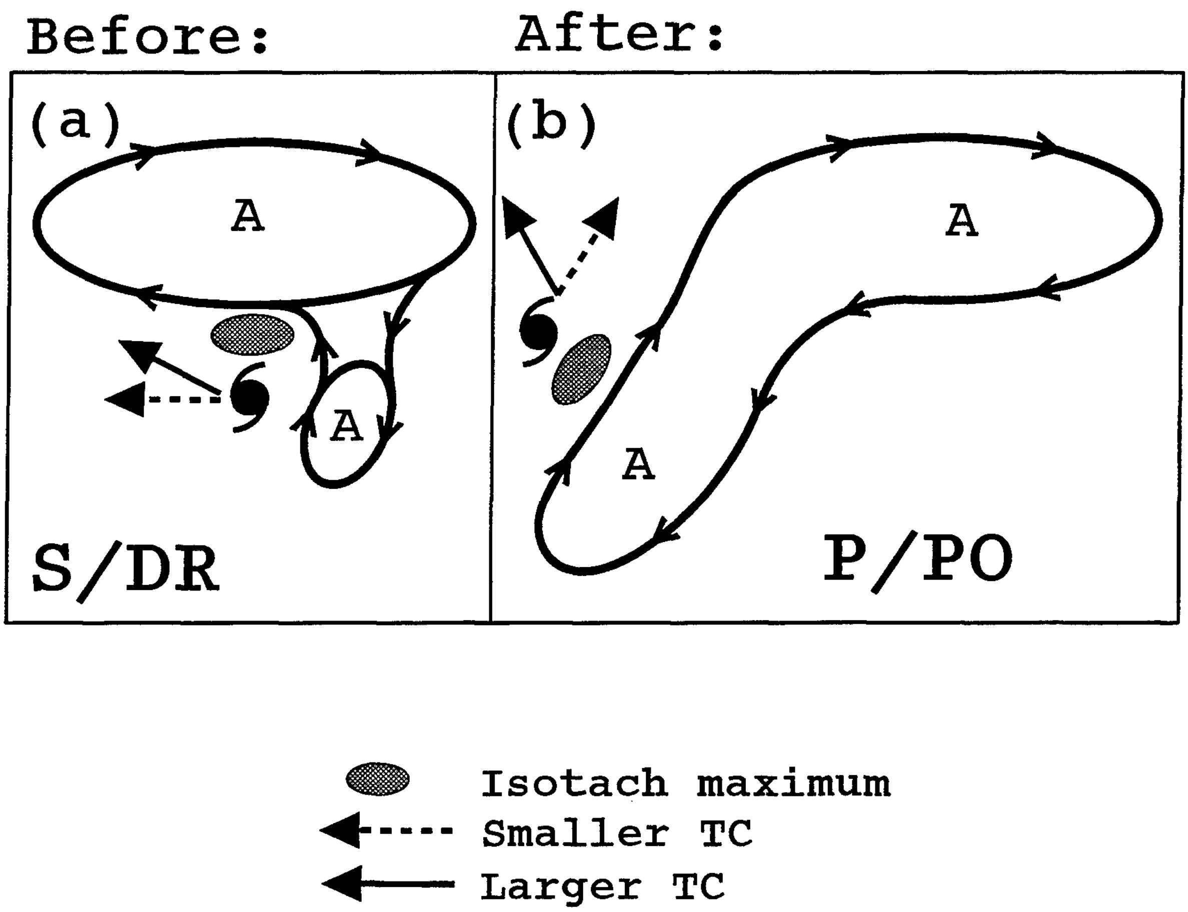
(b) in 1994, Typhoon Page (average) underwent a moderately sharp S/DR-P/PO track change. (See p. 71-72 and track on page A-6)

(c) in 1991, Typhoon Yuri (very large) underwent a comparatively smooth S/DR-P/PO track change. (Also see Oscar in 1995)

Cross-references:

Diagnosing Environmental Steering Direction p. 9
Standard (S) Pattern p. 19
Poleward (P) Pattern p. 29

S/DR to P/PO Transition
via
Ridge Modification by TC
(RMT)



Topic: RIDGE MODIFICATION BY A TC (RMT) (cont)

RMT SCENARIO DESCRIPTION

An example of an environment structure transition from S/DR to P/PO in response to RMT is shown at right for Typhoon Page during the period 11-16 May 1994 (see track on page A-6). Notice the following:

- in panel (b), the recent motion direction of the TC confirms that the structure of the environment is still S/DR despite the appearance of the substantial peripheral ridge, and the appearance (albeit temporary) of an isotach maximum to the southeast. Notice the inconsistency of the TC position, wind circulation center, and isotach maximum.

- in panel (c), the recent motion direction of the TC confirms the structure of the environment is still S/DR, although a slight slowing is occurring, which may indicate that a transition is imminent.

- in panel (d), the recent motion direction of the TC is consistent with the streamline orientation and the isotach maximum to the southeast, which confirms that the environment of the TC is now P/PO.

- in panels (e) and (f), the peripheral anticyclone to the southeast of Page follows the TC as it moves northeast, which delays the TC entry into the higher speed winds of the midlatitude westerlies. As a result, Page intensified from 65 kt at 0000 UTC 14 May 1994 to 90 kt at 1200 UTC 15 May 1994. During this same period, Page's translation speed increased only from 7 kt to12 kt.

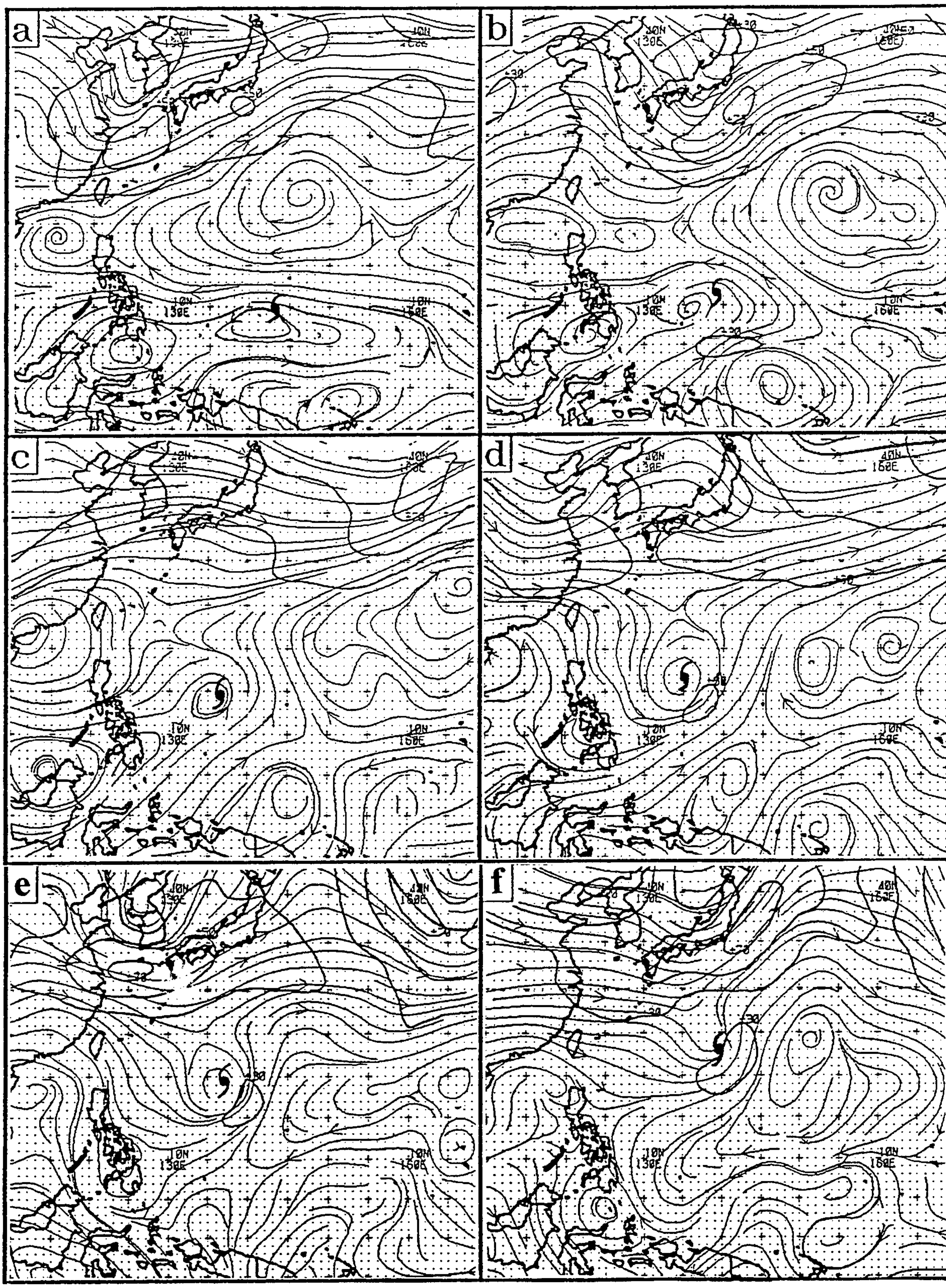
Cross-references:

Diagnosing Environmental Steering Direction p. 9

Standard (S) Pattern p. 19

Poleward (P) Pattern p. 29

Typhoon Page 11-16 May 1994 (0000 UTC)



TC-ENVIRONMENT TRANSFORMATIONS

Topic: REVERSE TROUGH FORMATION (RTF)

DESCRIPTION

The RTF concept is related to the Ridge Modification by a TC (RMT) concept, except that the peripheral anticyclones of two or more TCs are involved. When one TC is to the east of, and at a similar latitude to, a second TC (panel a), two effects are impacting the amplitude of the peripheral anticyclone of the western TC. The anticyclonic vorticity advection to the southeast of the western TC is acting to generate and amplify the peripheral anticyclone. To the extent the peripheral anticyclone "links" with the subtropical ridge (STR) circulation to the northeast, the associated steering flow will advect the western TC more poleward. At the same time, the peripheral anticyclone of the western TC imposes an equatorward steering influence on the eastern TC.

However, the cyclonic vorticity advection to the northwest of the eastern TC is acting to erode the peripheral anticyclone of the western TC. Depending on the size, orientation, and proximity of the eastern TC, the impact on the peripheral anticyclone of the western TC can be to:

- keep the anticyclone separated from the STR circulation to northeast of the anticyclone;
- keep the western TC peripheral anticyclone from forming at all; or
- constrain the formation of the anticyclone to be more south than east of the western TC.

If the eastern TC influence described above is significant, then the eastern TC may translate poleward faster than the western TC, particularly if a Multiple (M) pattern is temporarily established (see M pattern and STI summaries). As the eastern TC moves poleward of the western TC, the development of the peripheral anticyclone to the southeast of the western TC is no longer inhibited. Eventually, the peripheral anticyclones of the two TCs tend to superpose or "link up," and the associated steering flows tend to advect both TCs poleward. In this Reverse Trough Formation (RTF) scenario, the trough contains the two (or more) TCs that will near simultaneously turn to a poleward, and usually eastward, direction of motion.

NOTICE: If the contribution of the western TC to the growth of its associated peripheral anticyclone exceeds the damping effect on the eastern TC, the impact of the steering flow on the eastern TC will cause an equatorward deflection. This will be described later as an Indirect TC Interaction-East (ITIE). If the damping effect of the eastern TC erodes the peripheral anticyclone of the western TC, the tendency to develop a poleward steering across the western TC will be impeded --this is ITI-West or ITIW.

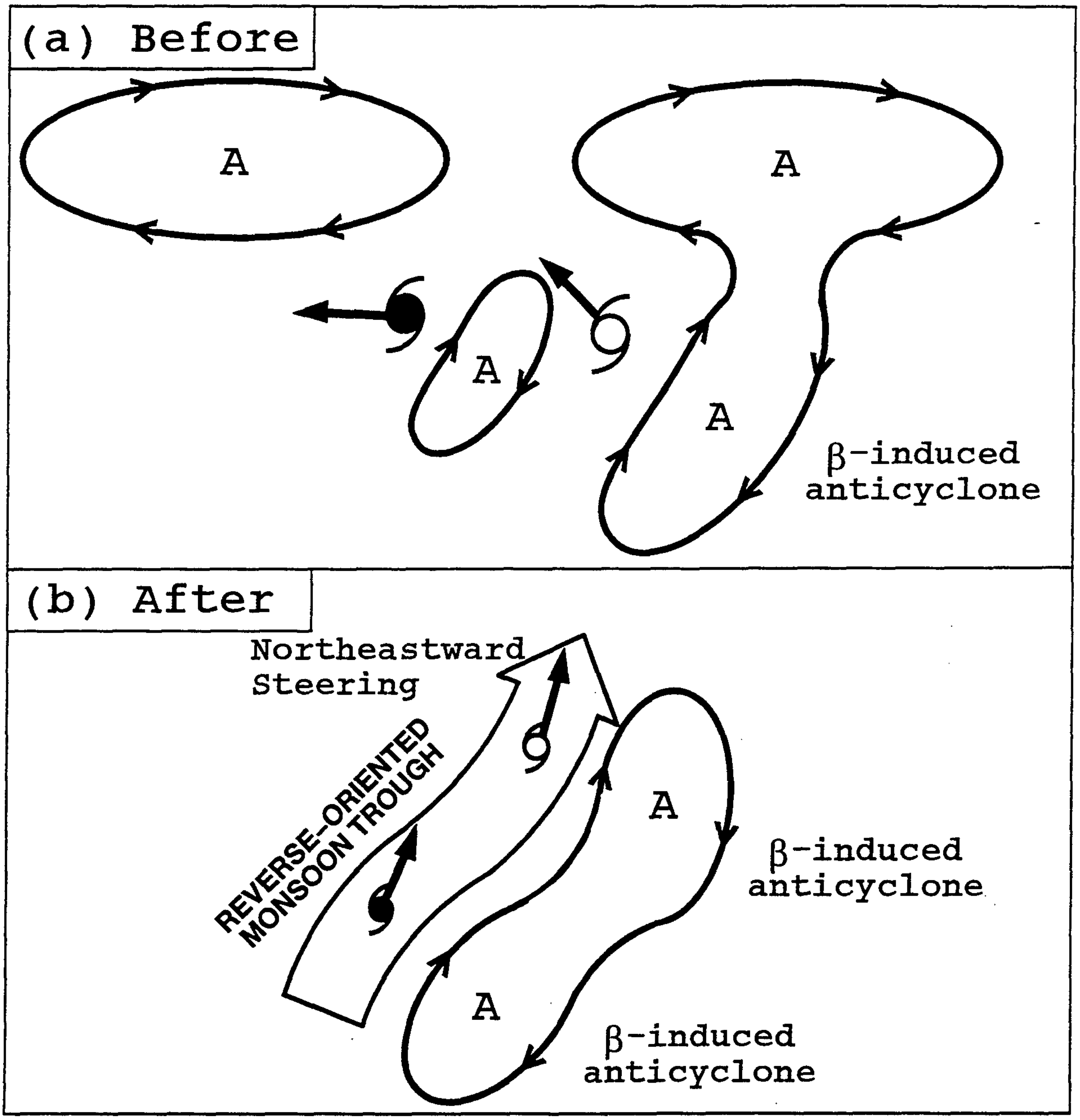
Cross-references:

Multiple (M) TC Pattern p. 47

Semidirect TC Interaction (STI) p. 97

Indirect TC Interaction (ITI) p. 87

REVERSE TROUGH FORMATION
(RTF) CONCEPTUAL MODEL



Topic: REVERSE TROUGH FORMATION (RTF) (cont)

SCENARIO ILLUSTRATION

The NOGAPS analysis series at right illustrates a RTF event involving Typhoons Ed (26W) and Flo (25W), and Tropical Depression 28W during October 1993. Each of the three tracks is shown on page A-7. On 2 October (panel a), TD 28W (western TC) and Ed (eastern TC) are both at a slightly lower latitude than Flo (middle TC), which gives the monsoon trough axis defined by the TCs a bent, but approximately zonal, orientation. Notice that:

- TD 28W is at the proper position to be in a Multiple (M) TC Equatorword Flow (EF) region formed by Flo and the STR anticyclone to the northwest; and

- Ed is at the proper position to be in a M/Poleward Flow (PF) region formed by Flo and the STR anticyclone to the northeast;

Thus, TD 28W (Ed) should be expected to be displaced equatorward (poleward) relative to Flo, which contributes a reverse SW-to-NE orientation of the monsoon trough (panel c).

- by 4 October, TD 28W and Ed have moved sufficiently south and north, respectively to establish a reverse-oriented monsoon trough. The peripheral anticyclones to the southeast of the TCs are becoming more extensive. Note also that the NOGAPS analysis clearly has Flo in the M/EF region because the isotach maximum is to the WNW.

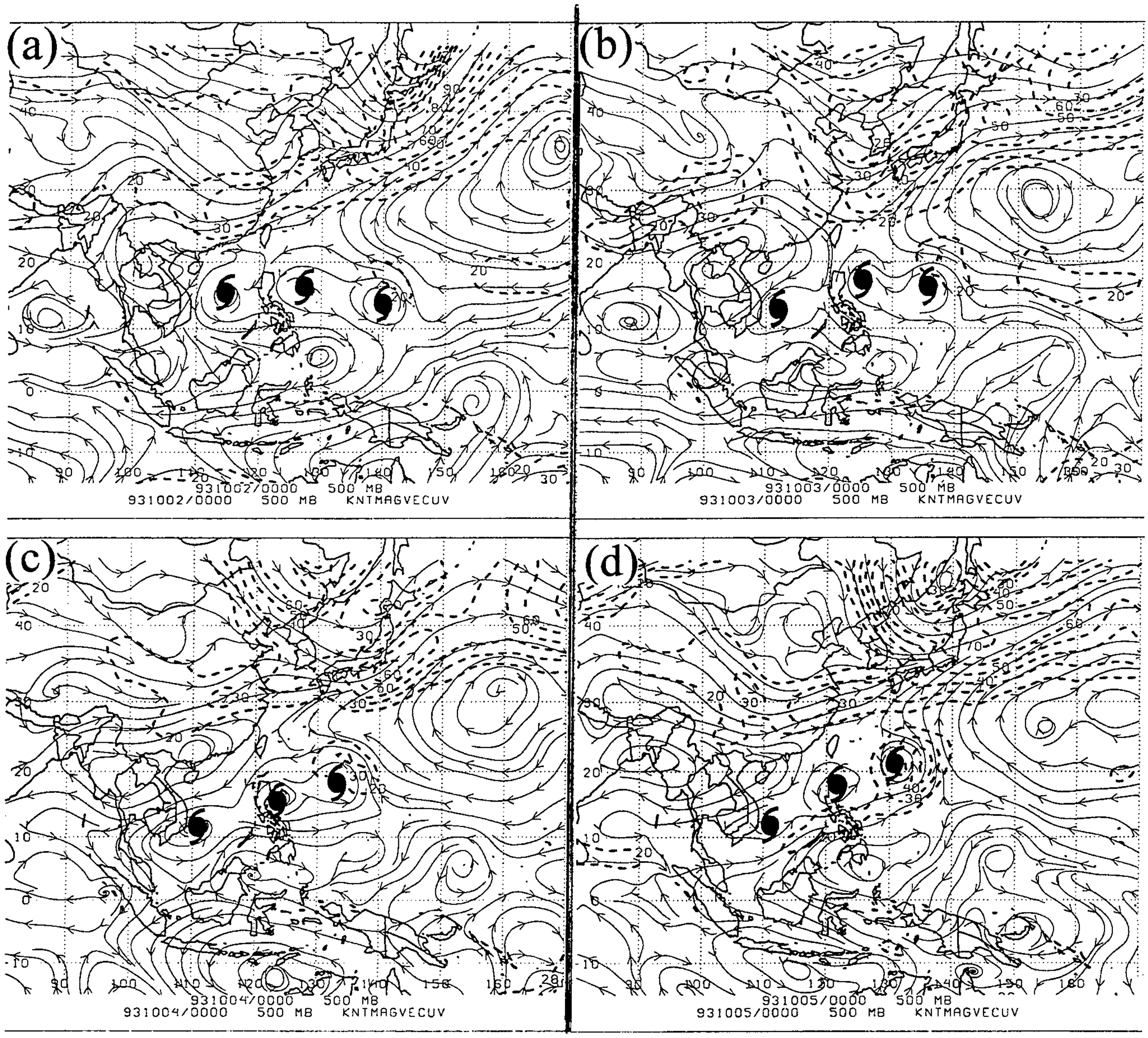
- by 5 October (panel d), an extended isotach maximum has developed southeast of the TCs, which indicates that the extended peripheral anticyclone has become strong enough to impose a steering to the northeast on both TCs. Coincidentally, the three TCs do turn to poleward and eastward headings, which confirms that the RTF event has in fact occurred.

Cross-references:

Multiple (M) TC pattern p. 47

Ridge Modification by a TC, Peripheral Anticyclone Development p. 65

Reverse Trough Formation (RTF) involving TCs TD28W, Typhoon Flo, and Typhoon Ed 02-05 October 1993



Topic: MONSOON GYRE (MG) - TC INTERACTION (MTI)

SATELLITE IMAGERY OF MTI

The satellite imagery sequence at right illustrates the evolving cloud patterns that are characteristic of Monsoon gyre-TC interaction (MTI) for two MG-TC pairs that involve Typhoon Sarah (22W) and Tropical Storm Tip (23W) during September 1989. Tracks for Sarah and Tip are shown on page A-8. Notice the following:

- on 7 September (panel a), the small cloud swirl that is Sarah (western T) is clearly distinct from the large ring of convection that is associated with the very large radius of maximum winds of the MG. Farther to the east, a fish hook pattern is forming that manifests the development of another MG in which Tip will form.

- on 8 September (panel b), the cloud pattern of Sarah is beginning to merge with the MG cloud pattern, and the cloud signature of Tip (eastern T) is becoming evident as the second MG fish hook cloud pattern continues to develop.

- on 9 September (panel c), the cloud pattern of Sarah is no longer distinct from the MG cloud pattern, which suggests that the two circulations have merged. Tip is now about 5° long. to the east of the second MG center, which has developed an extensive fish hook cloud pattern.

- on 10 September (panel d), the merged cloud pattern of Sarah and MG remains, and Tip also appears to be moving into the center of the second MG.

- on 11 September (panel e), the cloud patterns of Sarah and MG remain merged, and Tip now appears to be in the center of the second MG.

Cross-reference:

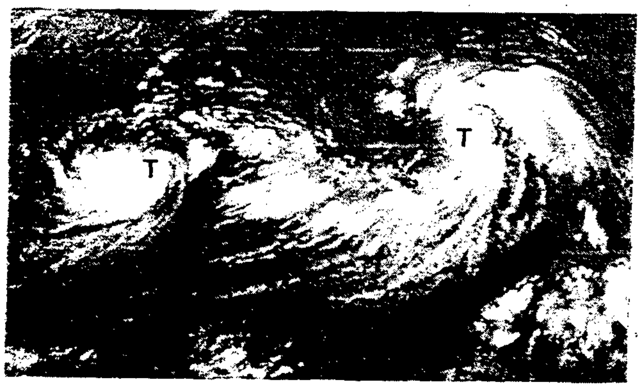
Gyre (G) Pattern p. 37

7 - 11 September 1989 (0300 UTC)

a

b

c



d

e

Topic: MONSOON GYRE (MG) - TC INTERACTION (MTI) (cont)

DESCRIPTION

The basic mechanism of the MTI process is illustrated at right in the streamfunction fields from the integration of a nondivergent, barotropic, numerical model (beta plane) with initial conditions of a larger, weaker cyclone (the MG), and a smaller/more intense cyclone (the TC) located 400 km to the east of the center of the large vortex. Notice that:

- in the first 24 h, the TC follows a cyclonic path around the MG as a peripheral anticyclone builds to the east in response to the beta effect on the MG circulation.

- by 36 h, the TC and MG have merged, and remained merged through the rest of the integration.

- from 36 to 96 h, the peripheral anticyclone, which is stronger and more eastward oriented than that generated for a single large TC (see RMT summary), advects the merged TC-MG (now effectively just a large TC) poleward.

- the predicted track of the TC (see 96-h field) is an equatorward turning loop that is followed by a brief quasi-stationary period, and then a strongly poleward-oriented and essentially straight track segment.

Varying the initial position of the TC relative to the MG center in the model affects the integration:

- TC positions out to 700 km east of the MG result in a MG-TC merger and produce the characteristic "kinked" track, whereas no merger occurs for separation distances greater than 800 km.

- TC positions to the SW-to-SE produce longer looping tracks before the stall occurs and then a poleward turn.

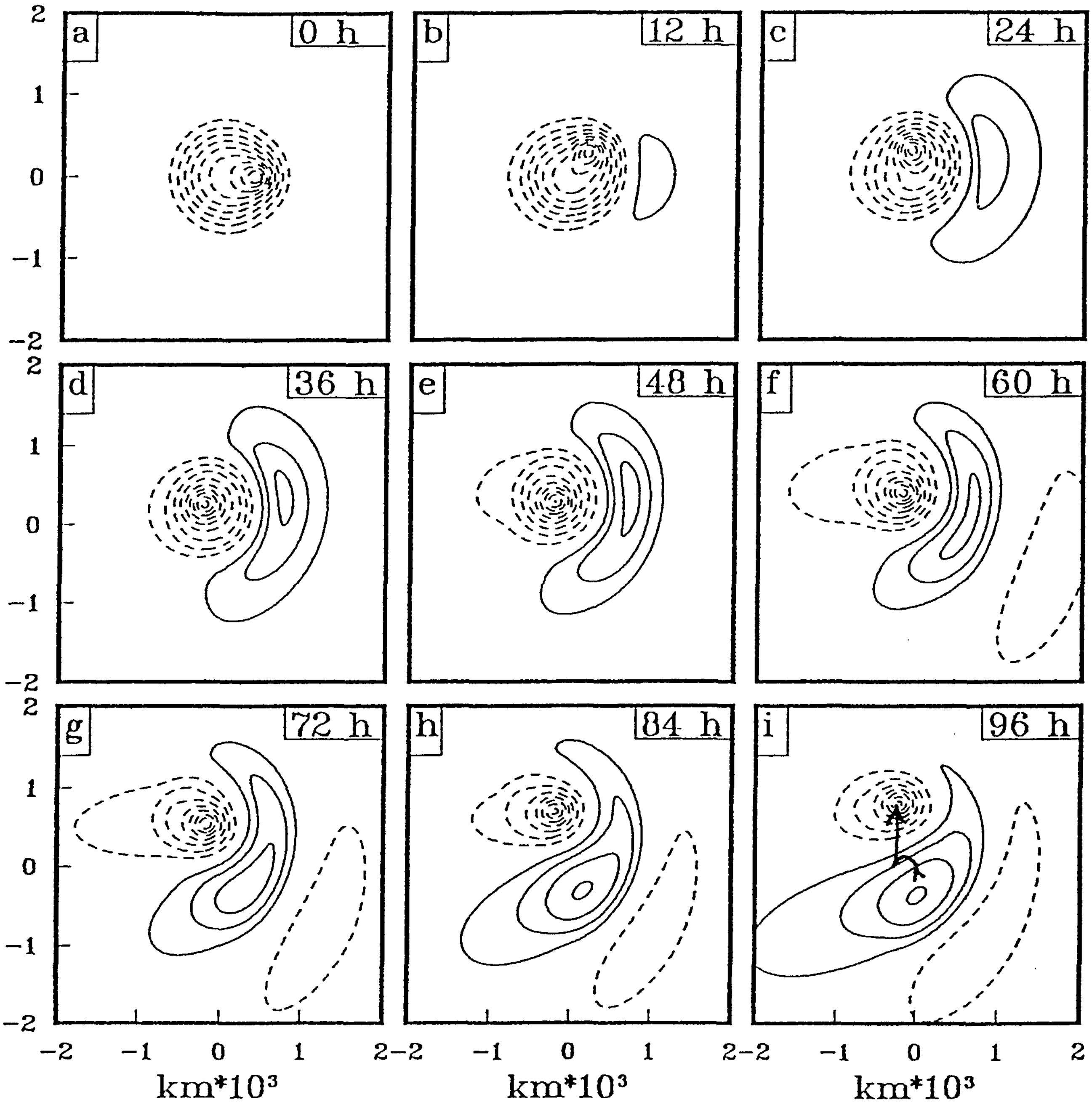
- TC positions to the NE-to-NW result in the stall becoming a loop, and then a poleward motion.

Cross-references:

Gyre (G) Pattern p. 37

Ridge Modification by a TC (RMT) p. 65

MTI MODELING



Topic: MONSOON GYRE (MG) - TC INTERACTION (MTI) (cont)

DESCRIPTION (cont)

As shown in the schematic at right, the MTI environment transformation results in a transition from a G pattern to a P/PO pattern/region combination. The transition may occur in two ways:

- if the TC is to the east of the MG (G/PO pattern/region) when the MTI begins, then a G/PO-to-P/PO transition occurs (as illustrated); or

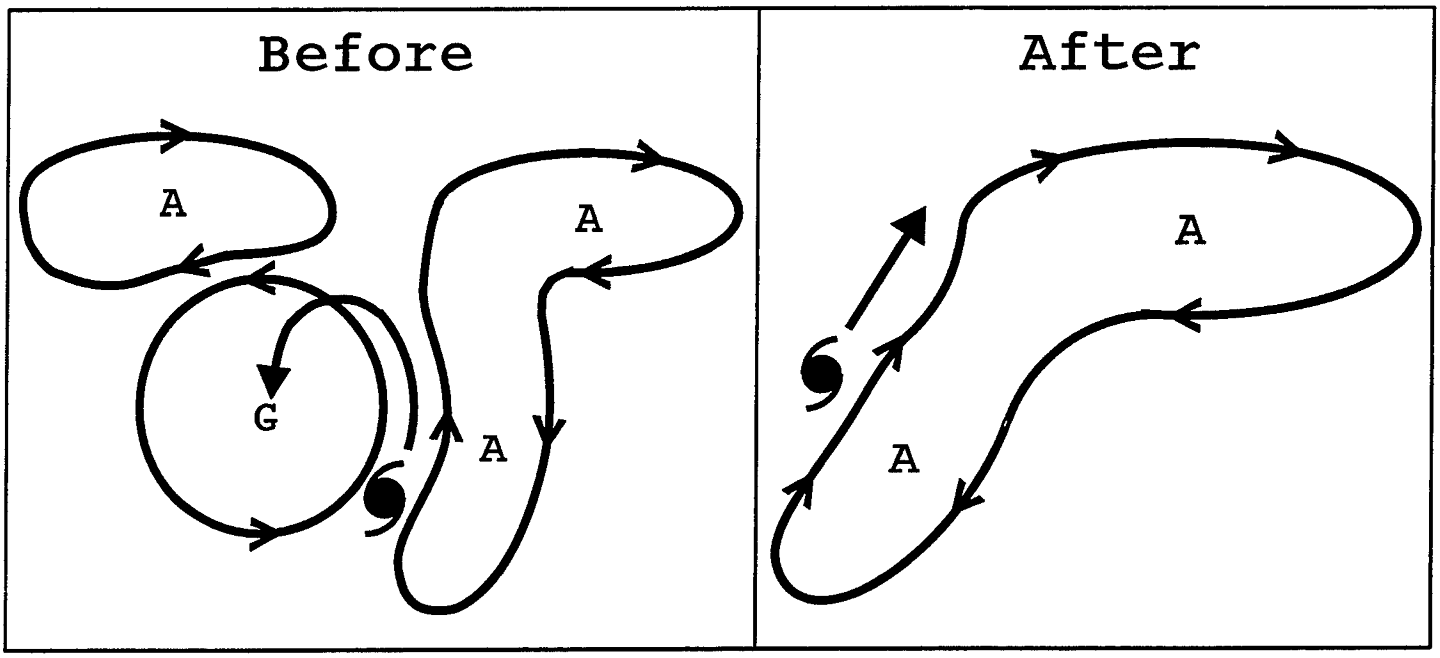
- if the TC is to the north of the MG (G/DR pattern/region) when the MTI begins, then a G/DR-to-P/PO transition occurs.

Cross-references:

Gyre (G) Pattern p. 37

Poleward (P) Pattern p. 29

MONSOON GYRE-TC INTERACTION
(MTI) CONCEPTUAL MODEL



Example of a G/PO to P/PO transition via monsoon gyre and TC merger

TC-ENVIRONMENT TRANSFORMATIONS

Topic: MONSOON GYRE (MG) - TC INTERACTION (MTI)

SCENARIO ILLUSTRATION

The NOGAPS analysis series at right illustrates separate, but nearly concurrent, MTI events involving Typhoon Sarah and Tropical Storm Tip during September 1989. The tracks of Sarah and Tip are also provided on page A-8 for comparison. Imagery corresponding to this analysis series appears on page 78. Notice the following:

- on 8 September(panel a), the position of Sarah (T) is located about 4° lat. (440 km) north of the model-analyzed (western M) wind circulation center, and another MG is forming to the east (eastern M).

- on 9 September (panel b), the position of Sarah (larger T) is nearly collocated with the center of the western MG, and Tip (smaller T) now appears to the southeast of eastern MG (M).

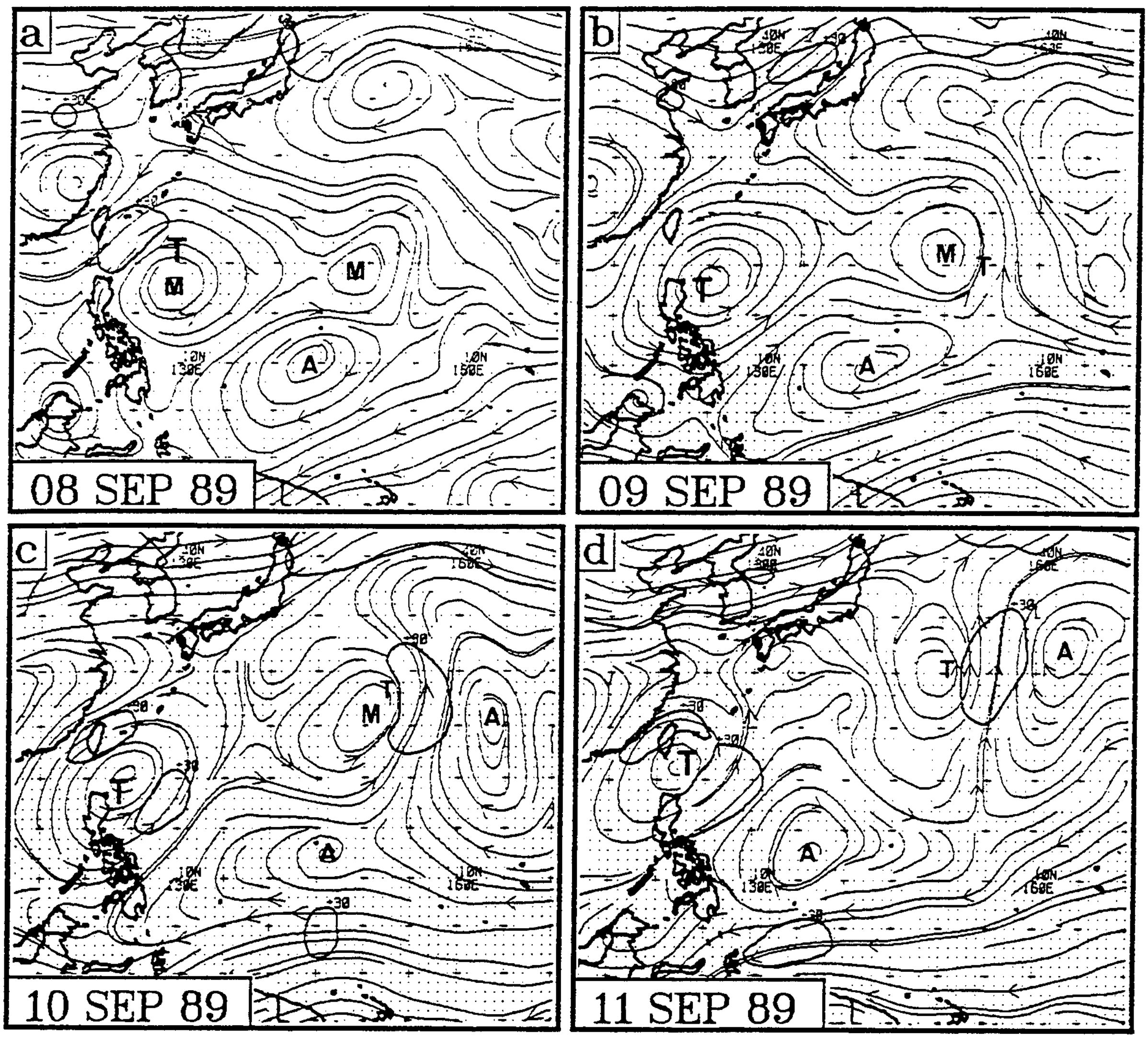
- on 10 September (panel c), the position of Sarah remains merged with the MG and a 30-kt isotach has appeared to the southeast, which indicates that the associated peripheral anticyclone is building. Tip is now several degrees lat. northeast of the center of the eastern MG.

- on 11 September (panel d), Sarah is moving in response to the steering from the strong peripheral anticyclone to the southeast. Tip is merging with the MG to the east, and a strong anticyclone has developed to the east (note isotach), which will begin to advect Tip poleward.

Cross-references:

Gyre (G) Pattern p. 37

Typhoon Sarah
and
Tropical Storm Tip



TC-ENVIRONMENT TRANSFORMATIONS

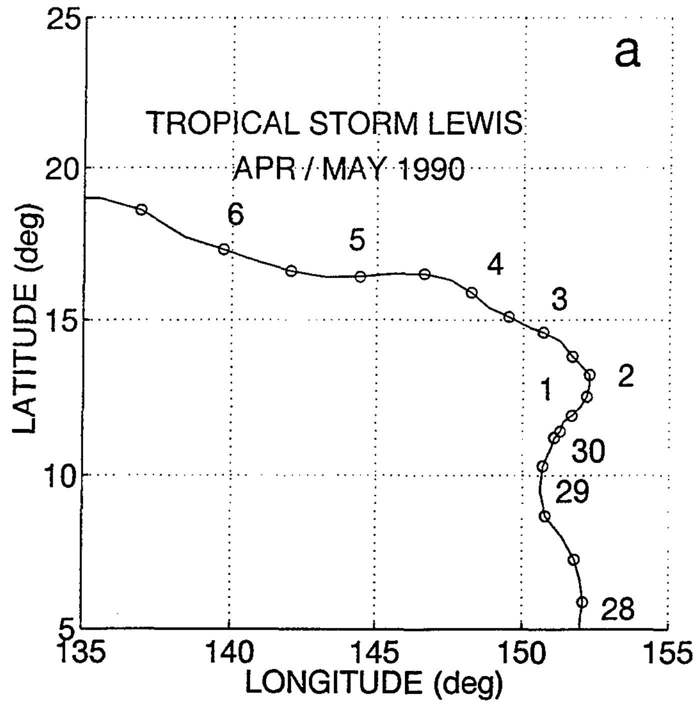
Topic: VERTICAL WIND SHEAR (VWS)

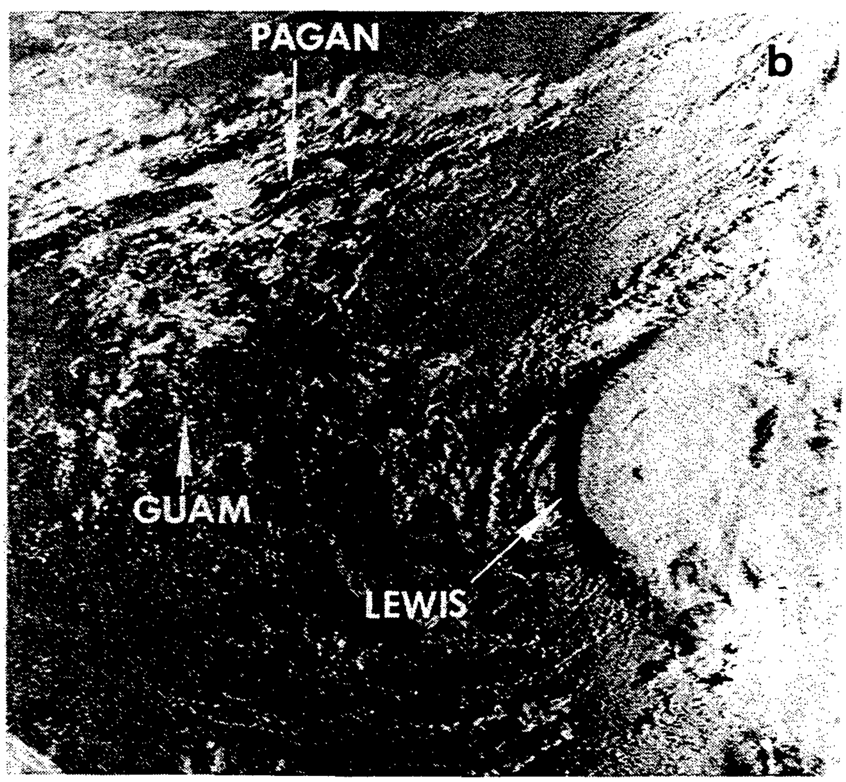
It is well known that VWS can have a profound effect on TC motion if the VWS is sufficiently strong to separate the convective cloud mass (CCM) of the TC from the low-level circulation (LLC) of the TC. If the CCM and LLC separate, then a large track change usually occurs as the TC ceases to follow the average environmental steering over the depth of the troposphere, and the remaining LLC begins to follow the environmental steering of the lower troposphere (typical steering level of 850 mb). From the perspective of the systematic approach, VWS results in an apparent change in the environment structure (i.e., synoptic pattern and/or region), because the level at which the TC steers is changed as the structure (i.e., intensity) of the TC is changed by the VWS.

Typically, strong VWS is encountered as the TC moves poleward past the axis of the mid-tropospheric subtropical ridge and approaches the mid-latitude westerlies. If the strength of the VWS is insufficient to decouple the CCM and LLC, the TC will recurve into the midlatitude westerlies and usually weaken gradually. By contrast, if the VWS separates the CCM from the LLC, then wind speed in the LLC with decrease rapidly. Concurrently, the TC will usually turn onto a predominantly westward track, since the lower tropospheric remnants of the TC circulation will be in the easterlies. Particularly strong VWS is routinely present in the vicinity of the northern Philippines and South China Sea during the northeast monsoon season (Oct - Mar). If the LLC decouples from the CCM in this situation, a west-southwest track occurs.

The impact of VWS on TC motion is strikingly illustrated in the case of Tropical Storm Lewis (opposite page). Prior to 2 April 1990, Lewis was following a strongly poleward-oriented track (panel a). Beginning late on 1 April 1990, increasingly strong VWS began to push the CCM of Lewis to the east of the LLC (panel b). Notice that the low sun-angle highlights how shallow the LLC of Lewis is compared to the CCM, which extends to the tropopause even though Lewis never exceeded minimal tropical storm intensity. Subsequently, Lewis turned onto a westward track as the exposed LLC began to follow the easterly steering equatorward of the 850 mb subtropical ridge.

Useful objective forecasts (and thus official forecasts) of the outcome of a VWS episode are not possible at present, primarily due to an inability to represent accurately the response of convection (and thus the TC wind field) to VWS in numerical TC prediction models. Thus, the TC motion response to VWS can only be nowcast, and forecasters should alert users of TC forecasts that either the recurving or non-recurving scenario can occur, regardless of which option is selected for the official forecast (i.e., promulgate an alternate scenario).


a
TROPICAL STORM LEWIS
APR / MAY 1990
LATITUDE (deg)
LONGITUDE (deg)
25
20
15
10
5
135
140
145
150
155
6
5
4
3
2
1
30
29
28


b
PAGAN
GUAM
LEWIS

TC-ENVIRONMENT TRANSFORMATIONS

Topic: INDIRECT TC INTERACTION ON EASTERN TC (ITIE)

An Indirect TC Interaction (ITI) involves two TCs with the eastern TC at a lower latitude and separated from the western TC by about 15° long. or more. As indicated in the schematic at right, the western TC in an ITIE scenario has a peripheral anticyclone of significant scale and strength, and appears connected or "linked" to the subtropical ridge (STR) as in a P/PO pattern/region. By contrast, the eastern TC is presently producing a weaker peripheral anticyclone. Although two ITI variations may occur simultaneously, in the ITI-East (or ITIE) variation, the track of the eastern TC may be significantly affected by the peripheral anticyclone of the western TC without the track of the western TC being affected by the presence of the eastern TC. As a result, the significant equatorward steering of the western peripheral anticyclone is able to temporarily turn the eastern TC from the typical WNW direction of motion expected equatorward of the STR to a more westward or even south of west direction of motion. During the period when the eastern TC track is deflected equatorward, an ITIE is said to be occurring.

The duration of ITIE is usually limited to 1-3 days for the following reason. Notice that the southeastward orientation of the western TC, its peripheral anticyclone, the eastern TC, and its peripheral anticyclone have the appearance of the Rossby wave train in barotropic simulations of beta-effect propagation. The frequent formation of an eastern TC in the cyclonic vorticity advection region east of the western TC peripheral anticyclone suggests that the eastern TC formation may be indirectly aided by the western TC. The eastern TC is also frequently observed to expand horizontally with time, presumably due to the same cyclonic vorticity tendency. The horizontal growth of the eastern TC results in a concurrent amplification of its peripheral anticyclone. After several days of amplification of the eastern peripheral anticyclone, the eastern TC will overcome the effect of the western peripheral anticyclone and will turn to an increasingly poleward track. A slow transition to an environment structure of P/PO often, but not always, results.

NOTE: Presently, a TC undergoing ITIE is classified in a S/DR environment since it is equatorward of, and thus is dominated by, the eastern STR circulation (albeit a strongly sloping one). Thus, the transition mechanism ITIE does not technically cause a pattern/region transition even though a significant track change can result.

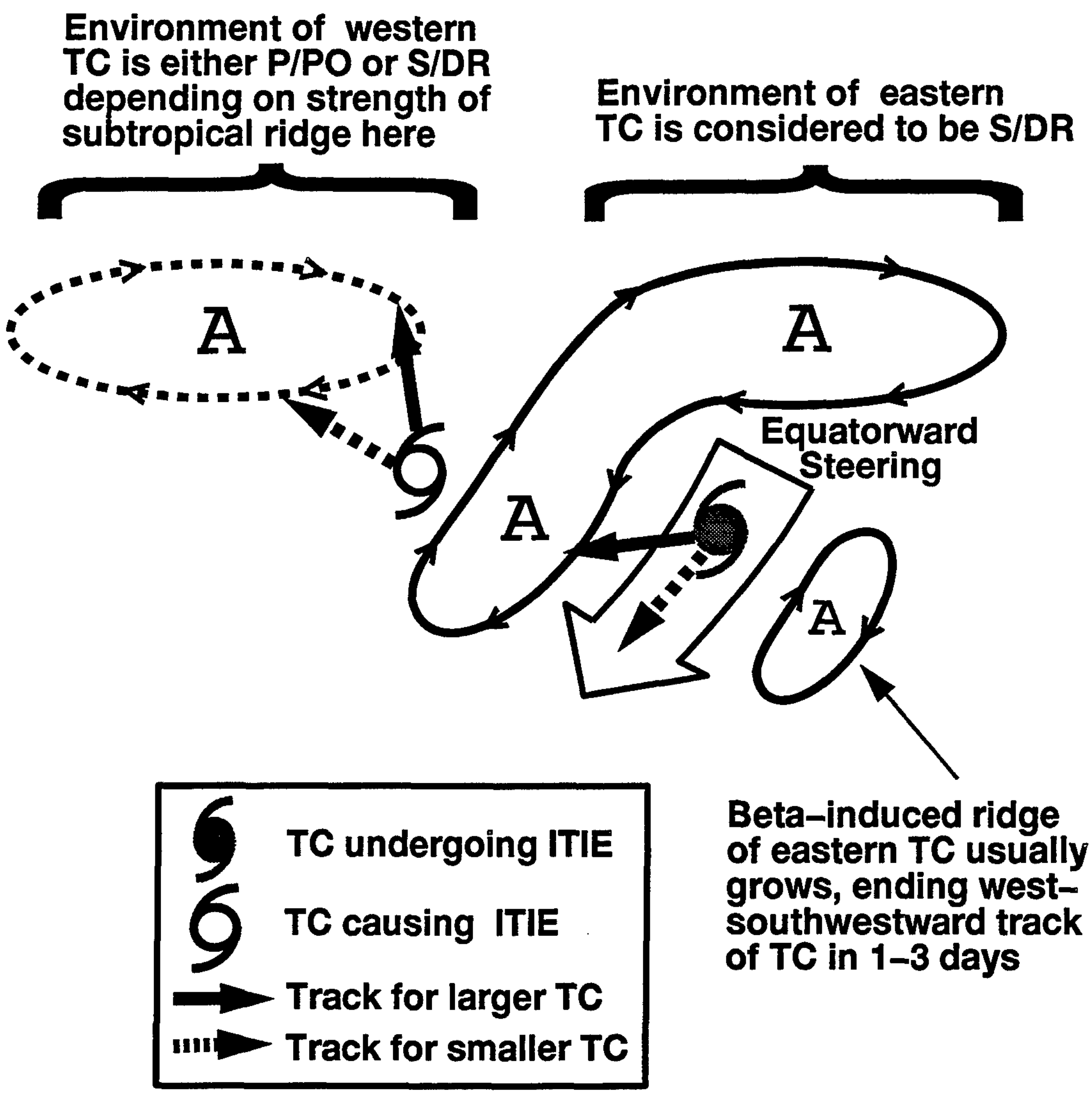
Cross-reference:

Beta-Effect Propagation, Peripheral anticyclone p. 57

Poleward (P) Pattern p. 29

Standard (S) Pattern p. 19

INDIRECT TC INTERACTION *ON* EASTERN TC (ITIE) CONCEPTUAL MODEL



TC-ENVIRONMENT TRANSFORMATIONS

Topic: INDIRECT TC INTERACTION ON EASTERN TC (ITIE) (cont)

MUTUAL ROTATION CHARACTERISTICS

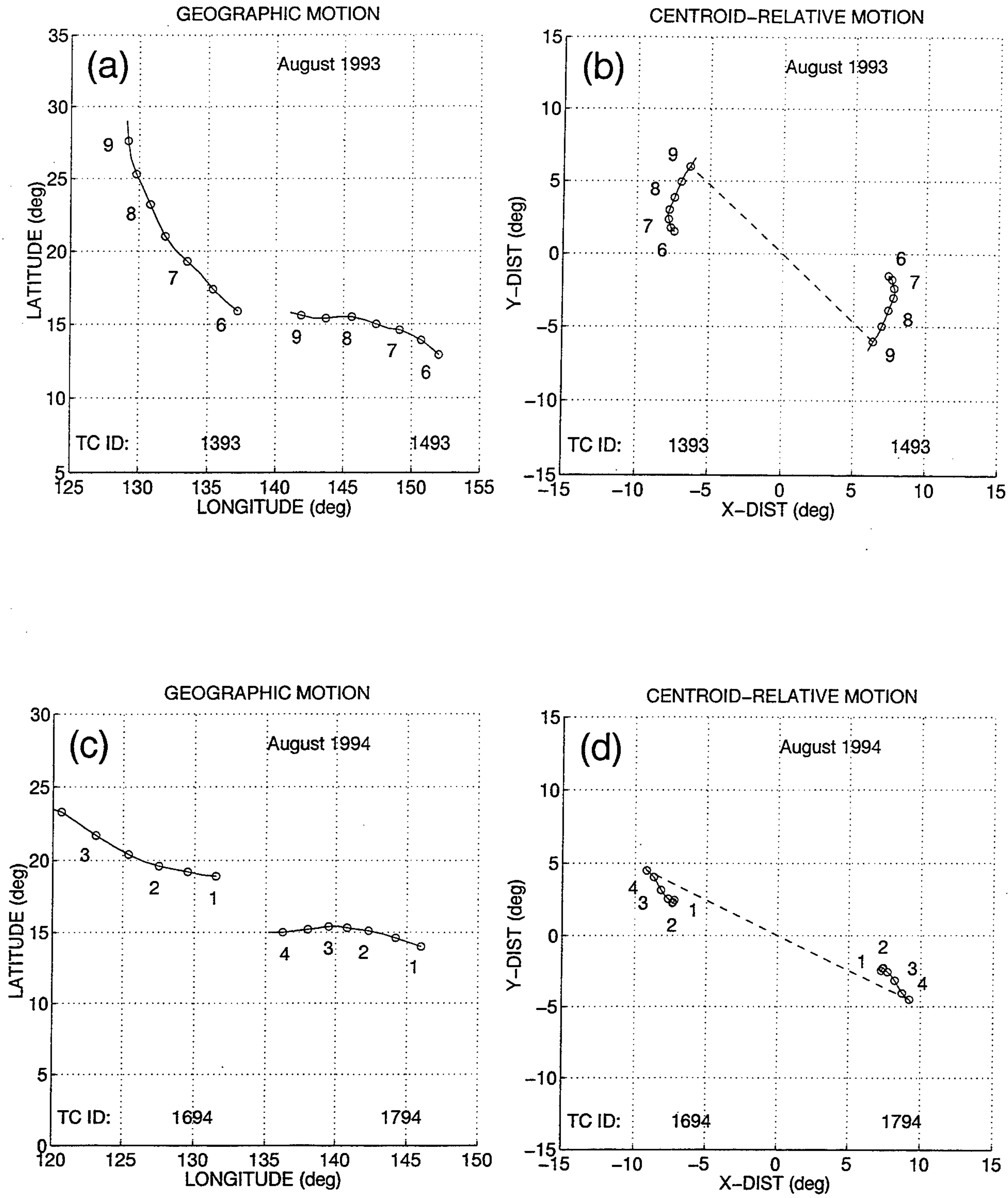
A relative rotation diagram has often been used to describe the Fujiwhara-type cyclonic rotation of a binary TC interaction. Even though the midpoint (centroid) between the two TCs should only be used if the two TCs are the same size, this midpoint is often used for convenience even when different size TCs are involved. For this case of ITIE, the purpose of the relative motion diagram is to emphasize that an apparent anticyclonic rotation will occur.

In a centroid-relative motion diagram, the onset of ITIE will normally be manifest as a change from negligible or weak cyclonic rotation to persistent anticyclonic rotation. The angular rotation rate will normally be greater than 1.0 degree per 6 hours. The separation distance may either increase, decrease, or remain about the same depending on the relative translation speeds of the two TCs.

Comparisons of the geographic motion and centroid-relative motion for a number of pairs of TCs are shown at right during the periods in which ITIE occurs.

Cross-reference:

Direct TC Interaction (DTI) p. 103


GEOGRAPHIC MOTION
(a)
August 1993
LATITUDE (deg)
LONGITUDE (deg)
TC ID:
1393
1493
CENTROID-RELATIVE MOTION
(b)
August 1993
Y-DIST (deg)
X-DIST (deg)
TC ID:
1393
1493
GEOGRAPHIC MOTION
(c)
August 1994
LATITUDE (deg)
LONGITUDE (deg)
TC ID:
1694
1794
CENTROID-RELATIVE MOTION
(d)
August 1994
Y-DIST (deg)
X-DIST (deg)
TC ID:
1694
1794

TC-ENVIRONMENT TRANSFORMATIONS

Topic: INDIRECT TC INTERACTION ON WESTERN TC (ITIW)

DESCRIPTION

In the ITI-West (or ITIW), the expected poleward deflection of the western TC may be significantly reduced via modification (damping) of the peripheral anticyclone by the eastern TC, even though the track of the eastern TC may not be affected by the presence of the western TC. As indicated in the schematic at right, the peripheral anticyclone of the western TC in the ITIW scenario is being eroded and "separated" from the subtropical ridge (STR) by the cyclonic vorticity advection associated with the presence of the eastern TC, which is (or is growing into) a large cyclonic circulation as implied by the large size of its peripheral anticyclone. A significant poleward displacement of the eastern TC further separates the western TC peripheral anticyclone from the STR. Two possible ITIW consequences are:

(1) if the western TC has previously been in a P/PO pattern/region, and thus had a strongly poleward track, then the influence of the eastern TC can cause a significant decrease in the poleward steeering such that the western TC may turn onto a primarily westward track, which represents a transition to S/DR.

(2) if the western TC has been in a S/DR environment, then any tendency for development of a poleward steering flow associated with the western TC peripheral anticyclone precludes the possibility of a transition to P/PO while ITIW is taking place.

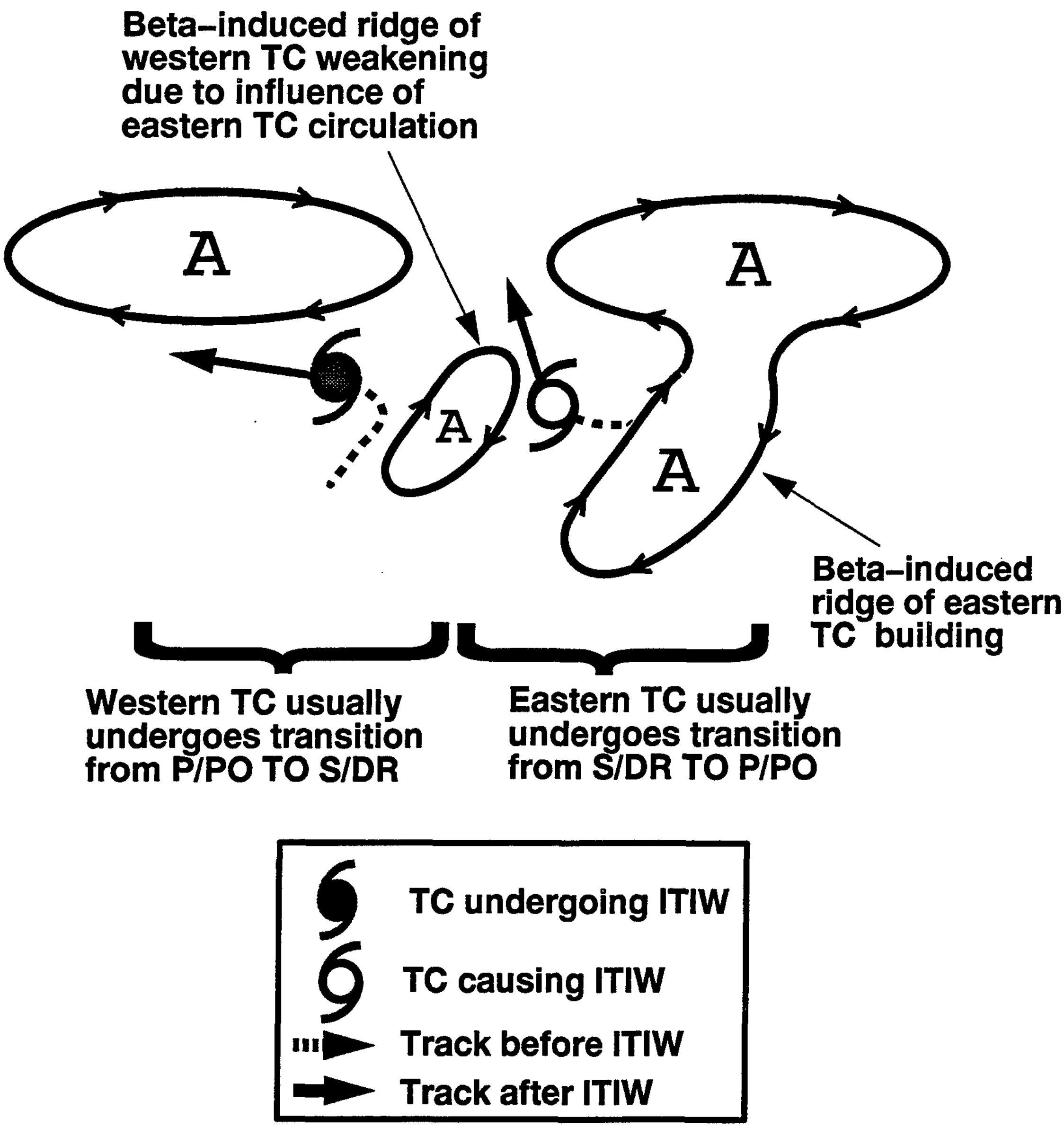
Cross-references:

Beta-Effect Propagation, Peripheral anticyclone p. 57

Poleward (P) Pattern p. 29

Standard (S) Pattern p. 19

INDIRECT TC INTERACTION *ON* WESTERN TC (ITIW) CONCEPTUAL MODEL



Topic: INDIRECT TC INTERACTION ON WESTERN TC (ITIW) (cont)

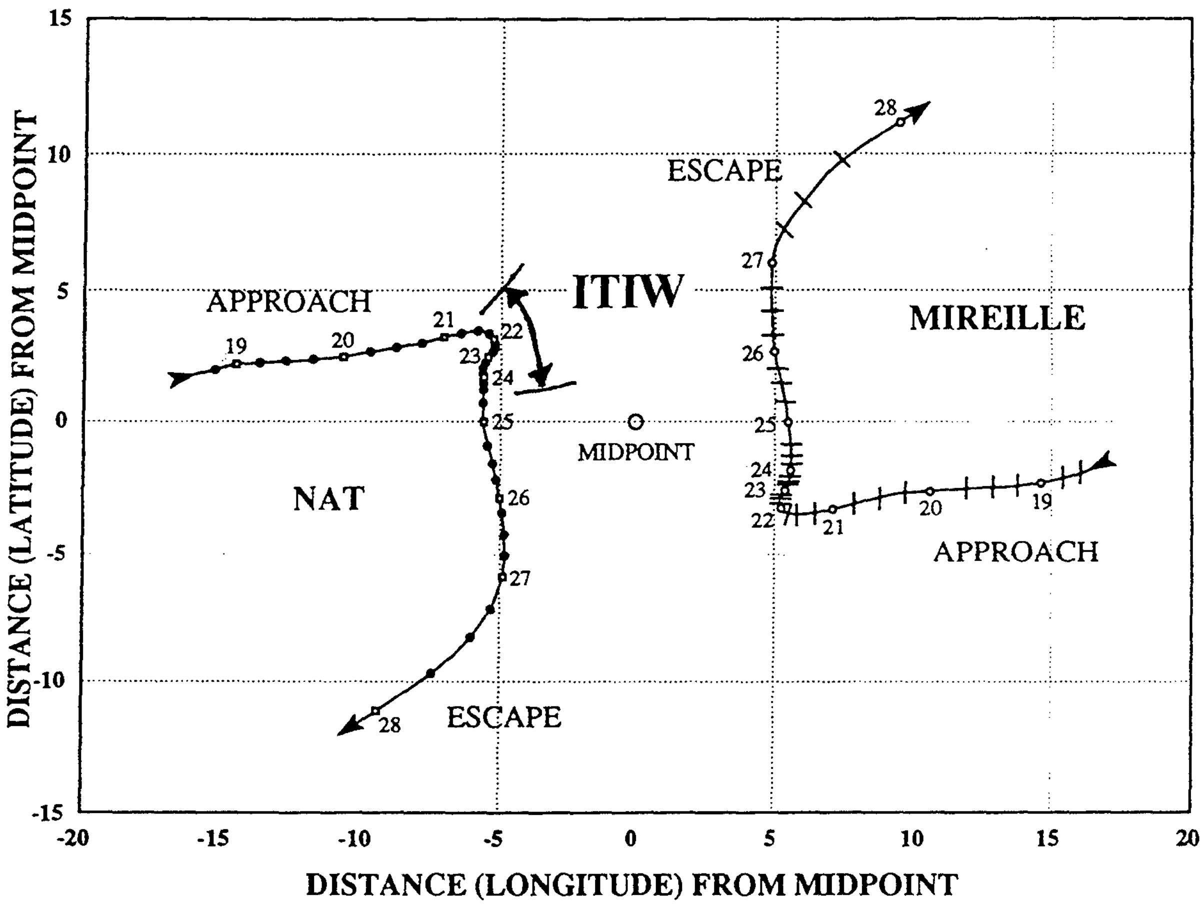
MUTUAL ROTATION CHARACTERISTICS

In a centroid-relative motion diagram, the onset of ITIW will normally be manifest as a change from negligible or weak anticyclonic rotation to persistent, but weak cyclonic rotation. The angular rotation rate will normally be greater than 1.0 degree per 6 hours. The separation distance may either increase, decrease, or remain about the same depending on the relative translation speeds of the two TCs.

For the Nat and Mireille case shown at right, the onset on ITIW is at about 1200 21 September 1991 when the TCs begin a slow cyclonic relative rotation. Notice that the cyclonic relative rotation rate significantly increases at about 1200 UTC 24 September 1991, which is a period of Direct TC Interaction (DTI) because the circulation of Mireille has grown to sufficient size to capture Nat. This period of one-way DTI continues until about 0000 UTC 27 September 1991 when Mireille begins to enter the midlatitude westerlies (MW region).

Cross-reference:

Direct TC Interaction p. 103


ITIW
APPROACH
ESCAPE
NAT
MIREILLE
MIDPOINT
DISTANCE (LATITUDE) FROM MIDPOINT
DISTANCE (LONGITUDE) FROM MIDPOINT
15
10
5
0
-5
-10
-15
-20
-15
-10
-5
0
5
10
15
20

Topic: INDIRECT TC INTERACTION (ITI) (cont)

ITIE AND ITIW SCENARIO ILLUSTRATION

The NOGAPS analysis series at right illustrates a period with both ITIE and ITIW that involves Tropical Storm Luke (20W), Super Typhoon Mireille (21W), and Typhoon Nat (22W) during the period 16-23 September 1991. Tracks of Luke, Mireille, and Nat are given on pages A-9, A-10, and A-11, respectively. Note the following from the analysis series:

(1) The development of the large peripheral anticyclone southeast of Luke (middle TC) on 17 September (panel b) starts steering Mirielle (eastern TC) onto a west-southwestward track, which is an example of ITIE affecting Mireille. Notice that the peripheral anticyclone generated by Luke lingers after Luke recurves and thus is still affecting Mireille on 19 September (panel d).

(2) On 20 September (panel e), the cyclonic vorticity advection northwest of Mireille (eastern TC) begins to erode and separate from the STR the peripheral anticyclone (from Luke) between Mireille and Nat (western TC). Until this time, that peripheral anticylone had been advecting Nat toward the east-northeast.

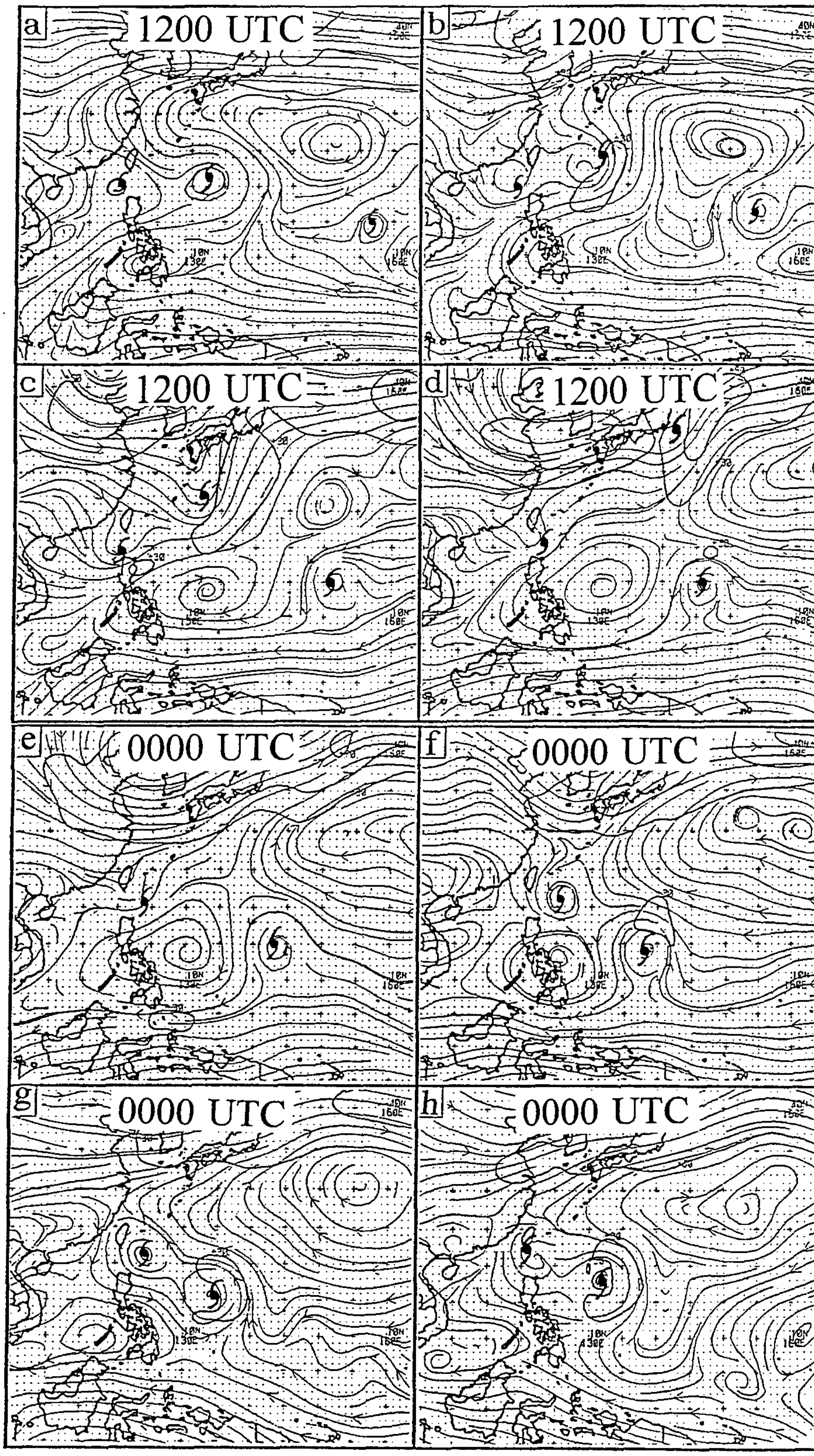
(3) By 21 September (panel f), cyclonic vorticity advection northwest of Mireille has succeeded in sufficiently eroding and separating from the STR the peripheral anticyclone that had been steering Nat. Nat now makes a sharp turn onto a westward heading, which is an example of ITIW that causes the environment of Nat to transition from P/PO to S/DR.

(4) The sizes of Mireille and its peripheral anticyclone may have increased substantially from the 16th (panel a) to the 23rd (panel h) as a result of the cyclogenetic tendency on the southeast side of the peripheral anticyclone generated and left behind by Luke. By the 23rd, the environment of Mireille is in transition to P/PO (i.e., Mireille is turning from a WSW track to a NW track).

Cross-reference:

Poleward (P) pattern p. 29

16 - 23 September 1991



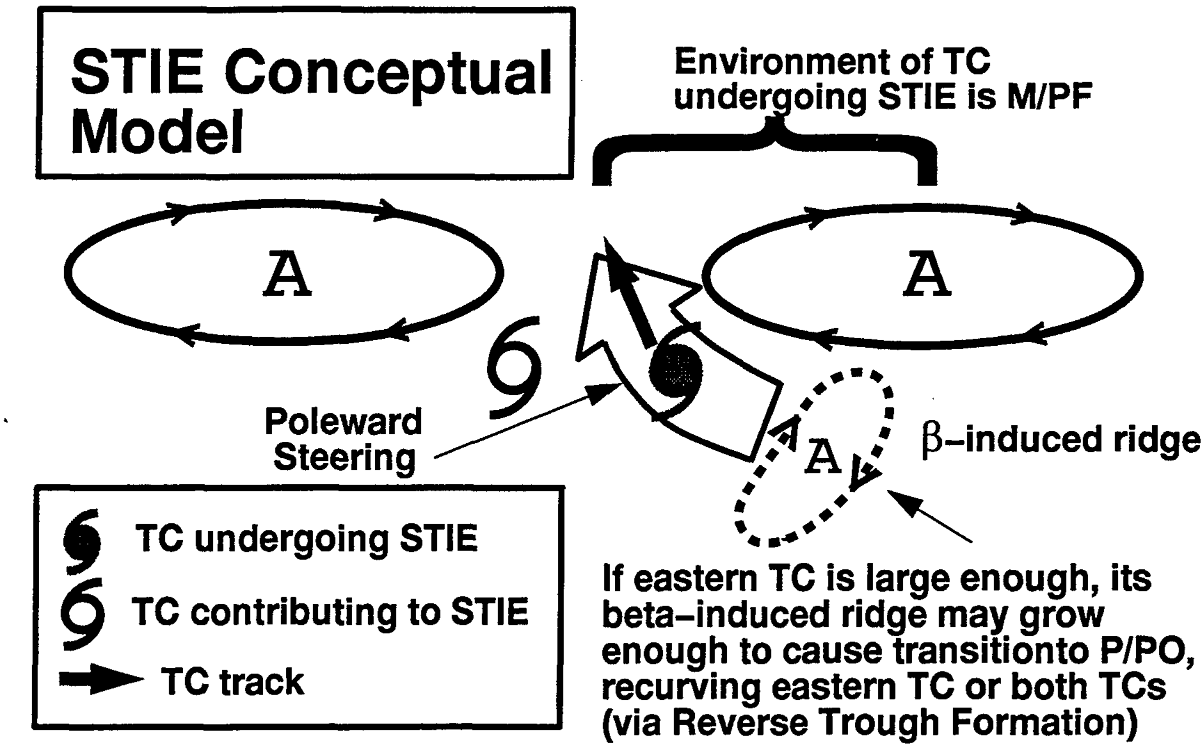
Topic: SEMIDIRECT TC INTERACTION (STI) AND M PATTERN

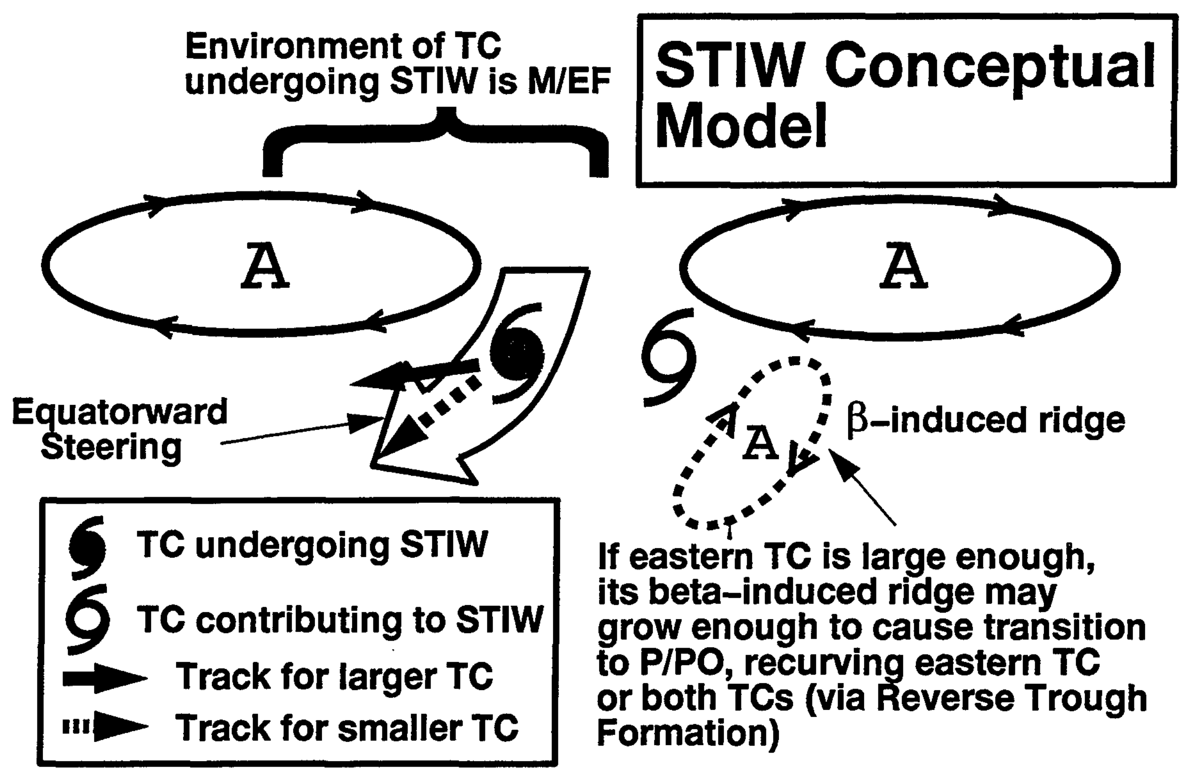
DESCRIPTION

In the Systematic Approach, the formation of a Multiple (M) TC synoptic pattern and the occurrence of Semidirect TC Interaction (STI) are somewhat synonymous. This overlap makes sense since, for the purposes of determining the steering flow affecting the TC of interest, another TC in the vicinity constitutes part of the "environment." When the location of the other TC relative to the TC of interest and the adjacent subtropical anticyclone cells satisfy certain requirements, a M pattern is formed as the TCs interact in a semidirect fashion. Another way to view the connection between the M pattern and STI is that the M pattern is the environment structure that results from the effect of a STI. Thus, the discussion that follows covers both the M pattern and the associated STI transitional mechanism. The eastern TC in the Poleward Flow (PF) region is said to be experiencing Semidirect TC interaction -- East (STIE), and the western TC in the Equatorward Flow (EF) region is said to be experiencing STI--West (STIW).

Cross-reference:

Multiple (M) TC Pattern p. 47


STIE Conceptual Model
Environment of TC undergoing STIE is M/PF
A
A
Poleward Steering
A
β-induced ridge
TC undergoing STIE
TC contributing to STIE
TC track
If eastern TC is large enough, its beta-induced ridge may grow enough to cause transitionto P/PO, recurving eastern TC or both TCs (via Reverse Trough Formation)


Environment of TC undergoing STIW is M/EF
STIW Conceptual Model
A
A
Equatorward Steering
A
β-induced ridge
TC undergoing STIW
TC contributing to STIW
Track for larger TC
Track for smaller TC
If eastern TC is large enough, its beta-induced ridge may grow enough to cause transition to P/PO, recurving eastern TC or both TCs (via Reverse Trough Formation)

TC-ENVIRONMENT TRANSFORMATIONS

Topic: SEMI-DIRECT TC INTERACTION (STI) AND M PATTERN

MUTUAL ROTATION CHARACTERISTICS

In a centroid-relative motion diagram, the onset of either STIE or STIW (which can occur simultaneously) will normally be manifest as a change from negligible or weak anticyclonic rotation to persistent, and moderate cyclonic rotation. The angular rotation rate will normally be from about 1.5 to 5.0 degrees per 6 hours. The rotation rate should be in the slower portion of this range if only STIE or only STIW (i.e., not both) is occurring. The separation distance usually remains about the same during the period of STI, and is greater than the typical 10°-12° lat. limit for Direct TC Interaction (DTI).

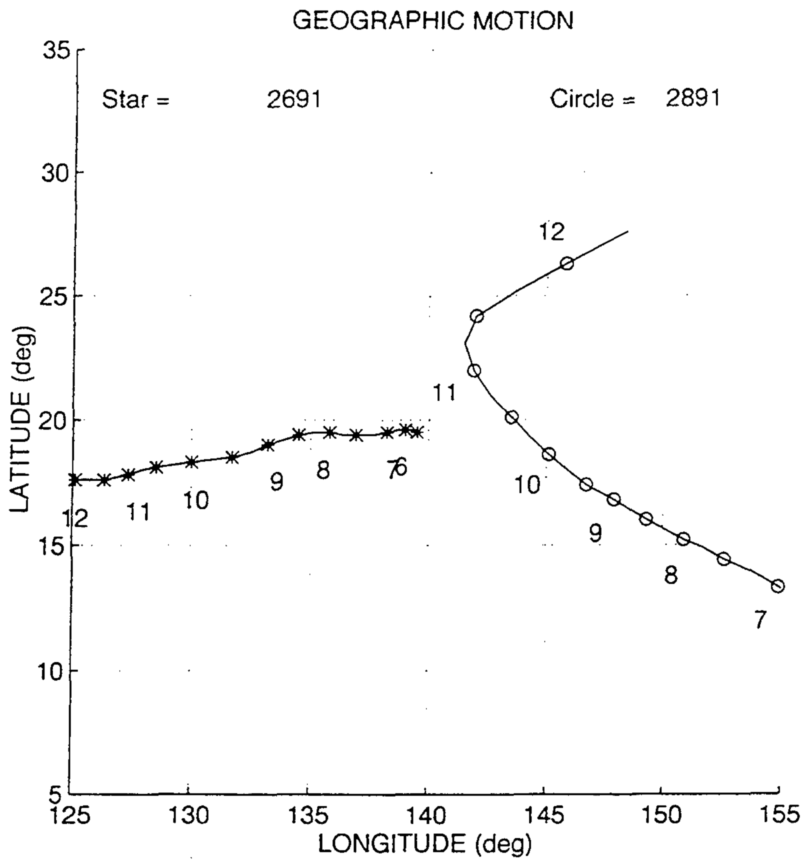
Comparison of the geographic motion and the centroid-relative motion for a pair of TCs is shown at right for the period in which STI occurs.

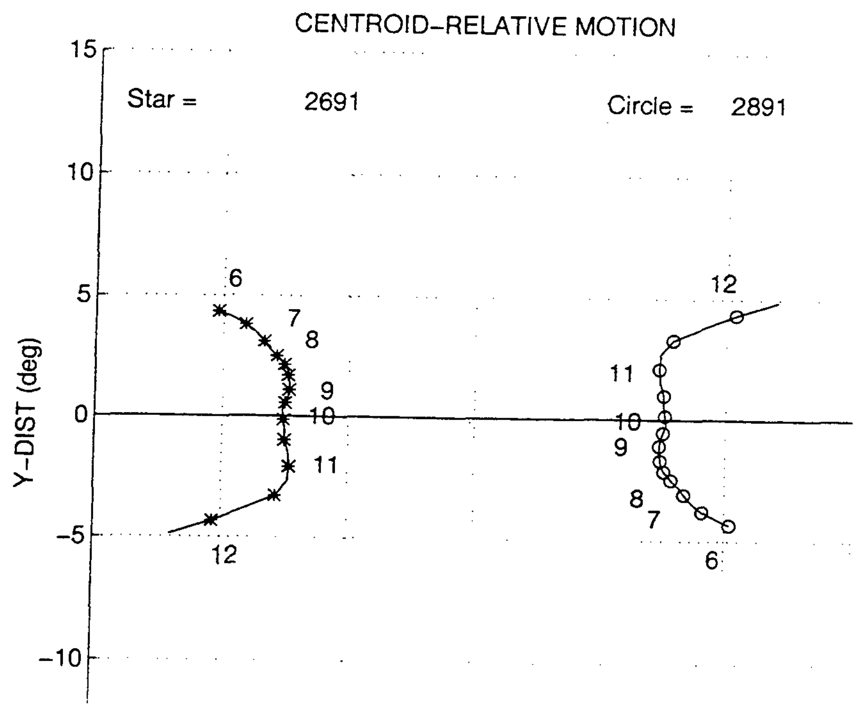
Cross-references:

Multiple (M) TC Pattern p. 47

Indirect TC Interaction on Eastern TC, Mutual Rotation Characteristics p. 89

Direct TC Interaction p. 103


GEOGRAPHIC MOTION
Star = 2691
Circle = 2891
LATITUDE (deg)
LONGITUDE (deg)
35
30
25
20
15
10
5
125
130
135
140
145
150
155
12
11
10
9
8
7
6


CENTROID-RELATIVE MOTION
Star = 2691
Circle = 2891
Y-DIST (deg)
15
10
5
0
-5
-10
6
7
8
9
10
11
12

Topic: SEMI-DIRECT TC INTERACTION (STI) AND M PATTERN (cont)

STI AND M PATTERN SCENARIO ILLUSTRATION

The NOGAPS analysis series at right illustrates a semi-direct TC interaction (STI) between Super Typhoon Seth (26W) and Tropical Storm Verne (28W) during November 1991. The tracks are on page A-12. Notice the following:

- at 0000 UTC 6 November (panel a), Seth (western TC) is at the ridge axis in a Standard/ Weakened Ridge (S/WR) pattern/region and is about to recurve (note isotach wrapped around to the south).

- by 0000 UTC 7 November (panel b), the circulation of Verne (eastern TC) has protruded into the subtropical ridge (STR) to the north. As a result, the isotach pattern around Seth has changed so that the isotach to the west of Seth is slightly larger, which indicates a weak equatorward flow across Seth. Thus, the environment structure of Seth is transitioning from S/WR to Multiple/Equatorward Flow (M/EF).

- by 0000 UTC 8 November (panel c), the isotach maximum to the west of Seth is clearly larger than the isotach to the east, which indicates that the environment structure has definitely transitioned to M/EF. At this time, Seth is not moving south, but west-southwest, which is presumably due to the northwestward BEP that is partially countering the equatorial steering in the EF region. At this time, Verne is moving northwestward at 9 kt, and thus is overtaking Seth.

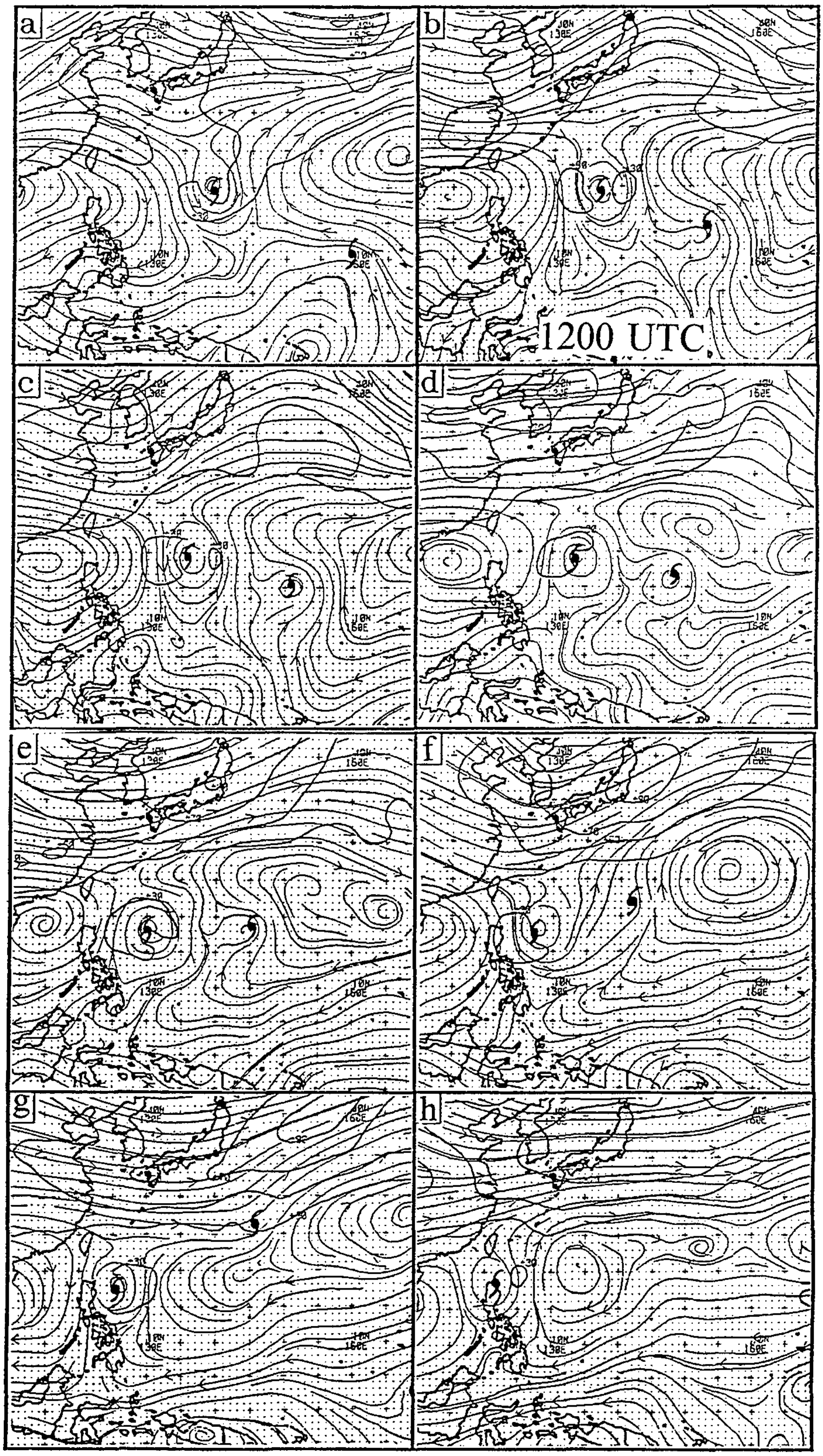
- although the speed of Verne temporarily slows to 6 kt by 0000 UTC 9 November (panel d) due to the passage of a midlatitude ridge to the north (an example of Subtropical Ridge Modulation) the translation speed of Verne over the next two 2 days actually increases to 12 kt as Verne approaches the axis of the STR, which indicates that Verne has been in the M/PF region since sometime on the 8th.

- as Verne recurves and moves away from Seth, the isotach maximum of Seth switches from the west side at 0000 UTC 11 November (panel f) to the east side at 0000 UTC 12 November (panel g), which indicates a transition from M/EF back to S/WR.

Cross-references:

Diagnosing Environment Steering Direction p. 9
Standard (S) Pattern p. 19
Multiple (M) TC Pattern p. 47
Subtropical Ridge Modulation p. 117

6- 13 November 1991 (0000 UTC)



TC-ENVIRONMENT TRANSFORMATIONS

Topic: DIRECT TC INTERACTION (DTI)

DESCRIPTION

As the name implies, Direct TC Interaction (DTI) requires that the cyclonic circulation of one TC overlaps the center of the other TC. Although both Semi-direct TC Interaction (STI) and DTI involve the cyclonic circulations of two TCs, the distinction is that STI "requires" the presence of a neighboring environment circulation (subtropical anticyclone). DTI can occur in the absence of an environmental circulation, because the adjacent TC has become the dominant feature in advecting the other TC.

As illustrated on the right, it is useful to view DTI as having three modes:

(1) One-way Influence (DTI1), in which the circulation of a larger TC advects the circulation of a smaller circulation, but not vice versa (at least the effect of the smaller TC is negligible in a practical sense).

(2) Mutual Interaction (DTI2), in which the circulations of both TCs advect each other, but usually in an asymmetric fashion (i.e., larger TC has more effect on the smaller TC).

(3) Merger (DTI3), in which the circulations not only rotate around each other, but also approach each other with one TC usually dissipating before the merger process is completed.

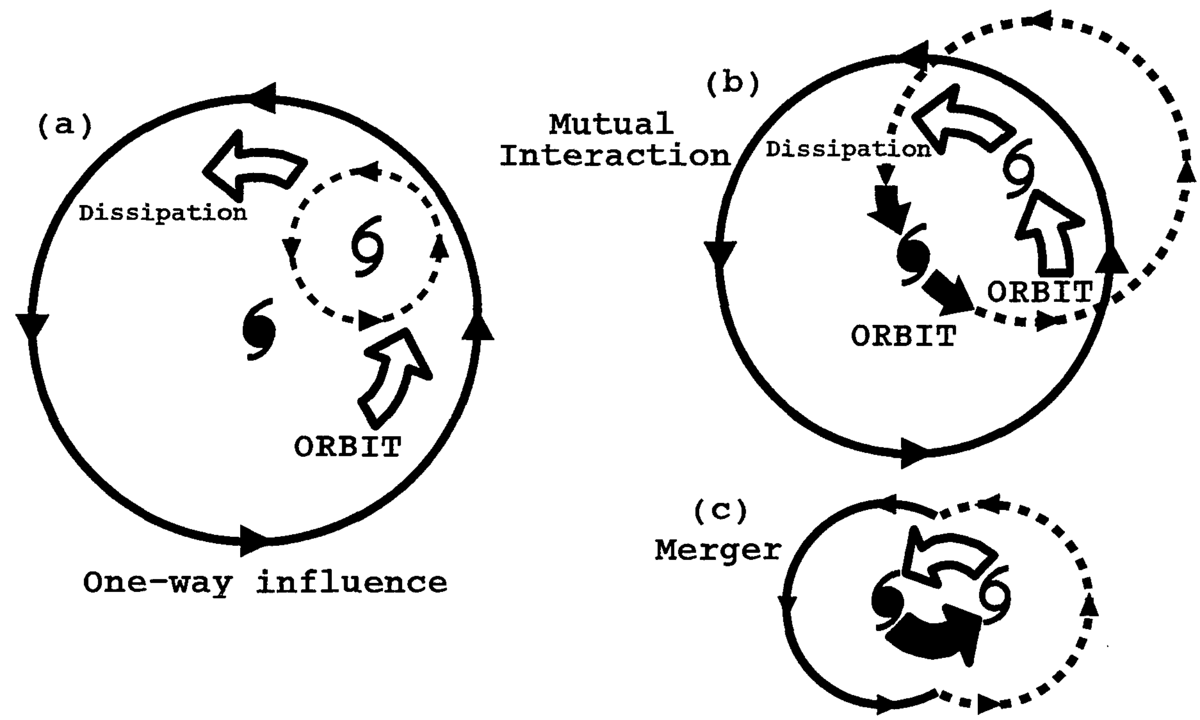
NOTE: Except in very unusual circumstances, DTI only occurs when the separation distance between the TCs is less than about 10-12 deg. lat. (600 - 720 n mi). If a cyclonic rotation is occurring at larger separate distances, then it is likely that either STI or ITIW is taking place.

Cross-references:

Semi-direct TC Interaction (STI) p. 97

Indirect TC Interaction--West (ITIW) p. 91

Maximum separation for DTI is 10-12° (600 n.mi. - 720 n.mi.)



TC-ENVIRONMENT TRANSFORMATIONS

Topic: DIRECT TC INTERACTION (DTI) (cont)

MUTUAL ROTATION CHARACTERISTICS

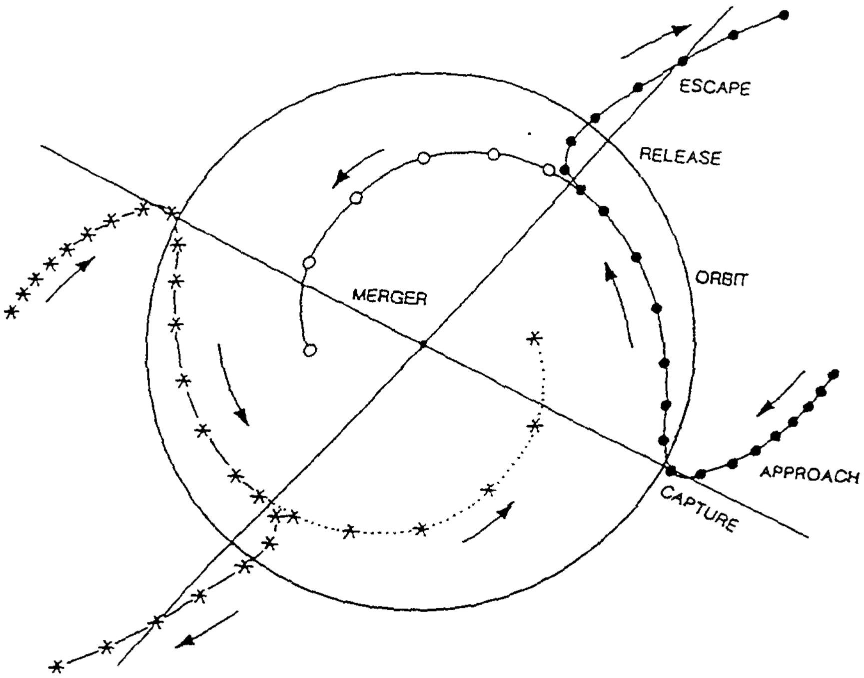
As shown in the hypothetical centroid-relative motion diagram at right the onset of Direct TC Interaction (DTI), which is labeled “capture,” follows a period of approach and begins a period of mutual rotation or “orbit” that has nearly constant separation distance. After rotation through an angle that averages about 100 degrees, one of two things will happen:

(1) one or both TCs "release" the other, and the separation distance begins to increase. By definition, release must occur when the one-way influence (DTI1) is occurring. Release may also occur when a mutual interaction (DTI2) is taking place; or

(2) merger (DTI3) begins, which usually "does not" proceed to zero separation distance because the two cloud systems become indistinguishable.

Dissipation of a smaller TC may occur in any of the three modes of DTI, because the horizontal and vertical shear of the larger TC may disperse or disrupt the warm core structure of the smaller TC.

DIRECT TC INTERACTION (DTI)



Topic: DIRECT TC INTERACTION (DTI) (cont)

MUTUAL ROTATION CHARACTERISTICS (cont)

In a centroid-relative motion diagram, the onset of a Direct TC Interaction (DTI) will normally be manifest as a change from negligible or weak anticyclonic rotation to persistent and significant cyclonic rotation.

During one-way influence (DTI1), or mutual interaction (DTI2), the rotation rate will normally be about 5 to 12 degrees per 6 hours, and the separation distance usually changes slowly.

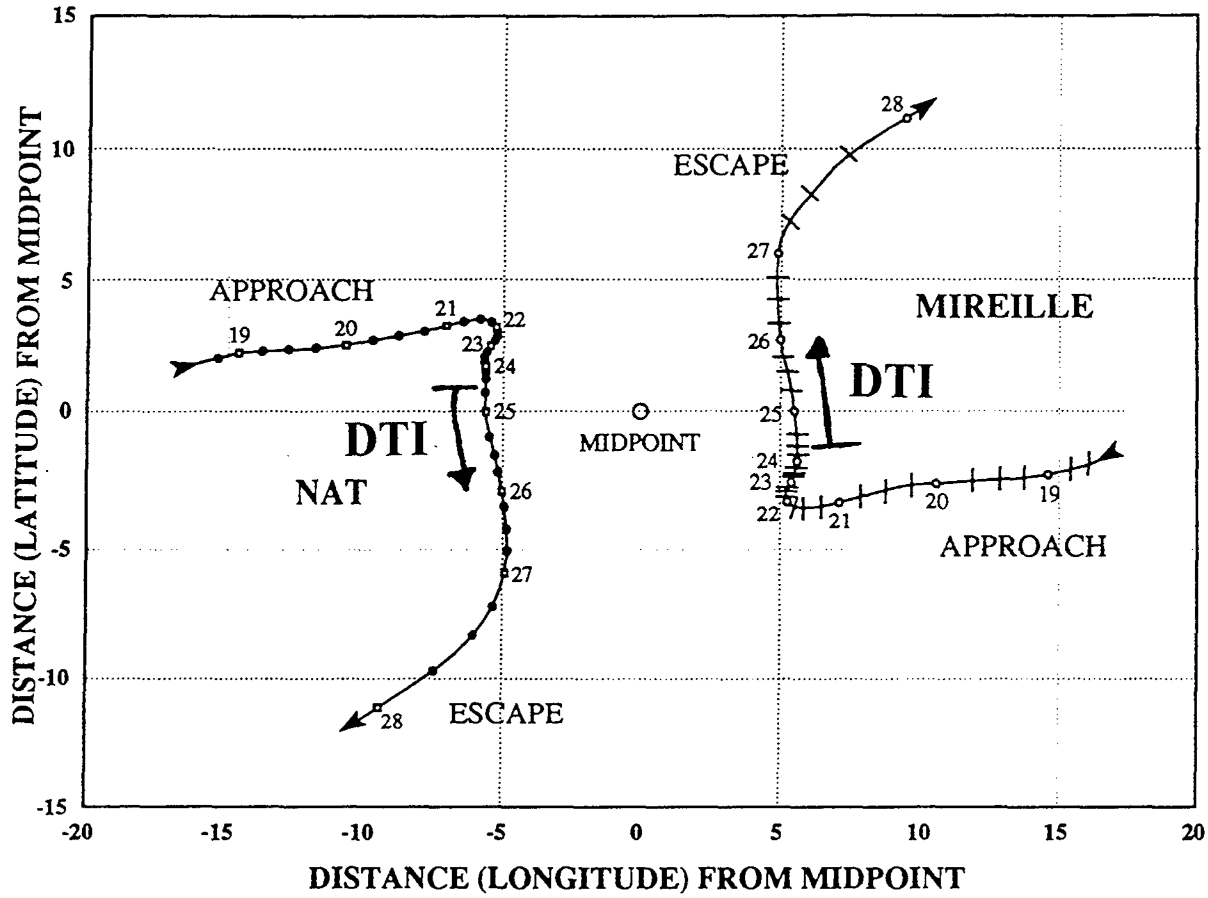
The onset of the merger mode (DTI3) is manifest as an accelerating increase in the rotation rate above about 12 degrees per 6 hours with an increasing rate of separation distance reduction.

Comparisons of the centroid-relative motion for two pairs of TCs are shown at right for the periods in which DTI occurs. For the Mireille and Nat case, the onset on DTI1 occurs at about 1200 UTC 24 September 1991 when the cyclonic rotation rate shows a distinct increase. Prior to that time, the slow cyclonic rotation rate is mainly due to Nat experiencing ITIW from Mireille.

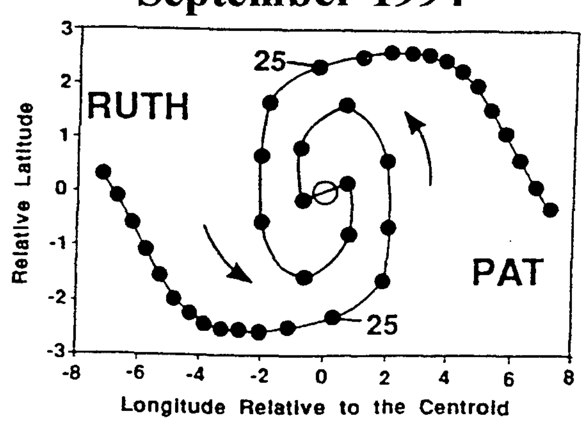
Cross-reference:

Indirect TC Interaction--West (ITIW) p. 91

September 1991



September 1994



Topic: DIRECT TC INTERACTION (DTI) (cont)

DTI SCENARIO ILLUSTRATION (ONE-WAY INFLUENCE)

The NOGAPS analyses on p. 110 illustrate a one-way influence DTI between the Typhoon Nat (22W) to the east and Supertyphoon Mireille (21W) to the west during 24-27 September 1991. Recall that these tracks are on pages A-11 and A-10, respectively. Notice the following:

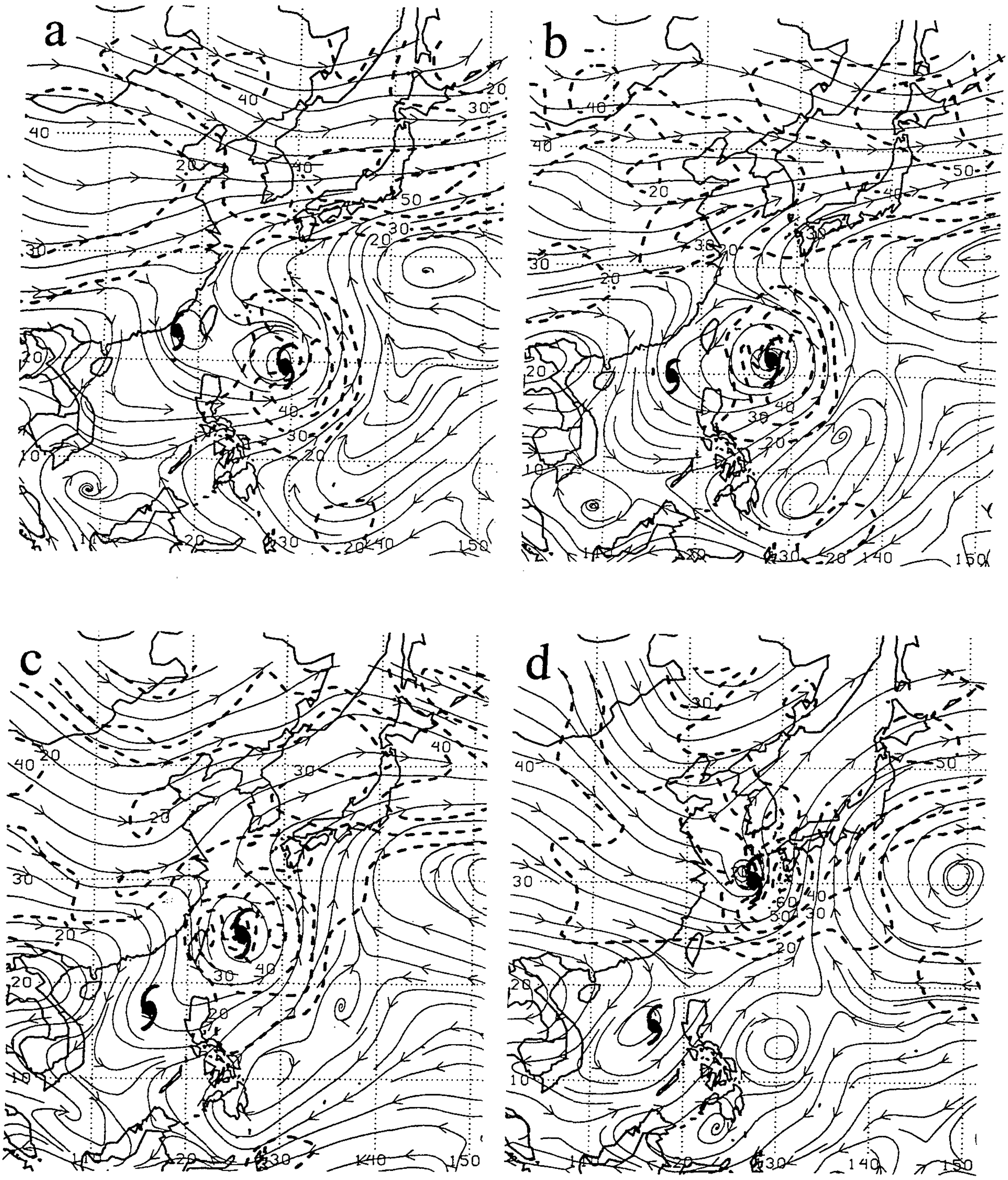
- at 0000 UTC 24 September (panel a), which is just before Nat turns south under the influence of Mireille, the NOGAPS analyses represents Nat as a closed circulation that is much smaller than Mireille. The sizes of the TC cloud signatures in the satellite imagery (not shown) also indicate that Nat (Mireille) was smaller (larger) than average.

- during the one-way DTI on 25 and 26 September (panels b and c), Nat no longer appears as a closed circulation at 500 mb, but rather as a region of troughing that rotates around Mireille. This appearance is typical in operational global numerical models when one TC is much smaller and weaker (Nat) than the other (Mireille).

- at 0000 UTC 27 September (panel d), which is after the period of one-way interaction has ended, the NOGAPS analysis again represents Nat as a closed circulation.

The result of the one-way influence on the smaller Nat is to cause an anomalous southward deflection. Little (or no) influence of the circulation of Nat on the larger Mireille is evident.

24 - 27 September 1991 (0000 UTC)



Topic: DIRECT TC INTERACTION (DTI) (cont)

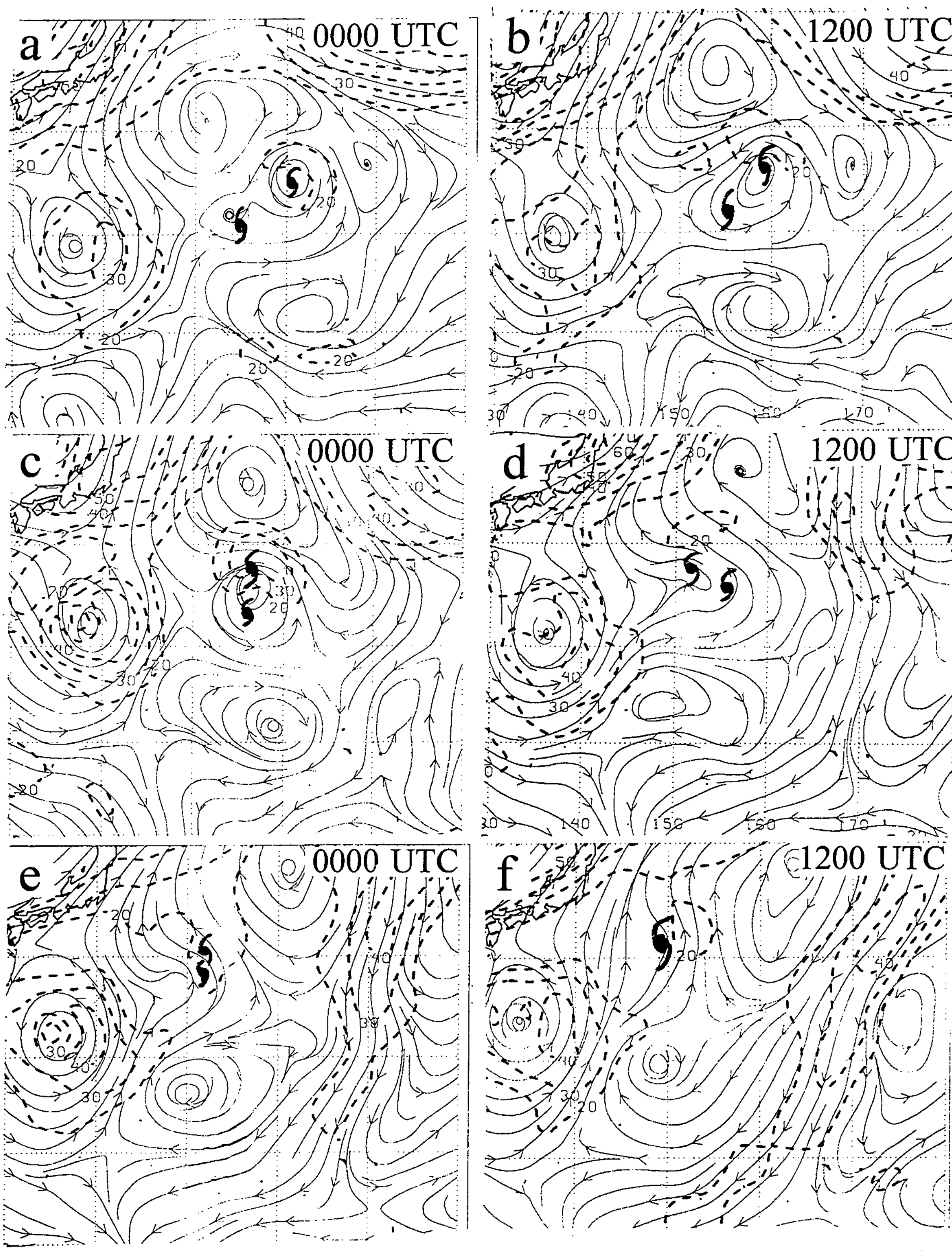
SCENARIO ILLUSTRATION (MERGER)

The NOGAPS analysis series at right illustrates a DTI merger occurring between the eastern Typhoon Pat (29W) and the western Tropical Storm Ruth (30W) during September 1994. These tracks are on page A-13. A large TY Orchid also was present to the west. Notice the following:

- only at 0000 UTC 24 September (panel a) does the NOGAPS analysis resolve the two TCs as distinct cyclones at 500 mb. This inability to resolve separate cyclones was also true in the surface pressure analyses, as 29W did not appear as a closed circulation (at least in the 2.5° lat./long. fields). By contrast, 29W remains a clearly separate cyclone in satellite imagery (not shown) to about 0600 UTC 26 September, or about 6 hours prior to merger. The actual sequence of positions is indicated by the two dots. The basic orientation of the two TCs in the NOGAPS analyses is resolved until 1200 UTC 25 September (panel d).

- by 1200 UTC 26 September (panel f), the NOGAPS analysis of the large Typhoon Orchid (28W) to the west does not resolve a closed 500 mb circulation for merged Pat/Ruth, even though the satellite imagery clearly shows such a separate circulation.

24 - 26 September 1994



Topic: TC-INTERACTION (TCI) FREQUENCY

A total of 279 TCs occurred during 1989-1996. Notice that only ten cases of one-way influence Direct TC Interaction (DTI1) occurred in the eight years. Mutual interaction (DTI2) is even more rare at about one occurrence every two years. However, all three of these cases resulted in a merger (DTI3).

The Semidirect TC Interaction (STI) is more common, in part because the two TCs do not have to be so close together. However, other special criteria of the Multiple (M) TC pattern have to be satisfied. During this eight-year period, the track of an eastern TC was influenced 15 times (STIE) and a western TC track was affected 16 times (STIW).

An Indirect TC Interaction (ITI) can occur at even larger separation distances, and thus is the most common TCI. The western TC track was changed (ITIW) in 40 cases during the eight years. The eastern TC was modified (ITIE) in 27 cases. Considering a total of 114 cases of all types of TCI were observed for 279 TCs, this phenomenon needs to be recognized, especially the ITI and STI events.

Cross-references:

Direct TC Interaction (DTI) p. 103

Semidirect TC Interaction (STI) p. 97

Indirect TC Interaction (ITI) p. 87

TC INTERACTION OCCURRENCES

(1989-1996)
(Out of 279 TCs)

MODE OF TC INTERACTION	MODE SUB-CATEGORY	NUMBER OF CASES & (YEARLY FREQUENCY)
DIRECT (DTI)	ONE-WAY MUTUAL [MERGER]	10 (1.2) 3 (0.4) [3] (0.4)
SEMI-DIRECT (STI)	EASTERN WESTERN	15 (1.9) 16 (2.0)
INDIRECT (ITI)	EASTERN WESTERN	27 (3.4) 40 (5.0)
ALL MODES OF TC INTERACTION		114 (14.3)
REVERSE TROUGH FORMATION (RTF)		8 (1.0)

ENVIRONMENT EFFECTS

Topic: SUBTROPICAL RIDGE MODULATION (SRM)

DESCRIPTION

The concept of Subtropical Ridge Modulation (SRM) stems from the traditional idea that migrating mid-latitude troughs can introduce breaks (i.e., cols) (see panel a) in the subtropical ridge (STR) through which a TC may recurve if the relative movement of the TC and trough bring the TC sufficiently close to the STR break. If the timing is not correct, the TC may have a "stair-step" track and return to a westward (or west-southwestward) track after approaching the STR break.

The SRM conceptual model expands this idea and views the mid-latitude trough as just one component of a wave of alternating troughs and ridges (panel a) that have a modulating effect on the structure of the STR. Depending on the amplitude and phase, the

- mid-latitude trough tends to introduce weaknesses or breaks (cols) in the STR to the south; or
- mid-latitude ridge tend to increase the strength of the STR to the south.

The STR weakening due to mid-latitude "T"roughs and STR strengthening due to "R"idges will be referred to as SRMT and SRMR, respectively.

Mid-latitude trough and ridges usually migrate eastward at significant speeds, and also can undergo significant changes in amplitude. As a rule, rapid eastward translation is associated with small or moderate wave amplitude, and slow eastward, quasi-stationary, or slow westward movement is associated with large mid-latitude wave amplitude.

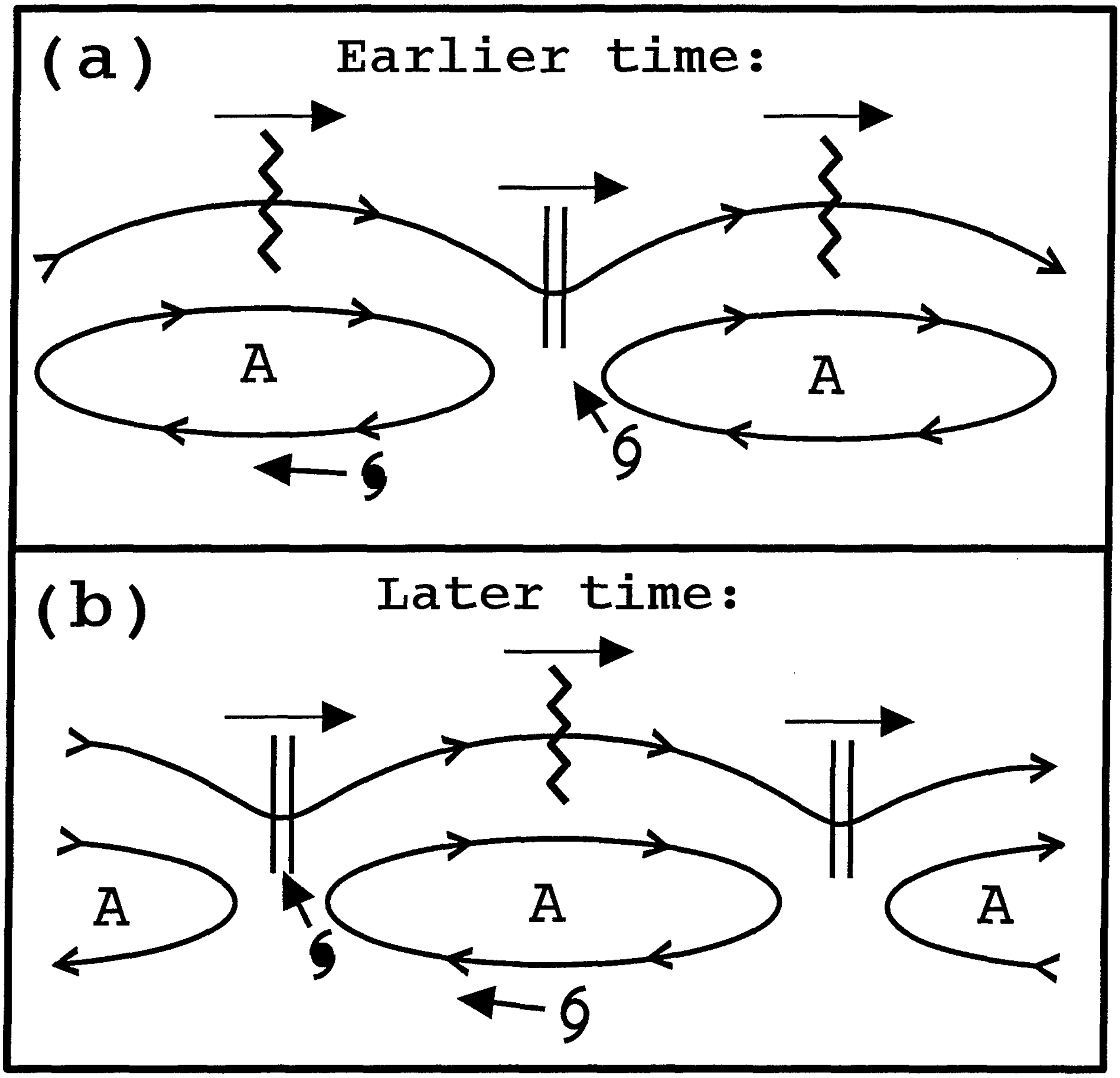
Given the above general information, events of SRM may be viewed as some combination of the following two idealized conceptual models:

WEAK TO MODERATE SRM. This is scenario (a) to (b) at right, in which an eastward-moving troughs and ridges of moderate and constant amplitude induce a decrease (i.e., SRMT) or an increase (i.e., SRMR) in STR strength, respectively. In the example, the mid-latitude wave has moved sufficiently (90 deg. in phase) to reverse the effect of the mid-latitude wave on the STR at any location (i.e., strengthened areas replaced by weakened areas and vice versa), which would affect the track of TCs as shown (i.e., west TC makes poleward turn; east TC makes equatorward turn). Notice that the TC-environment structure (i.e., Standard (S) in this illustration) may remain unchanged in the presence of moderate SRM.

Cross-reference:

Standard (S) Pattern p. 19

Moderate Subtropical Ridge
Modulation (SRM) by Moving
Midlatitude Trough/Ridge System



Topic: SUBTROPICAL RIDGE MODULATION (SRM) (cont)

DESCRIPTION (cont)

STRONG TO EXTREME SRM. This is scenario (a) - (b) at right, in which a mid-latitude wave with moderate amplitude troughs and ridges amplifies significantly, but without significant translation. Although existing areas of decreased (i.e., due to SRMT) or increased (i.e., due to SRMR) STR strength remain in the same general location, the overall structure of the STR is altered significantly. Large breaks, and even cut-off cyclones, may be introduced between the STR cells which are more circular (vice the zonal orientation characteristic of a S Pattern) with a considerable meridional extent. If the amplitude of the mid-latitude wave (i.e., the degree of SRM) is large enough, the TC environment can change from Standard (S) to Poleward (P), as in the case of the western TC in the figures on the opposite page.

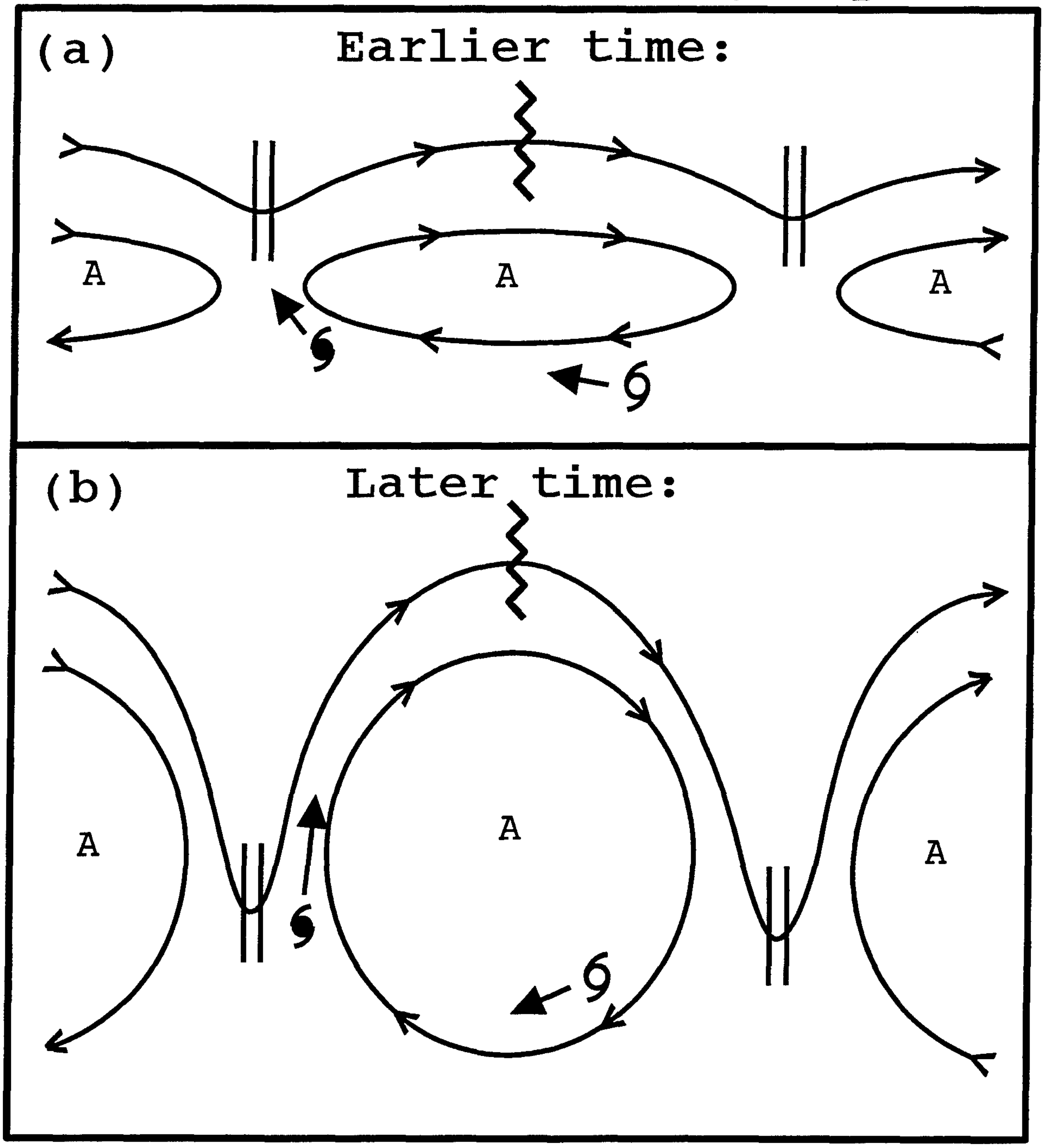
NOTE: Extreme SRM that results in the generation of large cut-off lows in the subtropics and tropics, and changes in synoptic pattern classification, is a regular occurrence in the eastern North Pacific and North Atlantic basins. By constrast, extreme SRM is rather infrequent in the western North Pacific, presumably due to the stabilizing influence of the strong thermal high over Southeast Asia that extends eastward into the Pacific. Nevertheless, extreme SRM does occasionally occur in the western North Pacific, and the forecaster must be aware of such a scenario and the associated large TC track changes (see following pages).

Cross-references:

Standard (S) Pattern p. 19

Poleward (P) Pattern p. 29

Strong Subtropical Ridge Modulation (SRM) by Building Midlatitude Trough/Ridge System



Topic: SUBTROPICAL RIDGE MODULATION (SRM) (cont)

WEAK/MODERATE SRM SCENARIO

Because mid-latitude waves are nearly always present, SRM frequently influences TC motion in minor ways, or contributes to secondary or significant track changes in conjunction with other transitional mechanisms such as BEP, RMT, etc.

Examples of weak/moderate SRM have been present in several of the NOGAPS analysis series used previously to illustrate other components of the Systematic Approach knowledge base:

- S/DR-S/WR TRANSITION (p. 28) Here a mid-latitude trough activity creates and maintains a break in the STR (SRMT) east of Taiwan that Typhoon Hattie moves into (due to the influence of Beta-Effect Propagation), which contributes to Hattie's subsequent recurvature.

- RMT SCENARIO ILLUSTRATION (p. 72). Here the passage of a mid-latitude trough during 11-12 May 1994 creates a weakness (SRMT) in the STR east of Taiwan. Despite the passage of a weak mid-latitude ridge (SRMR) that strengthens the STR during 13-14 May, the thin meridional extent of the STR seems to be a favorable factor to the RMT-induced S-to-P pattern transition by Page, which is only an average size TC.

- STI SCENARIO ILLUSTRATION (p. 106). Here the passage of a mid-latitude trough during 6-7 November 1991 assists the semidirect TC interaction (STI) from Tropical Storm Verne that turns Seth onto a west-southwestward track during 6 November. Notice that the passage of a moderate amplitude mid-latitude trough during 8 November corresponds to a temporary period of westward motion (see Geographic Motion plot on page preceding NOGAPS analysis series of Seth and Verne) in the midst of an otherwise steady west-southwestward track.

Cross-references:

Beta-Effect Propagation (BEP) p. 57

Ridge Modification by a TC (RMT) p. 65

Semidirect TC Interaction (STI) p. 97

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Topic: SUBTROPICAL RIDGE MODULATION (SRM) (cont)

STRONG SRM SCENARIO (S/WR - S/DR transition)

The NOGAPS analysis series at right illustrates a period of SRMT that is immediately followed by a period of SRMR, which results in a particularly severe "stair-step" track (see page A-14) by Typhoon Dan (27W) during October 1992. Notice the following:

- During the period 0000 UTC 28 October (panel a) to 1200 UTC 29 October 1992 (panel d), the combination of the STR weakening by a passing mid-latitude trough (SRMT) and strong poleward propagation of Dan brings Dan into a near-recurvature situation. Notice the isotach maximum to the east of Dan at 0000 UTC 29 October, which is consistent with Dan's nearly poleward motion at the time.

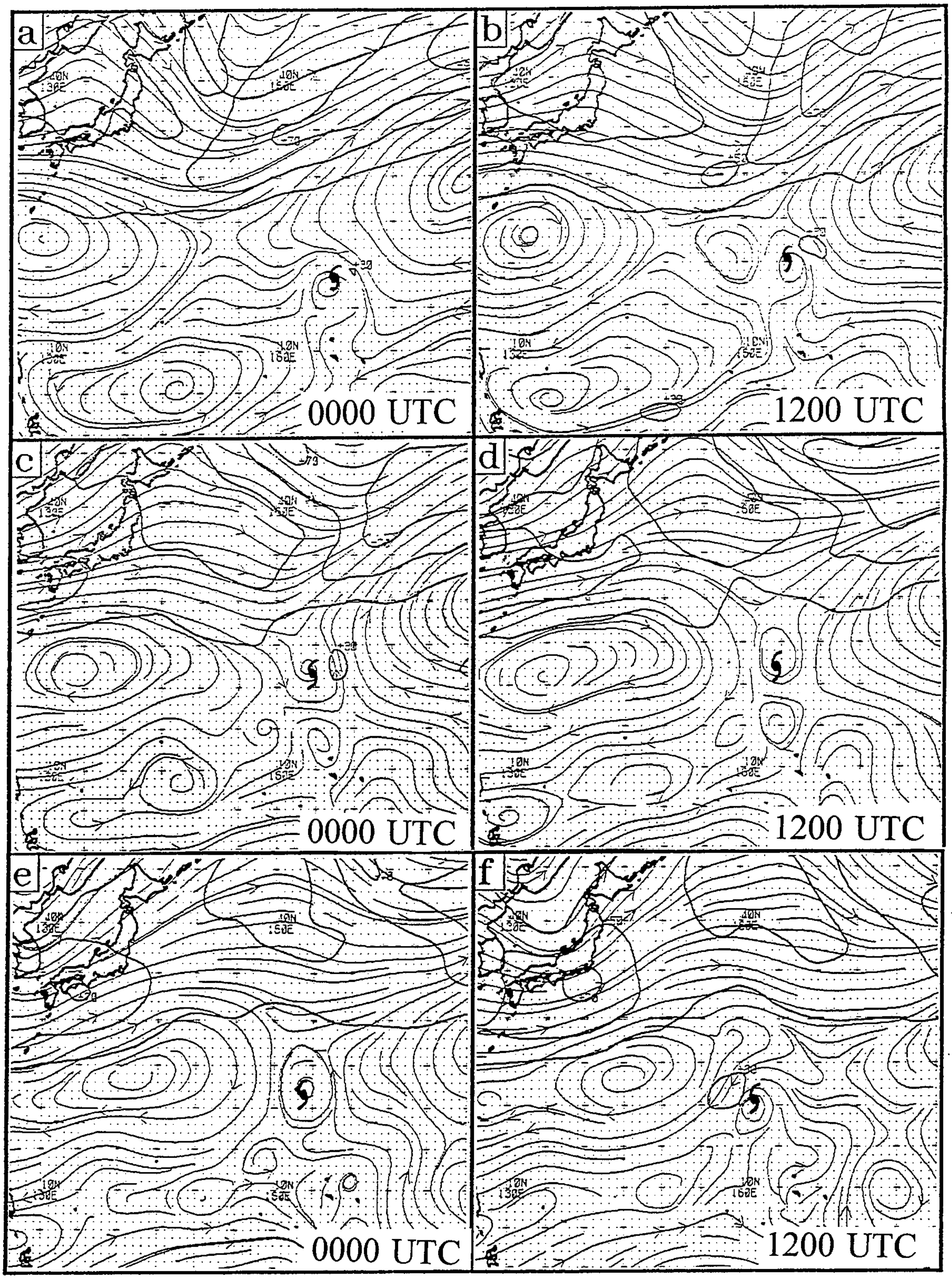
- However, the approach and passage of a mid-latitude ridge during the period 1200 UTC 29 October (panel d) to 1200 UTC 30 October (panel f), so strengthens the STR that Dan is advected west-southwestward (i.e., stair-step track). Notice the isotach maximum to the northwest of Dan at 1200 UTC 30 October, which is consistent with the southwestward motion at the time.

Cross-references:

Diagnosing Environmental Steering Direction p. 9

Standard (S) Pattern p. 19

28 - 30 October 1992



Topic: SUBTROPICAL RIDGE MODULATION (SRM) (cont)

STRONG SRM SCENARIO ILLUSTRATION (P/PO - S/DR transition)

The NOGAPS analysis series at right illustrates a period of decreasing SRMT that contributes to a P to S pattern transition for Tropical Storm Jack (05W) during May 1993. The track is on page A-15. Notice the following:

- During 16 May 1993 (panel a), the presence of a deep mid-latitude trough poleward of Jack has eroded the STR over an extensive area, which has left distinct STR circulations only near the Philippines and the dateline. This erosion of the STR and the presence of a peripheral anticyclone to the southeast have contributed to Jack moving poleward in the Poleward-Oriented (PO) region of a Poleward (P) pattern.

- During the period 17-19 (panels b-d) May, the mid-latitude trough fills and moves eastward, which allows the STR to become re-established. In particular, notice how the STR circulation just east of the Philippines on 16 May builds to the east during these three days.

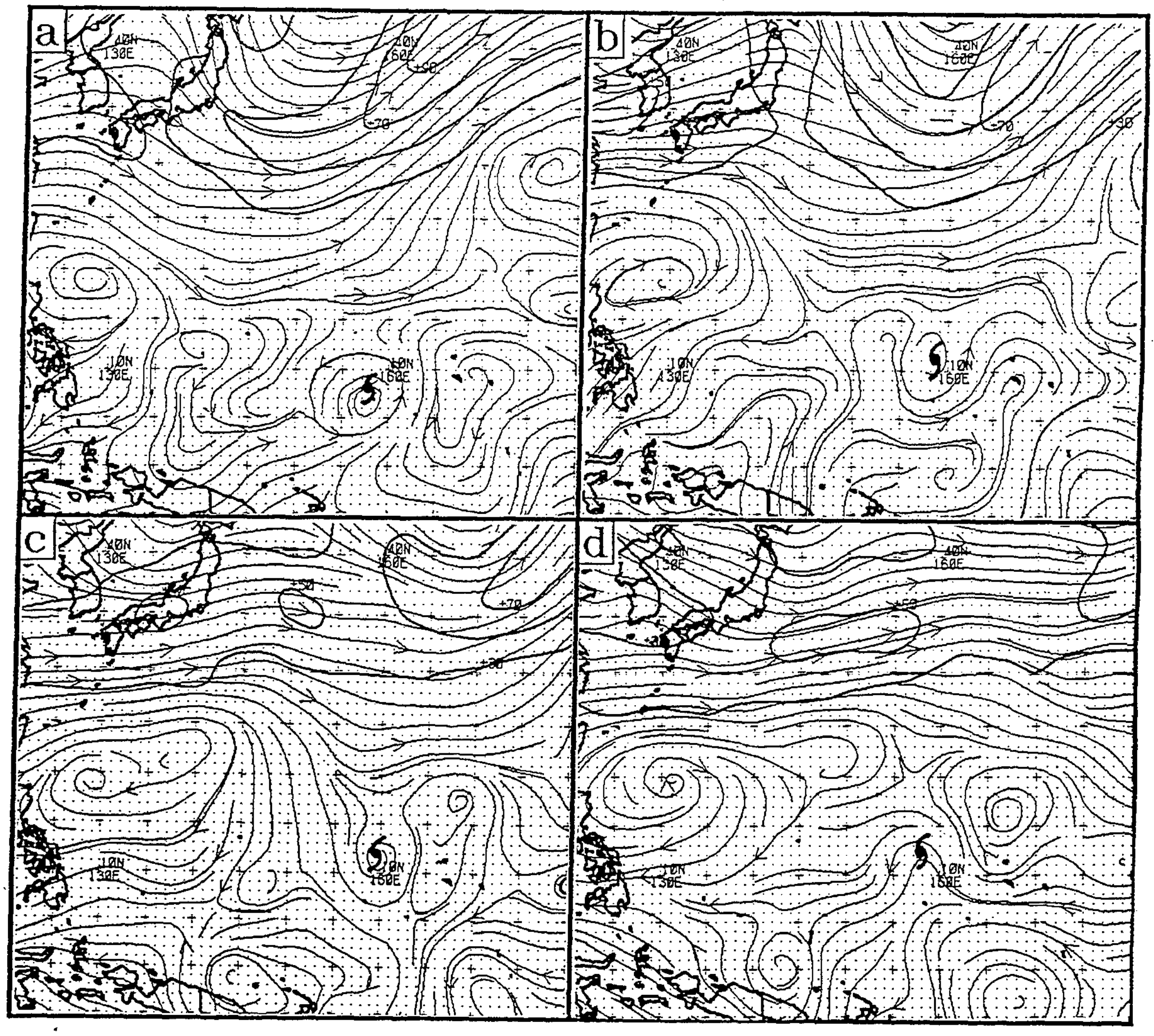
- the combined effect of the return of the mid-latitude flow to an essentially zonal pattern (cessation of SRMT) and the weakening of the anticyclone southeast of Jack causes the TC to turn from a poleward track to a westward track, which is consistent with an environment structure transition from P/PO to Standard/Dominant Ridge (S/DR).

Cross-references:

Poleward (P) Pattern p. 29

Standard (S) Pattern p. 19

16-19 May 1993 (0000 UTC)



Topic: SUBTROPICAL RIDGE MODULATION (SRM) (cont)

STRONG SRM SCENARIO (S/DR to P/PO transition)

The NOGAPS analysis series at right illustrates a period of decreasing SRMR that assists in a Standard (S) to Poleward (P) pattern transition for Typhoon Ward (21W) during October 1992. The track of Ward is on page A-16. Notice the following:

- At 0000 UTC 2 October 1992 (panel a), a distinct anticyclone to the southeast of Ward (presumably generated by beta-induced ridging from Ward) places Ward in a poleward steering flow, which would seem to be a P/PO environment structure. However, the strength of the STR to the northwest, which is being further strengthened by the approaching midlatitude ridge (SRMR), is sufficient to keep Ward in easterly steering, and thus in a Dominant Ridge (DR) region of a S pattern. Notice the isotach maximum poleward of Ward, which is also poleward of the analyzed wind circulation center at 500 mb, as expected in a consistent analysis for diagnosing the steering flow.

- By 0000 UTC 3 October (panel b), the passage of the mid-latitude ridge and approach of a mid-latitude trough (SRMT) causes a shift in the isotach pattern around Ward, which is initially suggestive of a S/WR situation and a subsequent northeastward track in the Midlatitude Westerlies (MW) region.

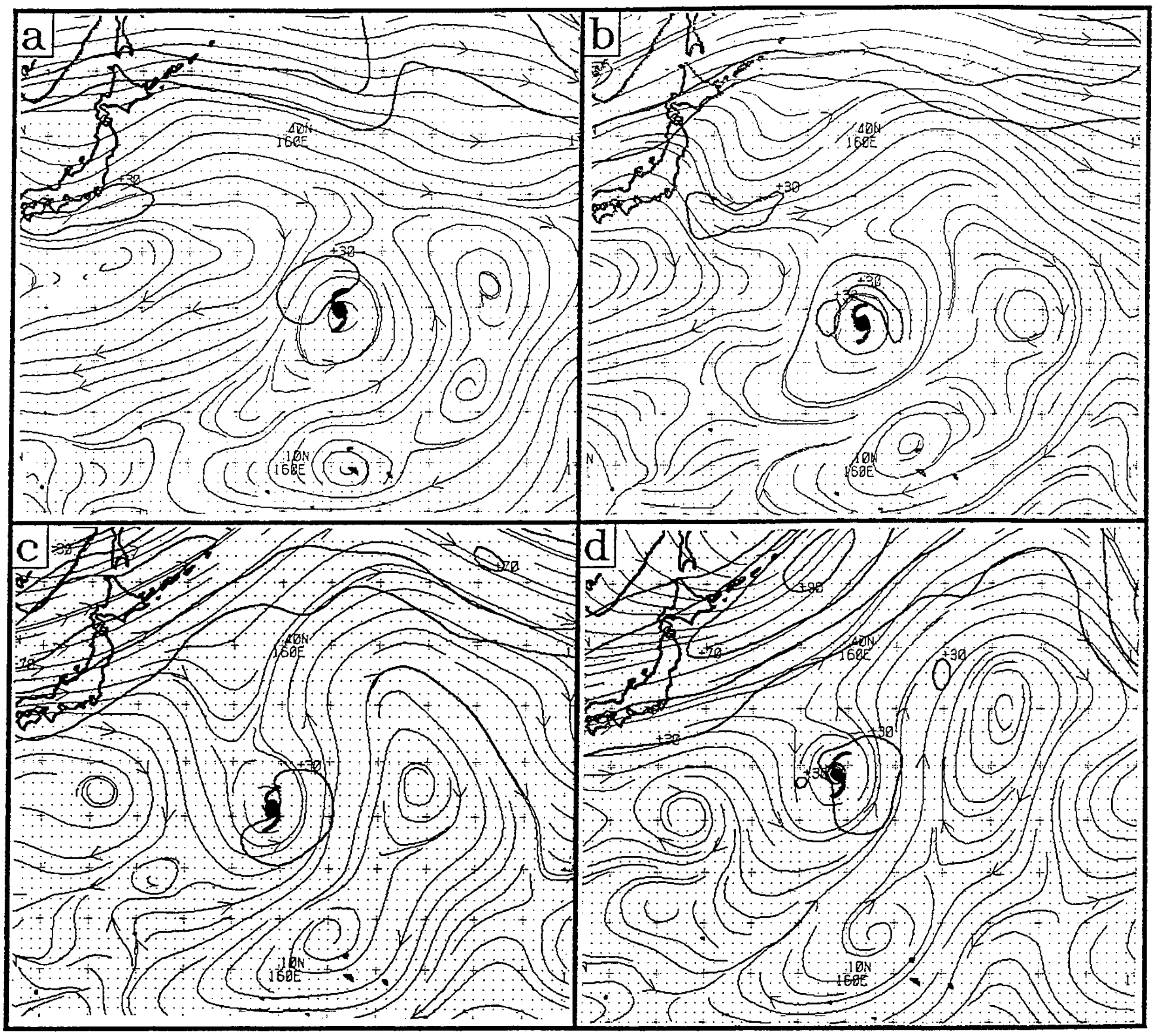
- However, the increasing amplitude of the approaching mid-latitude ridge apparently combines with the existing anticyclone to the southeast of Ward, which results in an extensive meridionally-oriented anticyclone that extends far poleward of Ward. As a result, Ward actually moves nearly due north and continues doing so until 0000 UTC 6 October-- a period of 48 hours. As a result of this strong SRMR, the environment of Ward has undergone a transition from S/DR to P/PO. Notice how the isotach maximum shifts to the east and just south of Ward, which is consistent with a P/PO environment structure.

NOTE: The extensive ridge formed by the combination of SRMR and the pre-existing peripheral anticyclone southeast of Ward has a more poleward orientation than in the usual RMT-induced S/DR-to-P/PO transition. Thus, Ward moves northward and less eastward than did Page in the RMT scenario illustration (p. 70). Depending on how the peripheral anticyclone and the passing midlatitude ridge are oriented, the orientation of the extended ridge (and associated TC motion) can even be somewhat westward of north, which is still consistent with a P/PO classification.

Cross-references:

Standard (S) Pattern	p. 19
Poleward (P) Pattern	p. 26
Diagnosing Environmental Steering Direction	p. 9
Ridge Modification by a TC (RMT)	p. 65

2 - 5 October 1992 (0000 UTC)



Topic: MONSOON GYRE FORMATION (MGF)

DESCRIPTION

A TC in a Gyre (G) pattern generated in the confluent, convectively active area between a pre-existing Monsoon Gyre (MG) and the accompanying peripheral anticyclone to the southeast. This was the case for Tropical Storm Val that is illustrated in the G pattern (p. 46), with the track on page A-5.

It is also possible for a pre-existing TC to encounter a forming MG. This encounter results in a change (i.e., a transition) in the TC-environment structure to either the Poleward-Oriented (PO) or (less frequently) the Dominant Ridge (DR) region in the G pattern. In the Systematic Approach meteorological knowledge base, Monsoon Gyre Formation (MGF) is treated as a possible transition mechanism of the TC-environment to a G pattern. Since there is presently no indication that MGF is significantly influenced by the presence of a TC (as opposed to the converse), MGF is classified as an Environment Effect rather than as a TC-Environment transformation.

A schematic of an environment structure transition from S/DR to G/PO as a result of MGF in the vicinity of a pre-existing TC is shown at right.

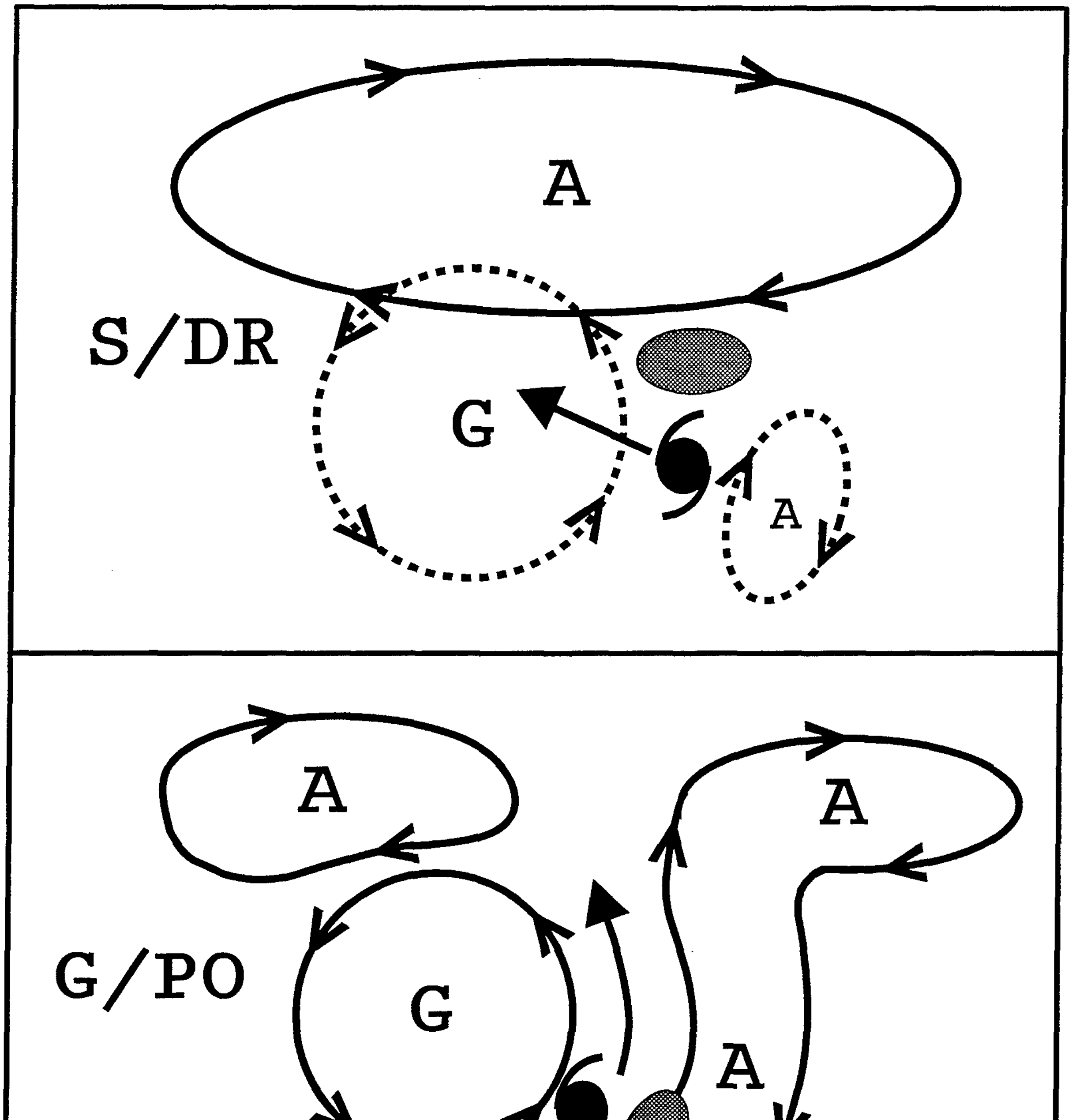
Cross-references:

Gyre (G) Pattern p. 37

Western North Pacific Knowledge Base p. 7

Standard (S) Pattern p. 19

Monsoon Gyre Formation (MGF)



Topic: MONSOON GYRE FORMATION (MGF) (cont)

SATELLITE IMAGERY OF MGF

An example of the characteristic cloud patterns that are associated with Monsoon Gyre Formation (MGF) is illustrated in the satellite imagery sequence at right for Typhoon Nathan (10W) and the associated MG during July 1993. The track of Nathan is given on page A-17. Notice that:

- on 20 July (panel a), the organized convection of Typhoon Nathan is clearly evident at about 15°N, 148°E. Nathan had been in existence for two days previous to this time, having formed at about 10°N, 155°E. Although convective activity is present southwest of Nathan, the fish hook cloud pattern that manifests the presence of a Monsoon Gyre (MG) is not evident.

- during the remainder of the imagery sequence, a characteristic fishhook cloud pattern does form to the south and west of Nathan. In the 24 July image (panel e), the distinction between the small convective cloud mass of Nathan at about 28°N,138°E and the fish hook cloud to the south is particularly evident. Typhoon Nathan is now moving northward in association with a Gyre (G) pattern.

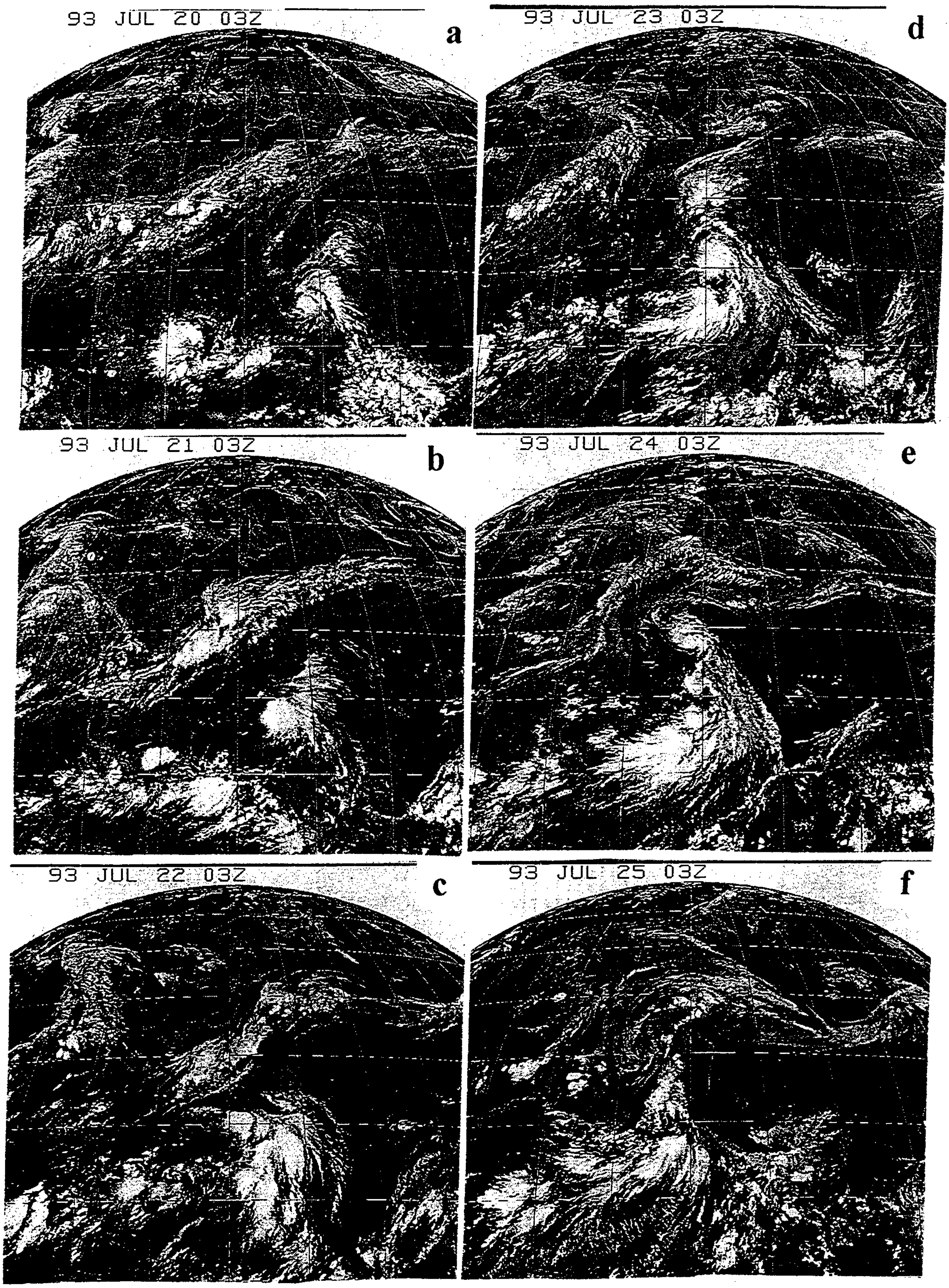
- on 25 July (panel f), the distinctly curved inner boundary of the MG cloud pattern that starts at the southern tip of Taiwan, extends east-southeast to about 19°N, 130°E, and then extends northeastward to about 30°N, 138°E. This curved inner cloud boundary is useful in distinguishing a MG from a reverse-oriented trough situation. See the Monsoon Gyre Dissipation (MGD) for a contrasting cloud pattern.

Cross-references:

Gyre (G) Pattern p. 37

Reverse-oriented Trough Formation (RTF) p. 74

Monsoon Gyre Dissipation p. 135


93 JUL 20 03Z
a
93 JUL 23 03Z
d
93 JUL 21 03Z
b
93 JUL 24 03Z
e
93 JUL 22 03Z
c
93 JUL 25 03Z
f

Topic: MONSOON GYRE FORMATION (MGF)

MGF SCENARIO ILLUSTRATION

The NOGAPS analysis series at right corresponds to the satellite imagery sequence on the previous page and shows Typhoon Nathan (10W) during July 1993. Notice that:

- on 20 July (panel a), Nathan is tracking northwestward (see page A-17) in the Dominant Ridge (DR) region of a Standard (S) pattern. Although the NOGAPS analysis has a large cyclonic area to the west of Nathan that might represent a Monsoon Gyre (MG), this feature is absent in the next two 12-h analyses.

- on 22 July (panel c), a cyclonic circulation begins to appear to the east of the Philippines, and an anticyclone is developing to the southeast of this cyclone. The locations of these features are consistent with the location of the developing fish hook cloud in the corresponding satellite image. Notice that this cyclone/anticyclone orientation is consistent with a Rossby wave train emanating from the developing MG. At this time, the environment structure for Nathan would be classified as in a transition state from S/DR to G/PO, with the MGF being assigned as the responsible transition mechanism.

- by 23 July (panel d), Nathan has turned poleward, which is a manifestation that the transition to G/PO is response to MGF has been completed. Notice that although the NOGAPS analysis has a large area of troughing to the east and south of Nathan, no closed wind center is evident. In a number of cases, the NOGAPS analysis may not resolve the MG circulation. This is why careful interpretation of satellite imagery is critical in detecting the development of a MG, and thus a transition of the TC-environment to the G pattern. (NOTE: The closed center to the northwest of Nathan is a cut-off cyclone from the passing midlatitude trough).

- by 24 July (panel e), Tropical Storm Ofelia, which has a small size characteristic of a MG-induced TC formation, now appears to be in a Poleward-Oriented (PO) region of the pre-existing MG. Thus, Ofelia is classified in a Gyre (G) pattern, and MGF is not invoked as a transitional mechanism.

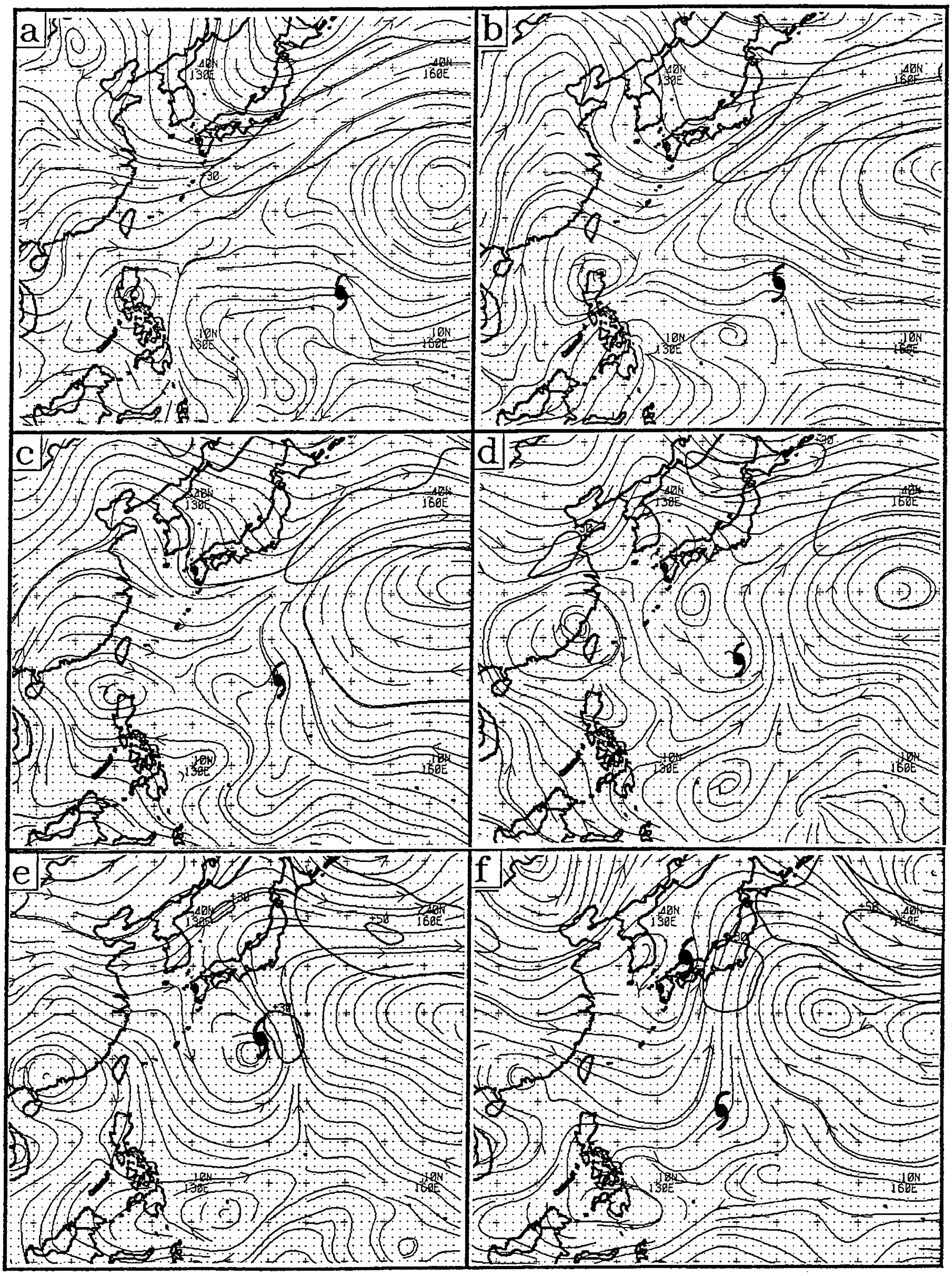
Cross-references:

Standard (S) Pattern p. 19

Gyre (G) Pattern p. 37

TC Size p. 15

20 - 25 July 1993 (0000 UTC)



ENVIRONMENT EFFECTS

Topic: MONSOON GYRE DISSIPATION (MGD)

DESCRIPTION

The transition mechanism Monsoon Gyre Dissipation (MGD) is included in the Systematic Approach meteorological knowledge base to account for the environment structure classification changing from the Gyre (G) pattern in either the Poleward-Oriented (PO) or Dominant Ridge (DR) region to some other pattern/region combination because the TC circulation persists after the MG had dissipated. Since there is presently no indication that MGD is significantly influenced by the presence of the TC, MGD is classified as an Environment Effect rather than a TC-Environment transformation. The environment structure transitions that typically result from MGD include (but are not limited to):

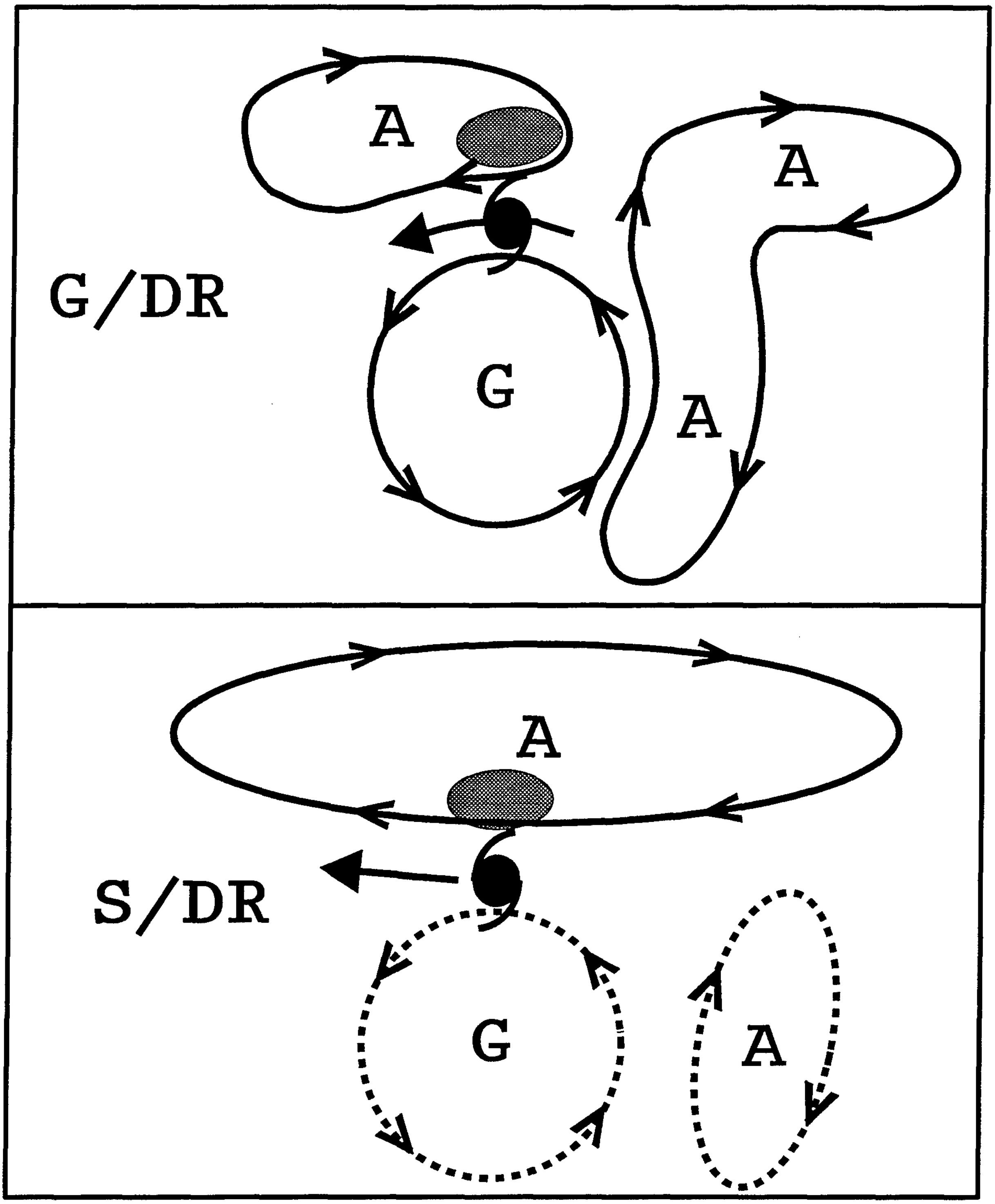
G/PO - P/PO: In this case, the Monsoon Gyre (MG) has essentially dissipated to leave a reverse-oriented monsoon trough. The TC will continue on a strongly poleward track during this transition, although a moderate turn from a west of north track direction to an east of north track may result.

G/DR - S/DR: In this case, the TC is tracking west between the subtropical ridge (STR) circulation to the north and the dissipating MG to the south. The TC will continue to track strongly westward, although a modest turn to a west-northwestward track is likely if the TC has previously had a south of west track while in the DR region of the G pattern. This scenario is illustrated in the schematic at right.

Cross-references:

Western North Pacific Knowledge Base	p. 9
Gyre (G) Pattern	p. 37
Poleward (P) Pattern	p. 29
Standard (S) Pattern	p. 19

Monsoon Gyre Dissipation (MGD)



Topic: MONSOON GYRE DISSIPATION (MGD) (cont)

MGD SCENARIO ILLUSTRATION (G/PO - P/PO transition)

The NOGAPS analysis series at right illustrates the dissipation of a Monsoon Gyre (MG) into a reverse-oriented monsoon trough during the existence of Tropical Storm Ofelia (10W) and Typhoon Percy (11W) during July 1993. Tracks for Ofelia and Percy are given on page A-18. Notice that:

- on 26 July (panel a), the MG is represented in the NOGAPS analysis as a large trough east of Taiwan. Also notice the cyclonically curved and eventually east-of-poleward track of Ofelia that is characteristic of TC motion in a G/PO environment (if the MG is not translating too fast). Typhoon Percy has just formed in the region between the MG and the peripheral anticyclone to the southeast.

- during the remainder of the period shown, the depth of the trough in NOGAPS diminishes and by 29 July (panel d), Ofelia is at the northeastern end of a thin reverse-oriented monsoon trough that extends to the southern tip of Vietnam. Notice that an extensive and nearly linear isotach maximum extends along the high-gradient region between the trough and the extensive peripheral ridge to the southeast. Notice also that the past track of Percy depicted on the 29 July analysis is essentially poleward and is consistent with motion in a P/PO environment. In contrast, Ofelia had a slightly more west of north track (depicted on the 27 July analysis in panel b), which is indicative of a G/PO environment.

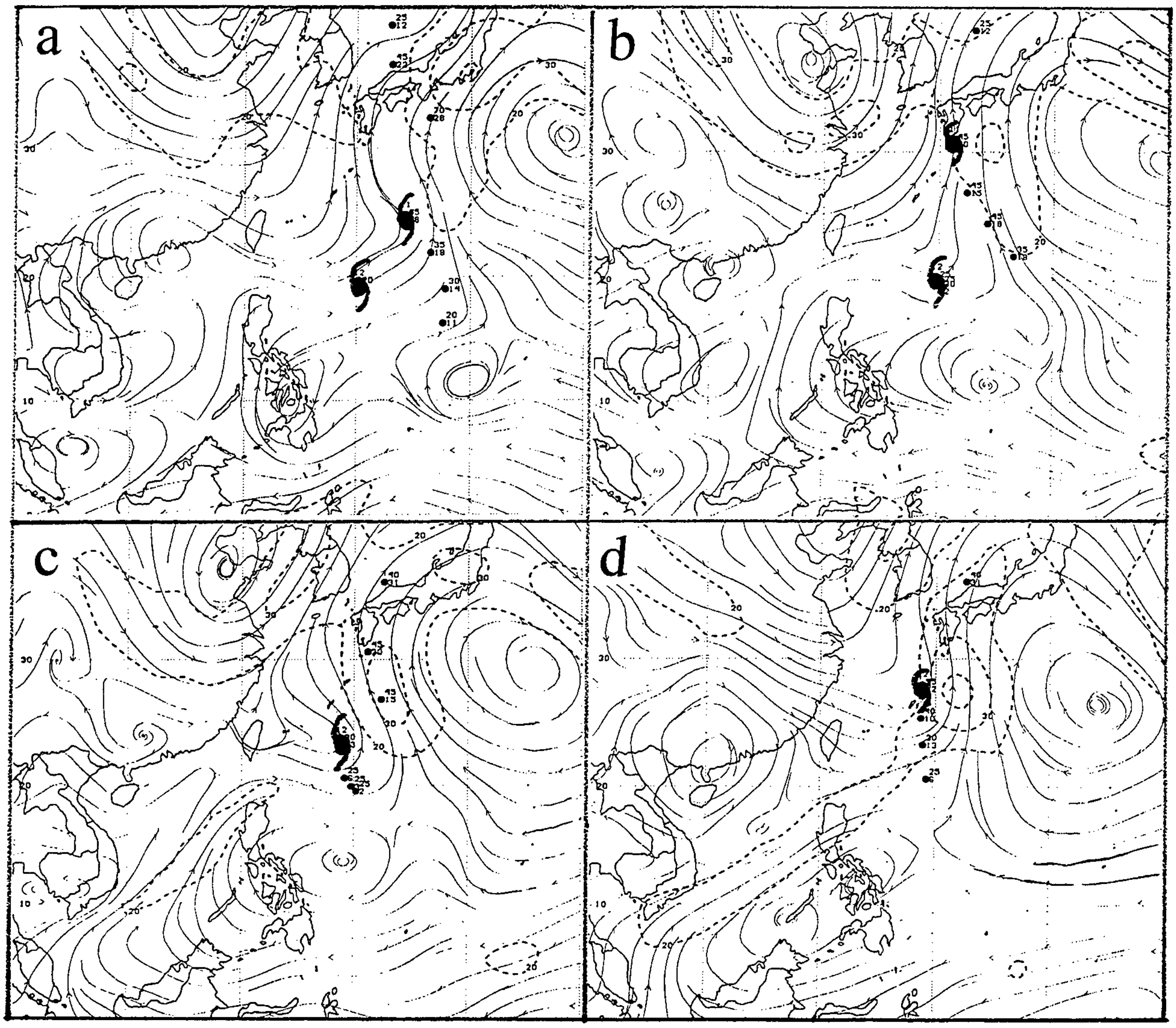
NOTE: Because of the influence of the numerical model forecast being used as the first-guess field in over-water (data-sparse) areas as compared to over-land (data-rich) areas, NOGAPS analyses will generally tend to under-represent the strength of the MG circulation as a MG develops, and over-represent the strength of the MG circulation as the MG dissipates. Thus, the weakening of the MG circulation in a NOGAPS analysis is strong evidence that the MG is really dissipating. This fact is particularly useful in assessing the G/PO to P/PO transitions in which comparatively subtle changes are evident in the pattern of monsoonal convection in the satellite imagery (see next page).

Cross-references:

Gyre (G) Pattern p. 37

Poleward (P) Pattern p. 29

26 - 29 July 1993 (0000 UTC)



Topic: MONSOON GYRE DISSIPATION (MGD) (cont)

SATELLITE IMAGERY OF MGD (G/PO - P/PO transition)

The satellite imagery sequence at right illustrates the subtle changes that occur during the dissipation of a Monsoon Gyre (MG) that leads to a transition from a Gyre/Poleward-Oriented (G/PO) to a Poleward (P)/PO pattern/region combination for the embedded TC. Notice:

- on 26 July (panel a), the distinctly curved inner cloud boundary extending eastward and poleward from just east of Taiwan to the small convective cloud mass of Ofelia at about 25°N, 134°E (see track on page A-18). This cloud boundary is a key indicator that a closed MG cyclonic circulation is still present.

- by 28 July (panel c), the curvature of the inner cloud boundary is no longer evident, and the larger pattern of convection has a southwest-to-northeast orientation that is indicative of a reverse-oriented monsoon trough. Thus, the environment structure of Ofelia and just-formed Percy (23°N, 129°E) has changed from G/PO to P/PO.

NOTES:
1. Because of the subtle nature of the changes in the convection pattern during a transition from G/PO to P/PO, the weakening of the MG circulation in the NOGAPS analyses on the previous page is critical to recognizing the transition. During a MG dissipation leading to a P/PO environment, more attention (weight) should be given to numerical analyses indicators than satellite imagery interpretation indicators. During MG formation, more weight should be given to satellite imagery indicators than numerical analyses, since the numerical models are normally slow to represent the MG.
2. In contrast to the above situation, when MG dissipation results in a transition from a G to a Standard (S) pattern, very distinct satellite imagery indicators are present: namely, the prominent fish hook pattern dissipates and the region south of the TC takes on the comparatively inactive convective character (compared to the G and P patterns) indicative of the S pattern.

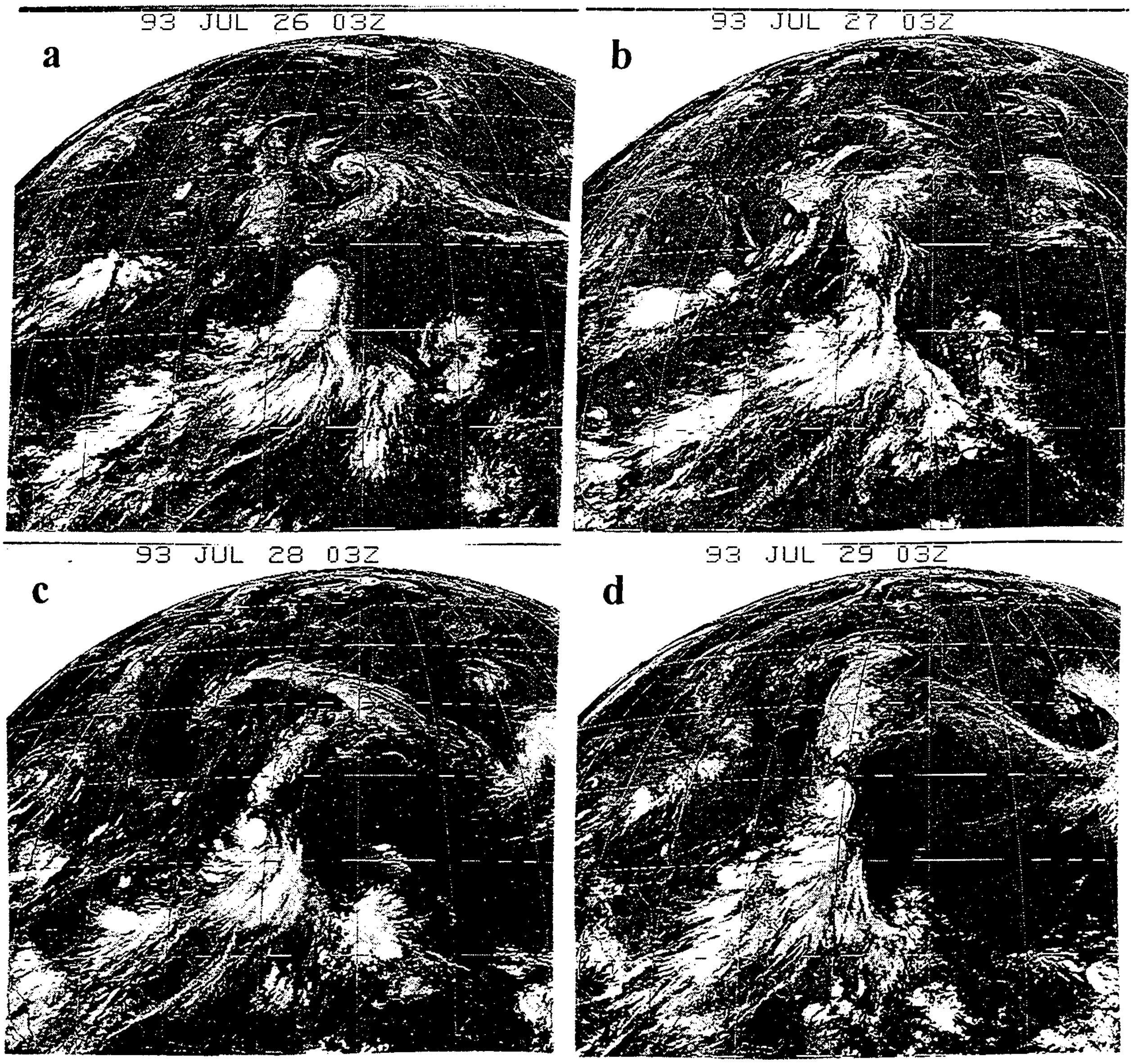
Cross-references:

Gyre (G) Pattern p. 37

Poleward (P) Pattern p. 29

Reverse-oriented Trough Formation p. 73

Monsoon Gyre Formation p. 129


93 JUL 26 03Z
a
93 JUL 27 03Z
b
93 JUL 28 03Z
c
93 JUL 29 03Z
d

ENVIRONMENT EFFECTS

Topic: ADVECTION THROUGH PATTERN (ADV)

DESCRIPTION

The easterly steering flow in a Standard/Dominant Ridge (S/DR) environment will generally not tend to advect a TC poleward toward the subtropical ridge axis, particularly if the ridge is unbroken. Rather, a phenomenon such as TC propagation (BEP) is needed. In other words, advection (ADV) by the steering flow in the DR region is not normally a transition mechanism.

By contrast, the TC in certain pattern/region situations will necessarily move from one region to another as a natural consequence of the direction of steering flow provided by the environment. In these situations, the synoptic region classification of the TC will eventually change even if:

- the structure of the large-scale features in the environment is not evolving with time; or

- the TC is not interacting significantly with the environment.

In these situations, the transition mechanism responsible for the change in region classification is Advection by the Environment (ADV). Examples of these situations include:

P/PO - P/MW: The poleward flow in the Poleward-Oriented (PO) region of a persistent Poleward (P) pattern will eventually, and necessarily, advect (ADV) the TC into the Midlatitude Westerlies (MW) region without the need for any interaction with the TC in terms of propagation (BEP). See P pattern summary for illustration.

G/PO - G/DR: If the TC is not too far from the center of a MG, the flow in the PO region will naturally tend to advect (ADV) the TC around the MG and into the DR region to the northwest of the MG. See G pattern summary for illustration.

G/PO - G/MW: If the TC is not too close to the center of a MG, and the peripheral anticyclone and subtropical ridge to the northeast form a single large unbroken ridge circulation, the flow in the PO region will naturally tend to advect (ADV) the TC poleward into the MW region. See G pattern for illustration.

Cross-references:

Beta-Effect Propagation (BEP)	p. 57
Standard (S) Pattern	p. 19
Poleward (P) Pattern	p. 29
Gyre (G) Pattern	p. 37

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TRANSITION CLIMATOLOGY

Topic: TRANSITION FREQUENCIES

DESCRIPTION:

The figure at right shows the frequency of recurring transitions in environment structure from one pattern/region combination to another in the western North Pacific from 1989-1996. If a transition path was to or from the S, P, or G patterns, then recurring was defined to be four or more times. Because of the comparatively infrequent occurrence of the M pattern, all transitions to or from the M pattern that occurs more than once were considered to be recurring.

Among the 278 TCs that formed in the western North Pacific during the period of the database, 379 recurring transitions occurred, or about four transitions in environment structure for every three TCs. Notice that the most frequent transition paths are:

- S/DR to P/PO (83 times), in which the TC turns from a westward track to a poleward track;

- P/PO to P/MW (73 times), in which the TC recurves into the midlatitude westerlies after being advected poleward by a beta-induced ridge to the southeast of the TC;

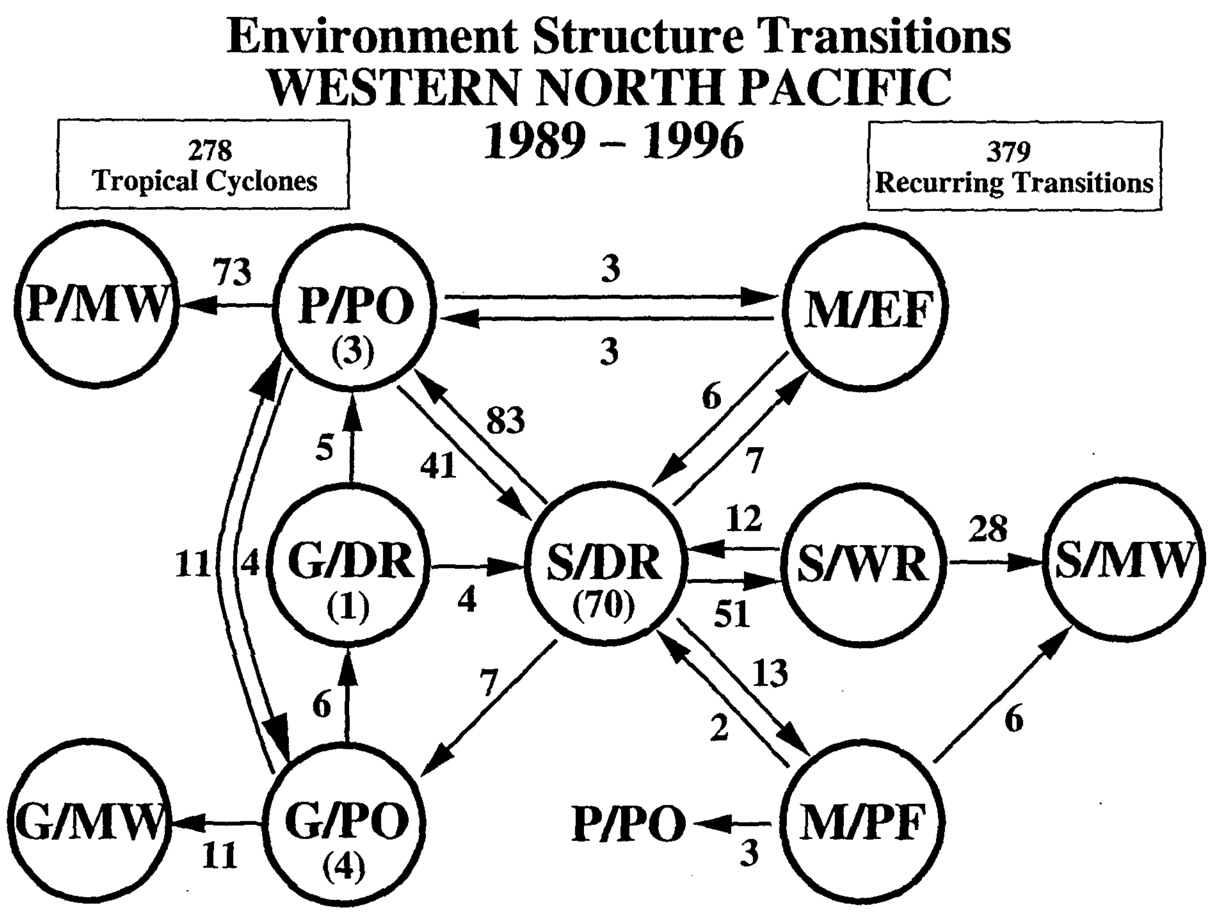
- S/DR to S/WR (51 times), in which the TC slows and moves into a weakness in the subtropical ridge;

- P/PO to S/DR (41 times), in which the TC turns from a poleward track to a westward track; and

- S/WR to S/MW (28 times), in which the TC recurves into the midlatitude westerlies after moving through a weakness in the subtropical ridge.

The numbers in parentheses indicate the number of TCs that remained in that pattern/region combination for the duration of their existence. Notice that 70 of the 278 TCs, or 25% remained in the S/DR pattern/region combination. These are the "straight-runners" that develop and remain in the tropical easterlies until they either make landfall or dissipate.

Although the diagram at right looks complicated, it is important to remember that only the transitions paths that are of concern to the forecaster at any time are those that are leaving the particular pattern/region combination characterizes the current environment of the TC. Analysis of the relative frequency, and thus the climatological probability, of each path. The diagrams of the following pages provide this information.



Environment Structure Transitions
WESTERN NORTH PACIFIC
1989 - 1996
278
Tropical Cyclones
379
Recurring Transitions
P/MW
73
P/PO
(3)
3
M/EF
3
83
6
5
41
7
11
4
G/DR
(1)
4
S/DR
(70)
12
S/WR
28
S/MW
51
13
7
6
2
6
G/MW
G/PO
(4)
11
P/PO
3
M/PF

TRANSITION CLIMATOLOGY

Topic: TRANSITION PROBABILITIES FROM THE S PATTERN

DESCRIPTION:

The panels at right show the relative probabilities and associated transitional mechanisms for transitions from the (a) S/DR, (b) S/WR, and (c) S/MW pattern/region combinations. Although there are comparatively many paths of environment structure change that may affect a TC currently in the S/DR pattern/region, it is important to note that:

- the transitions to the M pattern require the presence of another suitably positioned TC so that semi-direct TC interaction (STI) occurs, and thus are not applicable in a single TC situation or some multiple TC situations; and

- the transition to the G/PO pattern/region requires the approach (ADV) or formation (MGF) of a suitably positioned (i.e., to the west of the TC) monsoon gyre (MG), which has been observed to occur only during the months of June to October.

In the absence of a suitably positioned monsoon gyre or second TC, the forecaster need consider only three paths of roughly equal climatological probability:

- a transition to P/PO, which represents the formation of a beta-induced ridge to the southeast of the TC via the Ridge Modification by a TC (RMT) mechanism or Reverse Trough Formation (RTF) mechanism (if a suitably positioned TC is present); or

- a transition to S/WR, which represents the movement of the TC into a weakness (col) between two subtropical ridge circulations, usually aided by beta-effect propagation (BEP), and typically aided by a weakening modulation of the subtropical ridge by a midlatitude trough to the poleward and westward of the TC (SRMT).

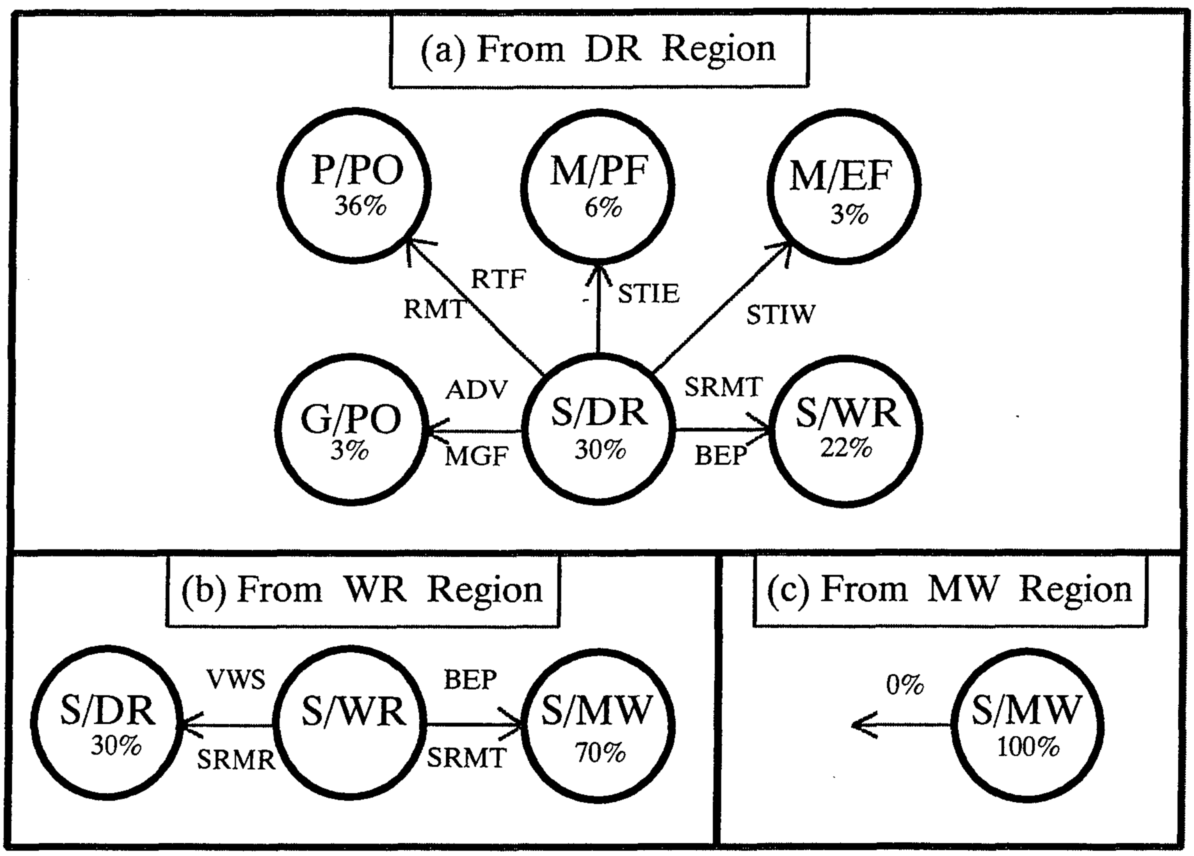
- no transition from S/DR, owing to a sufficiently strong subtropical ridge circulation poleward of the TC, and which is more likely to occur for smaller TCs that are expected to exhibit less BEP.

From the S/WR pattern/region there are only two possible transition paths:

- a much more likely transition to S/MW, which is a recurvature of the TC, usually aided by BEP and SRMT.

- a much less likely transition to S/DR, which is a “stair-step” turn from a poleward to a westward heading, owing to increasing midlatitude ridging poleward of the TC (SRMR) or a separation of the TC low-level circulation from the deep convection by vertical wind shear (VWS).

S PATTERN TRANSITION PROBABILITIES



TRANSITION CLIMATOLOGY

Topic: TRANSITION PROBABILITIES FROM THE P PATTERN

DESCRIPTION:

The panels at right show the relative probabilities and associated transitional mechanisms for transitions from the (a) P/PO and (b) P/MW pattern/region combinations. Although there are four paths of environment structure change that may affect a TC currently in the P/PO pattern/region, it is important to note that:

- the transition to the M pattern requires the presence of another suitably positioned TC so that the semi-direct TC interaction (STI) occurs, and thus is not applicable in a single TC situation or some multiple TC situations; and

- transition to the G/PO pattern/region requires the formation (MGF) of a suitably positioned (i.e., to the west of the TC) monsoon gyre (MG), which has been observed to occur only during the months of June to October.

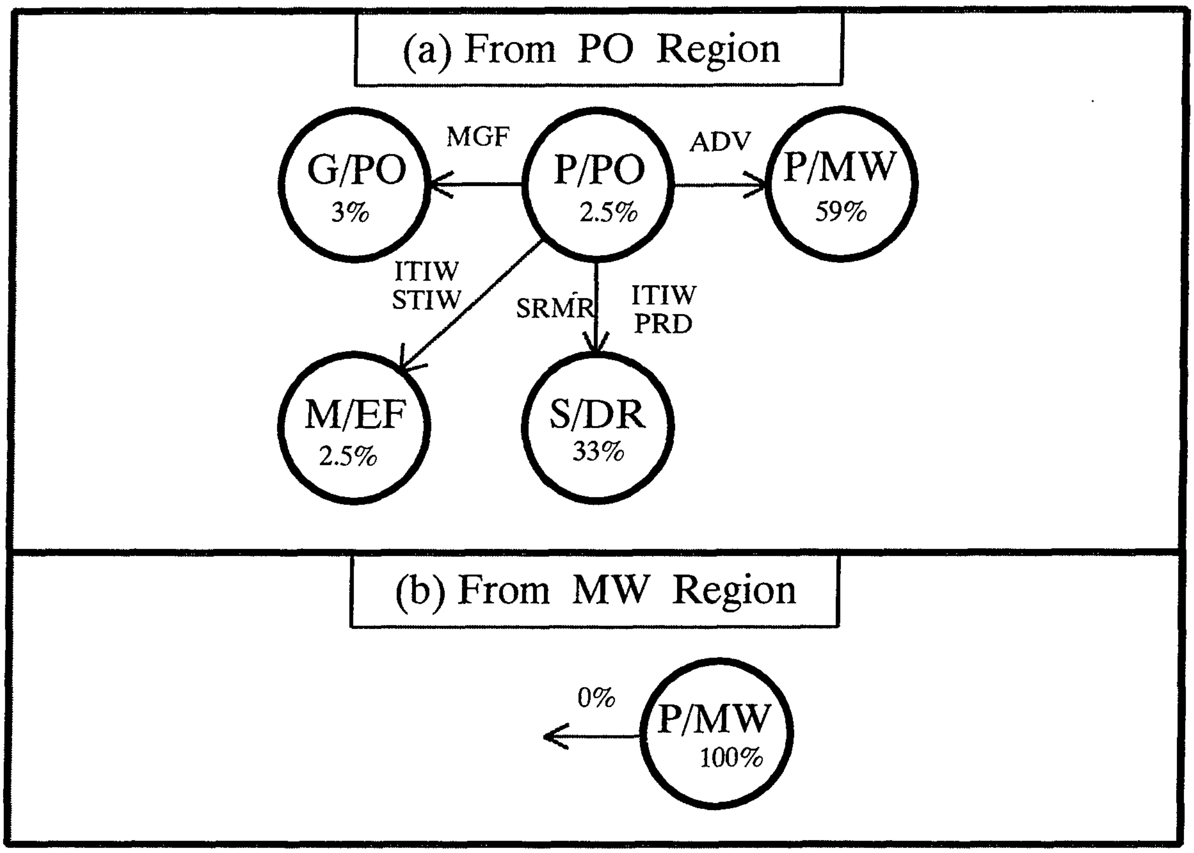
In the absence of a suitably positioned monsoon gyre or second TC, the forecaster need consider only two possible transition paths with highly dissimilar climatological probabilities:

- a much more likely transition to P/MW, which is a recurvature of the TC into the midlatitude westerlies following a period of poleward movement owing to advection (ADV) by a beta-induced anticyclone to the equatorward and east of the TC.

- a much less likely transition to S/DR, owing to sufficient building of the subtropical ridge (SRMR) poleward of the TC, and/or dissipation of the beta-induced peripheral ridge or anticyclone (PRD) that has been responsible for the previous poleward motion of the TC.

Notice that no transitions from P/MW region have been observed.

P PATTERN TRANSITION PROBABILITIES



Topic: TRANSITION PROBABILITIES FROM THE G PATTERN

DESCRIPTION:

The panels at right show the relative probabilities and associated transitional mechanisms for transitions from the (a) G/PO, (b) G/DR, and (c) G/MW pattern/region combinations. There are four paths of environment structure change that may affect a TC currently in the G/PO pattern/region. The more probable, and equally likely, paths are:

- a transition to G/MW pattern/region, in which poleward steering by the monsoon gyre (MG) advects (ADV) the TC sufficiently poleward so that it encounters, and passes through, a weakness (col) in the subtropical ridge that is usually aided by the presence of a midlatitude trough (SRMT) to the north; or

- a transition to the P/PO pattern/region, via an interaction of the TC with the MG (MTI) in which the TC merges with the MG (following a cyclonically curved track) to become a single large TC, and then the large TC moves poleward in response to the poleward steering from a strong peripheral ridge to the southeast that usually results from the MTI process.

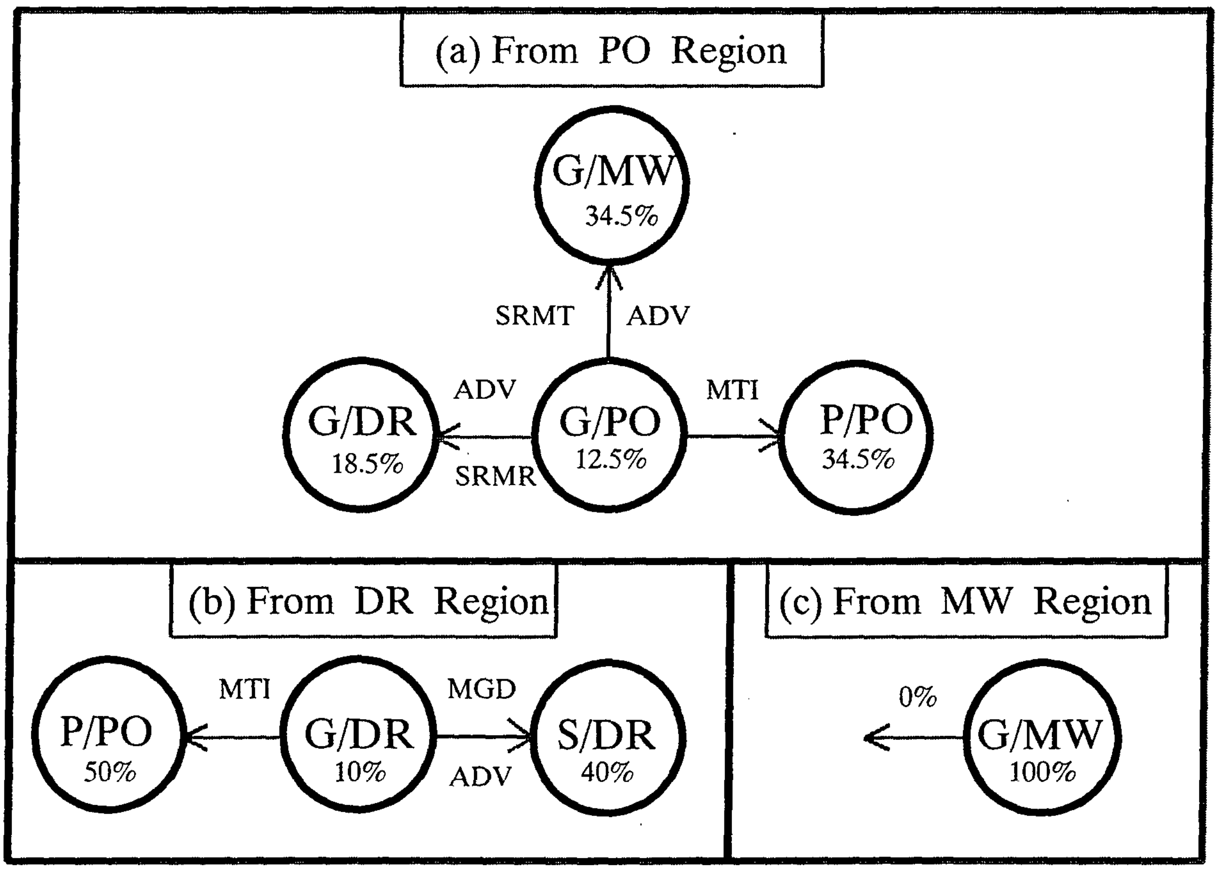
The two remaining, and less probable, transition paths are:

- a transition to the G/DR pattern/region, which represents the TC being advected (ADV) sufficiently far around the east and then north side of the MG to enter the easterly or even east-northeasterly steering between the MG and the subtropical ridge to the northwest; or

- no transition from the G/PO pattern/region, meaning that the TC dissipates before one of the other possible transition paths can take place.

Notice that no transitions from the G/MW region have been observed.

G PATTERN TRANSITION PROBABILITIES



TRANSITION CLIMATOLOGY

Topic: TRANSITION PROBABILITIES FROM THE M PATTERN

DESCRIPTION:

The panels at right show the relative probabilities and associated transitional mechanisms for transitions from the (a) M/PF and (b) M/EF pattern/region combinations. In order of decreasing probability (which may be meaningless due to small sample size), there are three paths of environment structure change that may affect a TC currently in the M/PF pattern/region:

- a transition to S/MW, which naturally results from the poleward steering flow on the eastern TC causing by semi-direct TC interaction (STIE), which is favored if there is a significant midlatitude trough weakening the subtropical ridge from the north (SRMT); or

- a transition to P/PO, which may occur as the eastern TC moves poleward of the western TC in the M pattern, and if the two are producing significant beta-induced ridging to their east and south, and if the beta-induced ridges link-up to form a single extensive ridge that simultaneously advects both TCs poleward (if this occurs, the TCs have effectively formed a reverse-oriented monsoon trough (RTF)); or

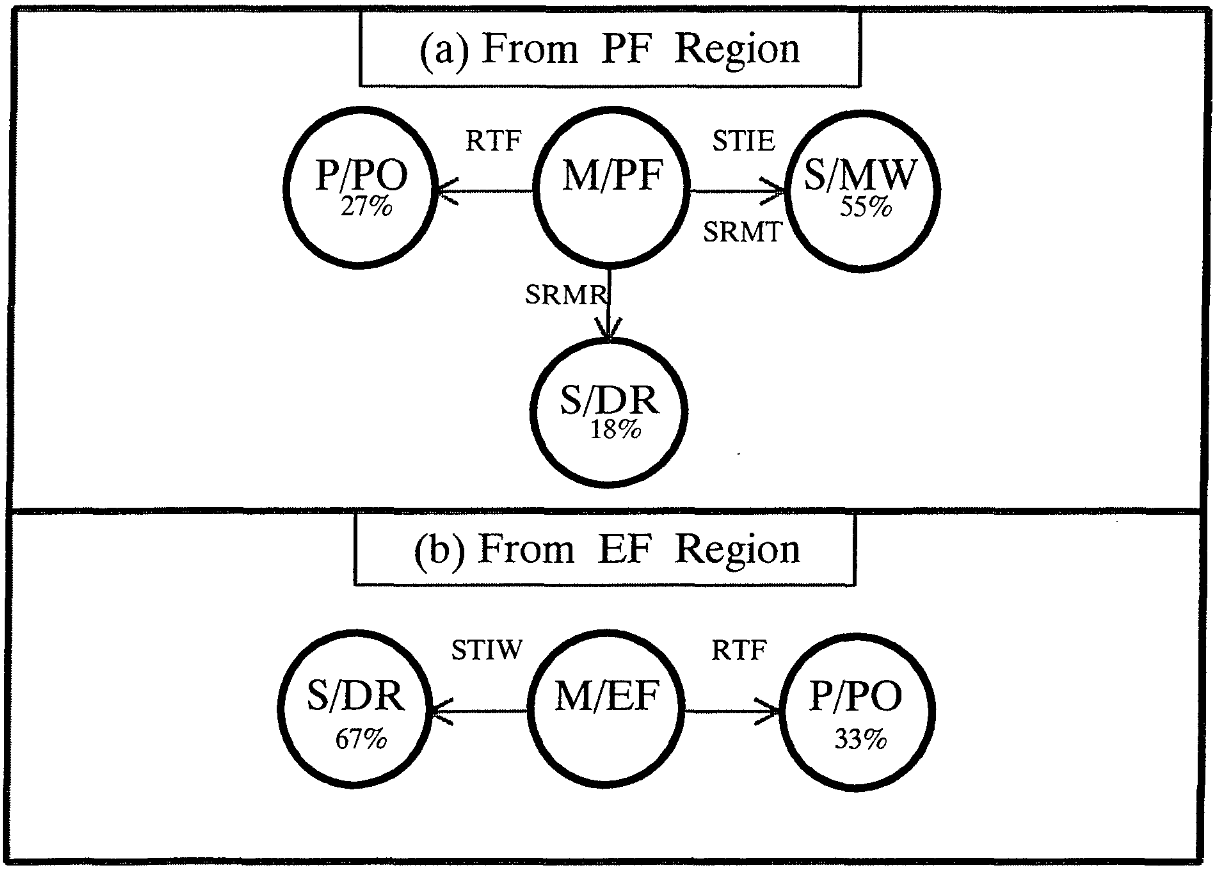
- a transition to S/DR, usually caused by a building of the subtropical ridge poleward of the TC due to a passing midlatitude ridge (SRMR).

There are two possible transition paths from a M/EF pattern/region combination, with highly dissimilar climatological probability:

- a transition to P/PO via the RTF mechanism described above; or

- a transition to S/DR that naturally tends to occur due to the effect of the semi-direct TC interaction mechanism on the western TC (STIW).

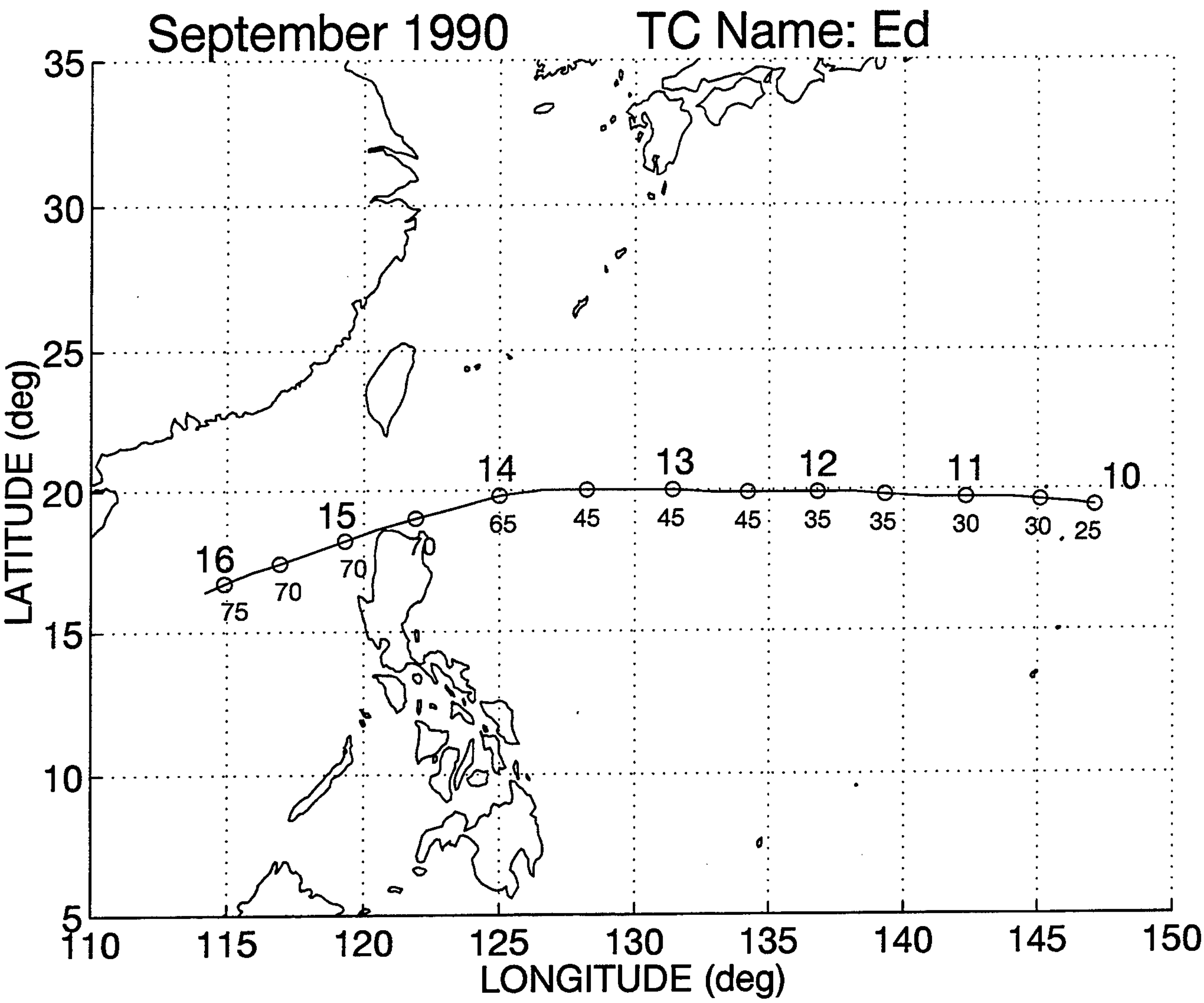
M PATTERN TRANSITION PROBABILITIES



Appendix A

On the following pages are the TC track segments that are referred to in the various case studies in the main body of this report. Best-track positions are indicated by circles and are shown every twelve hours. The 0000 UTC positions are accompanied by a larger number label that denotes the day of the month. The smaller number labels that appear on the opposite side of the track from the day labels denote the intensity (kt) of the TC as assigned by JTWC. Depending on the complexity of the track segment, and how slowly the TC is moving, intensity labels may appear every 12 hours, every 24 hours, or may not be displayed at all. If two TC tracks appear on one graphic, the TC names shown at the upper right are ordered to correspond to the east-west orientation of the two TC track segments.

Page A-	TC Name(s)	Month/Year
2	Ed	9/90
3	Hattie	10/90
4	Walt	7/94
5	Val	9/92
6	Page	5/94
7	Flo/Ed/TD28W	10/93
8	Sarah/Tip	9/89
9	Luke	9/91
10	Mireille	9/91
11	Nat	9/91
12	Seth/Verne	11/91
13	Ruth/Pat	9/94
14	Dan	10/92
15	Jack	10/93
16	Ward	10/92
17	Nathan	7/93
18	Percy/Ofelia	7/93


September 1990 TC Name: Ed
LATITUDE (deg)
LONGITUDE (deg)
35
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125
130
135
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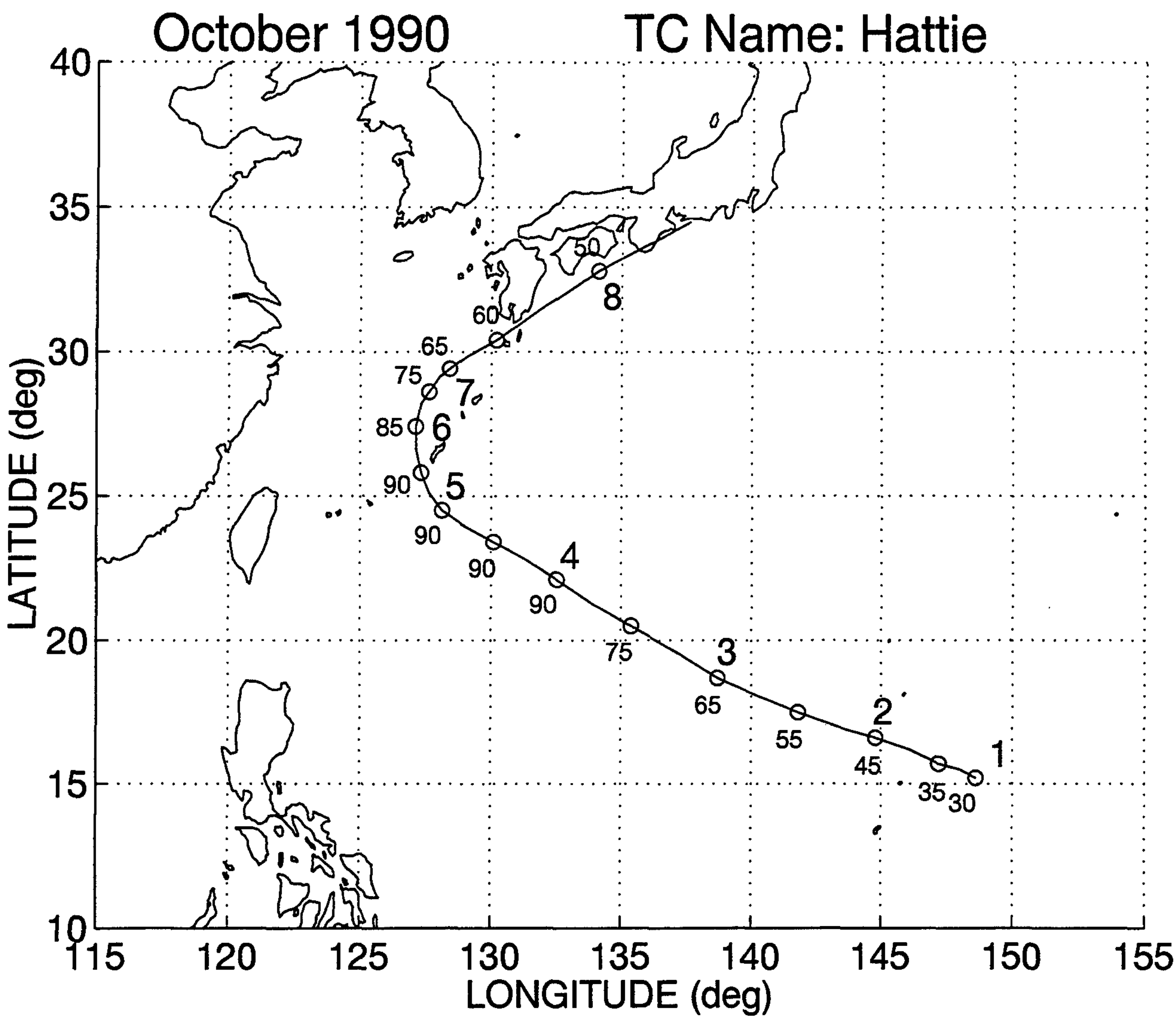

October 1990
TC Name: Hattie
LATITUDE (deg)
LONGITUDE (deg)
40
35
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115
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155
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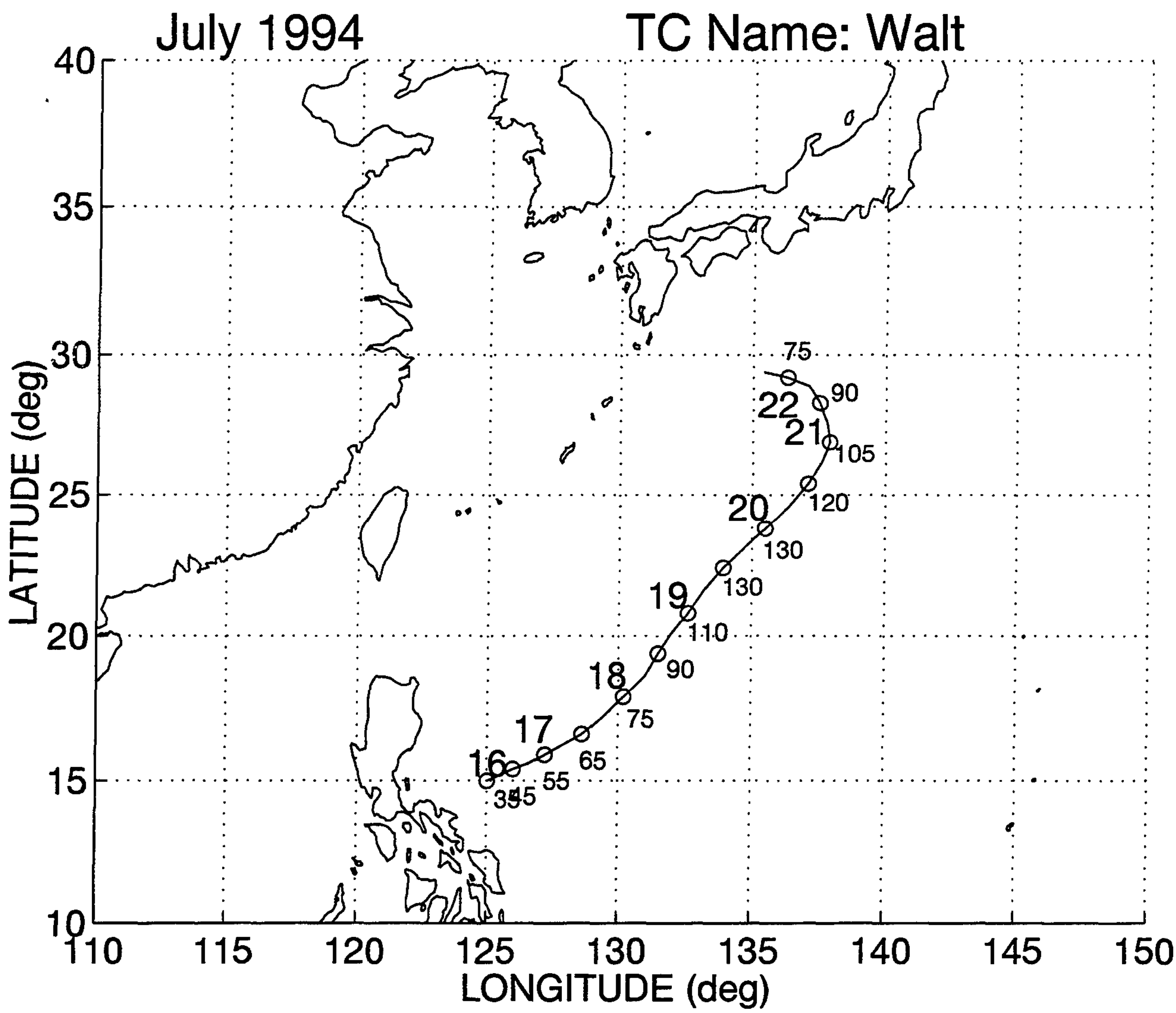
July 1994
TC Name: Walt
LATITUDE (deg)
LONGITUDE (deg)
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75
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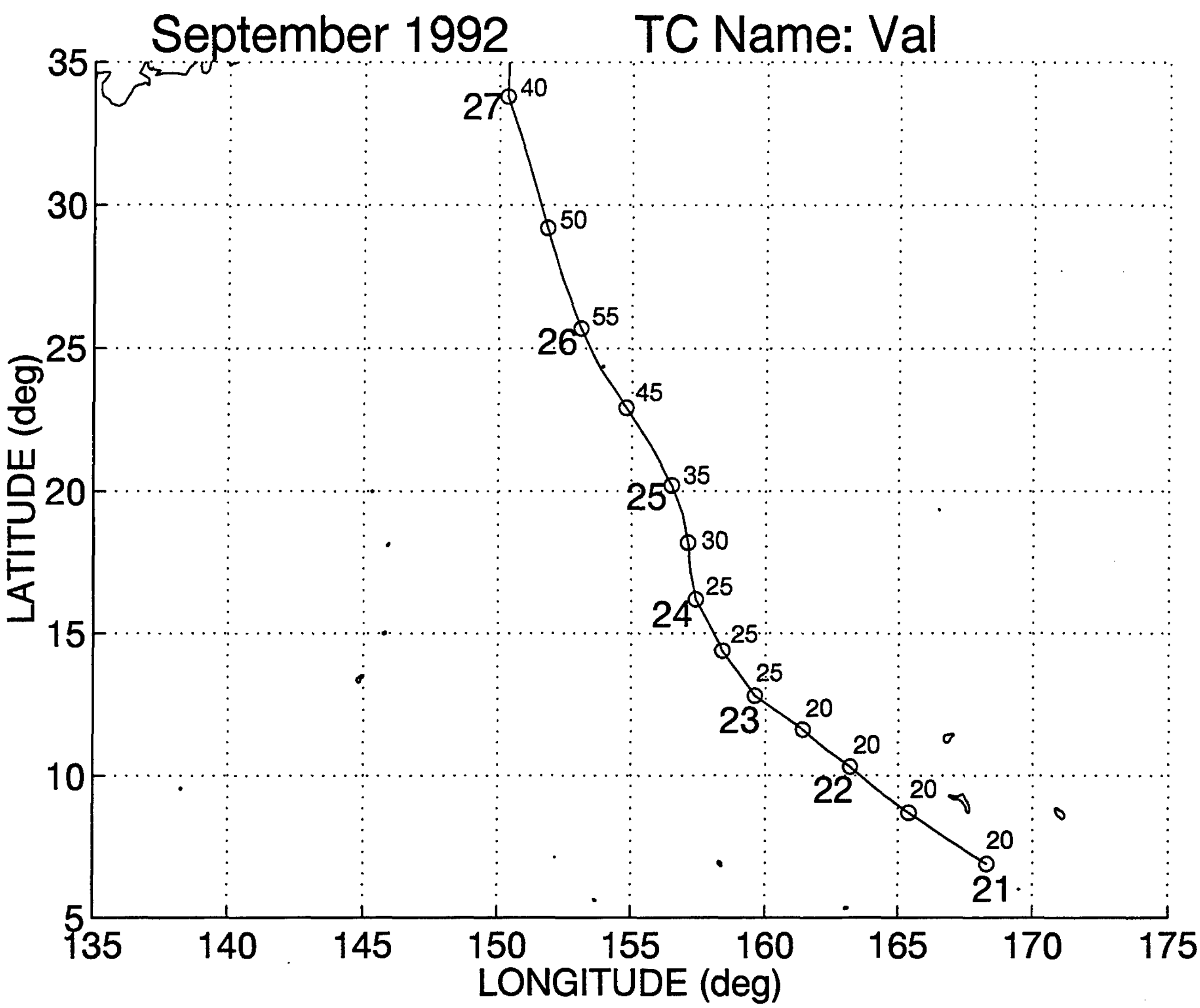
110
130
130
120
105
90
75


September 1992
TC Name: Val
LATITUDE (deg)
LONGITUDE (deg)
35
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135
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145
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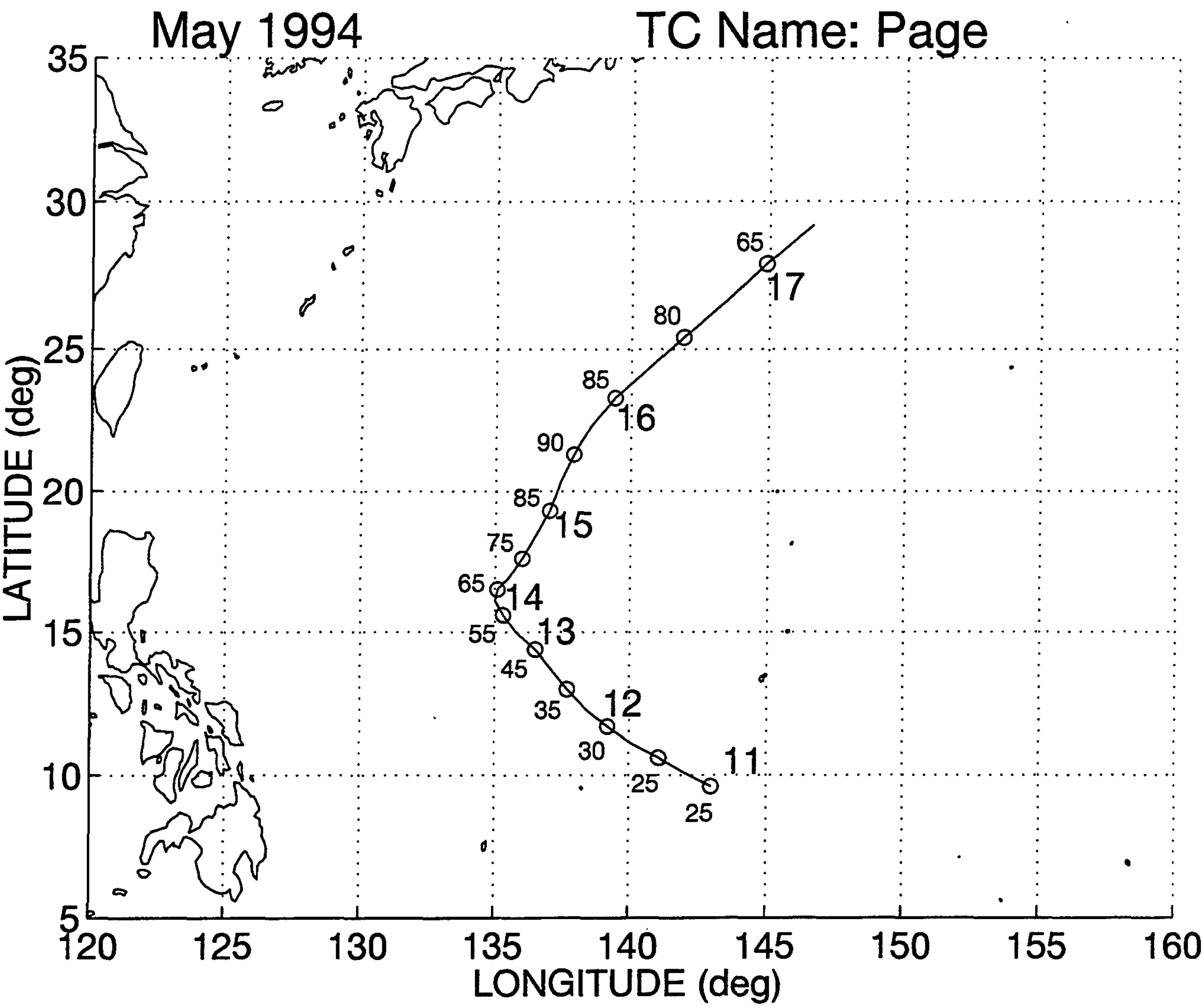

May 1994
TC Name: Page
LATITUDE (deg)
LONGITUDE (deg)
35
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120
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160
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80
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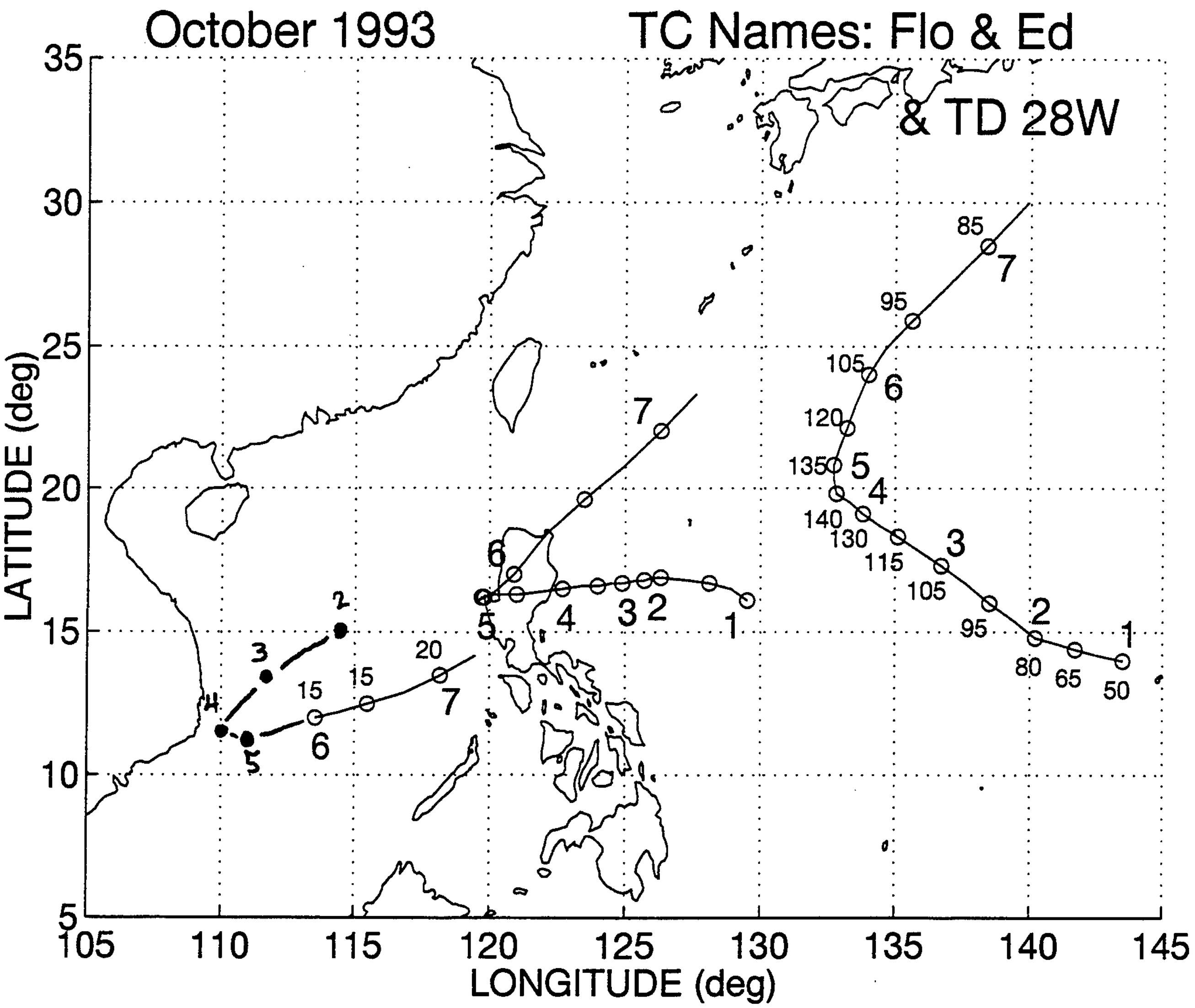

October 1993
TC Names: Flo & Ed
& TD 28W
LATITUDE (deg)
LONGITUDE (deg)
35
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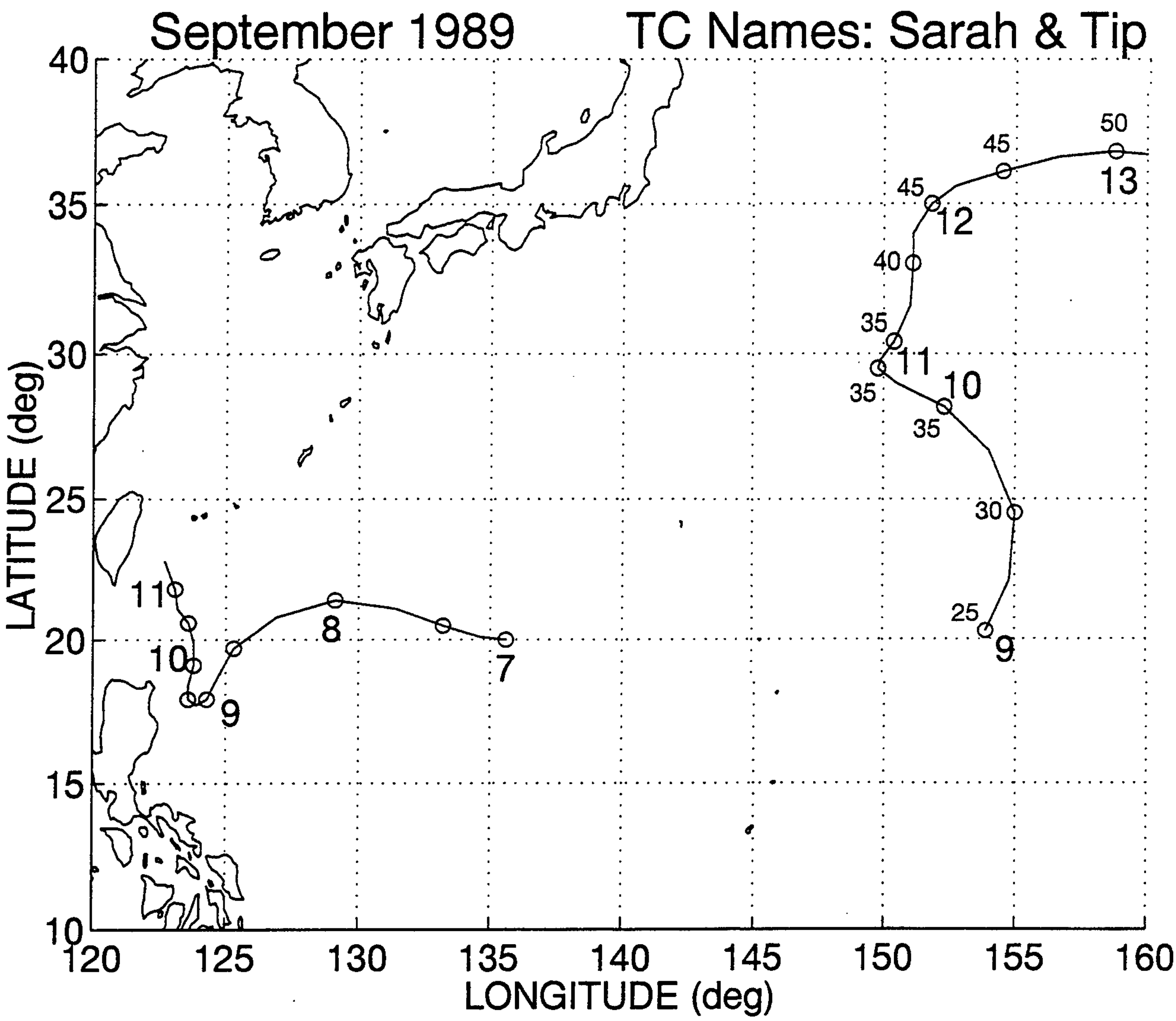
105
110
115
120
125
130
135
140
145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LATITUDE (deg)
LONGITUDE (deg)
40
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120
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130
135
140
145
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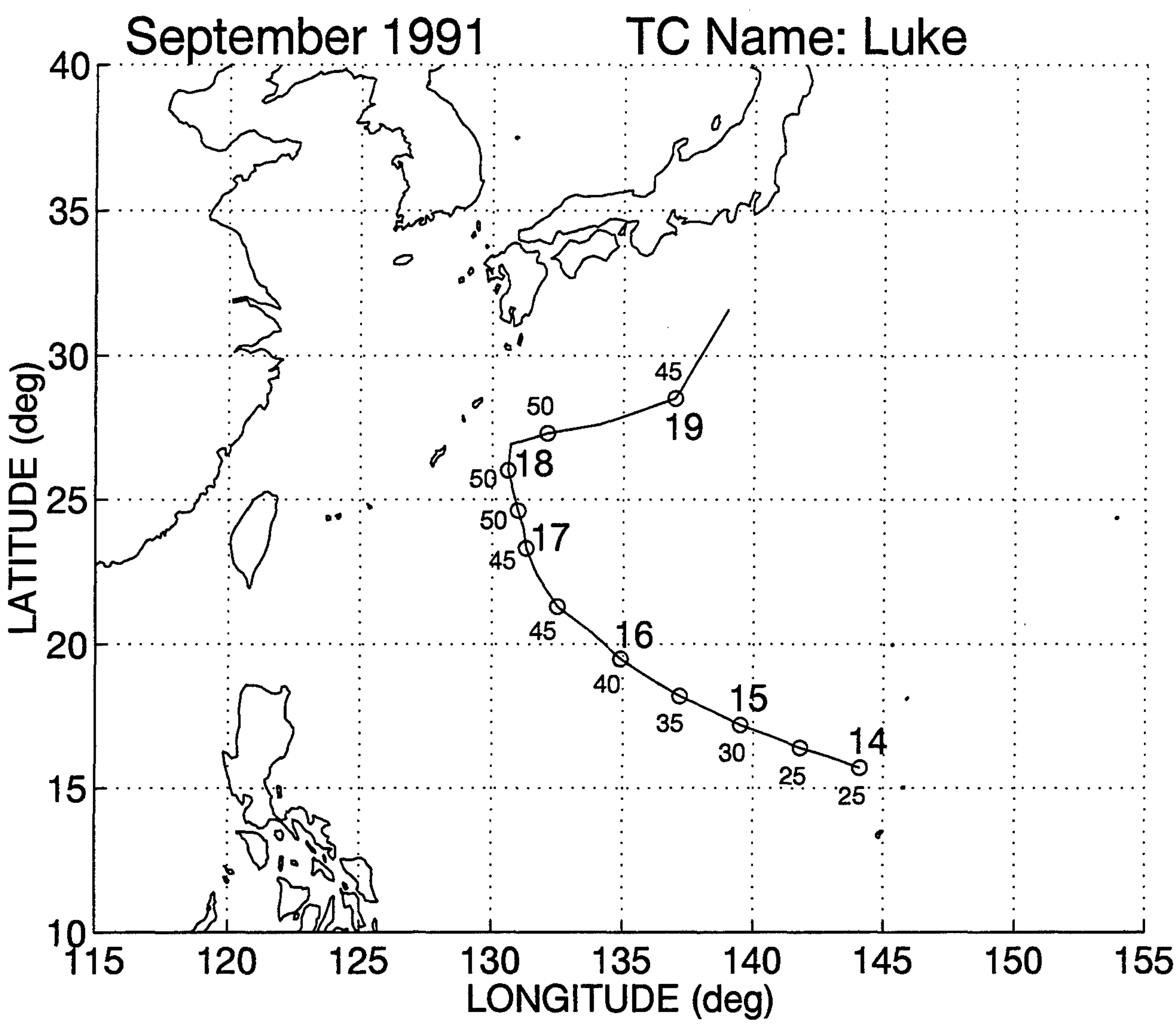
September 1991
TC Name: Luke
LATITUDE (deg)
LONGITUDE (deg)
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125
130
135
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145
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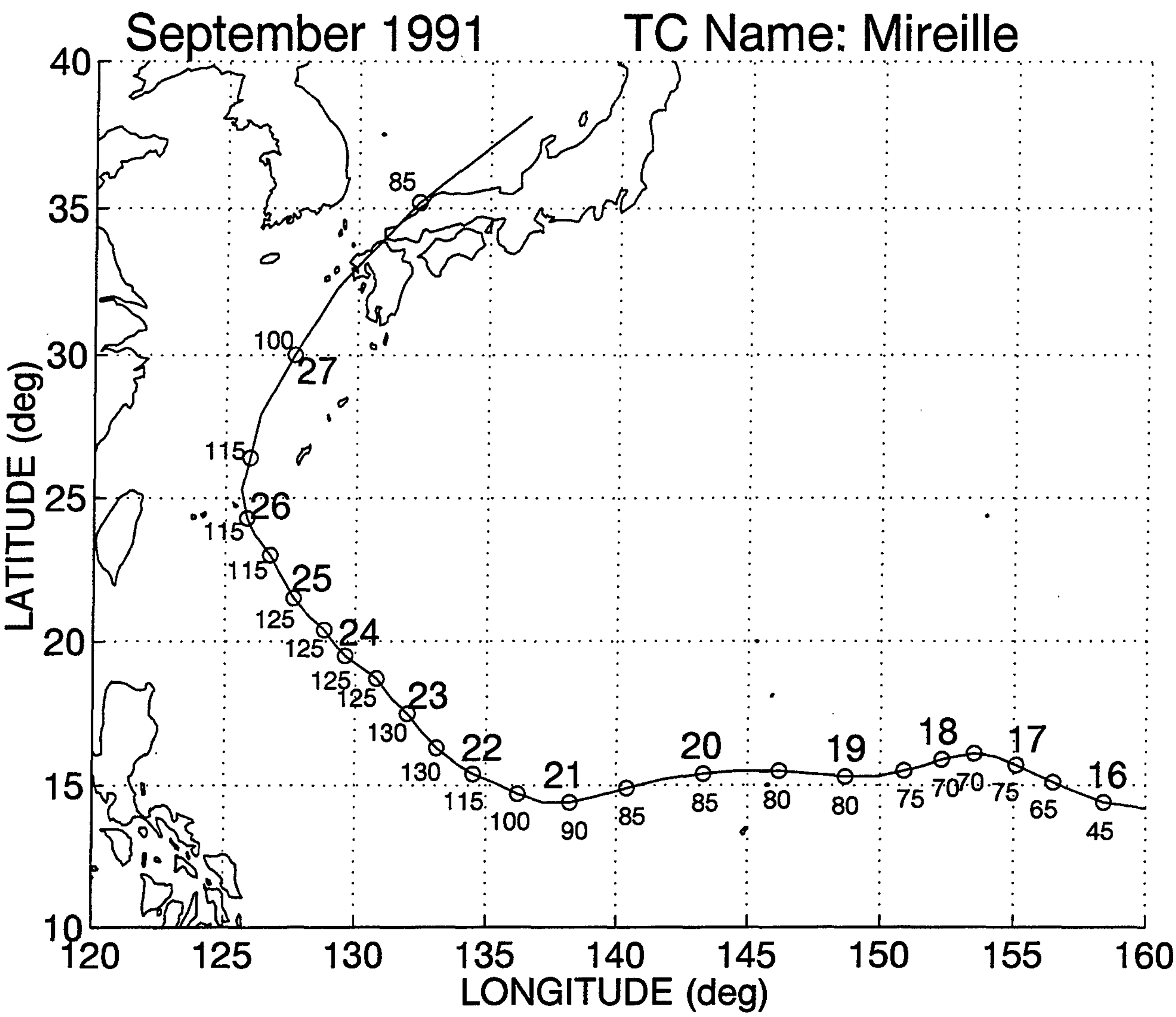
September 1991
TC Name: Mireille
LATITUDE (deg)
LONGITUDE (deg)
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115
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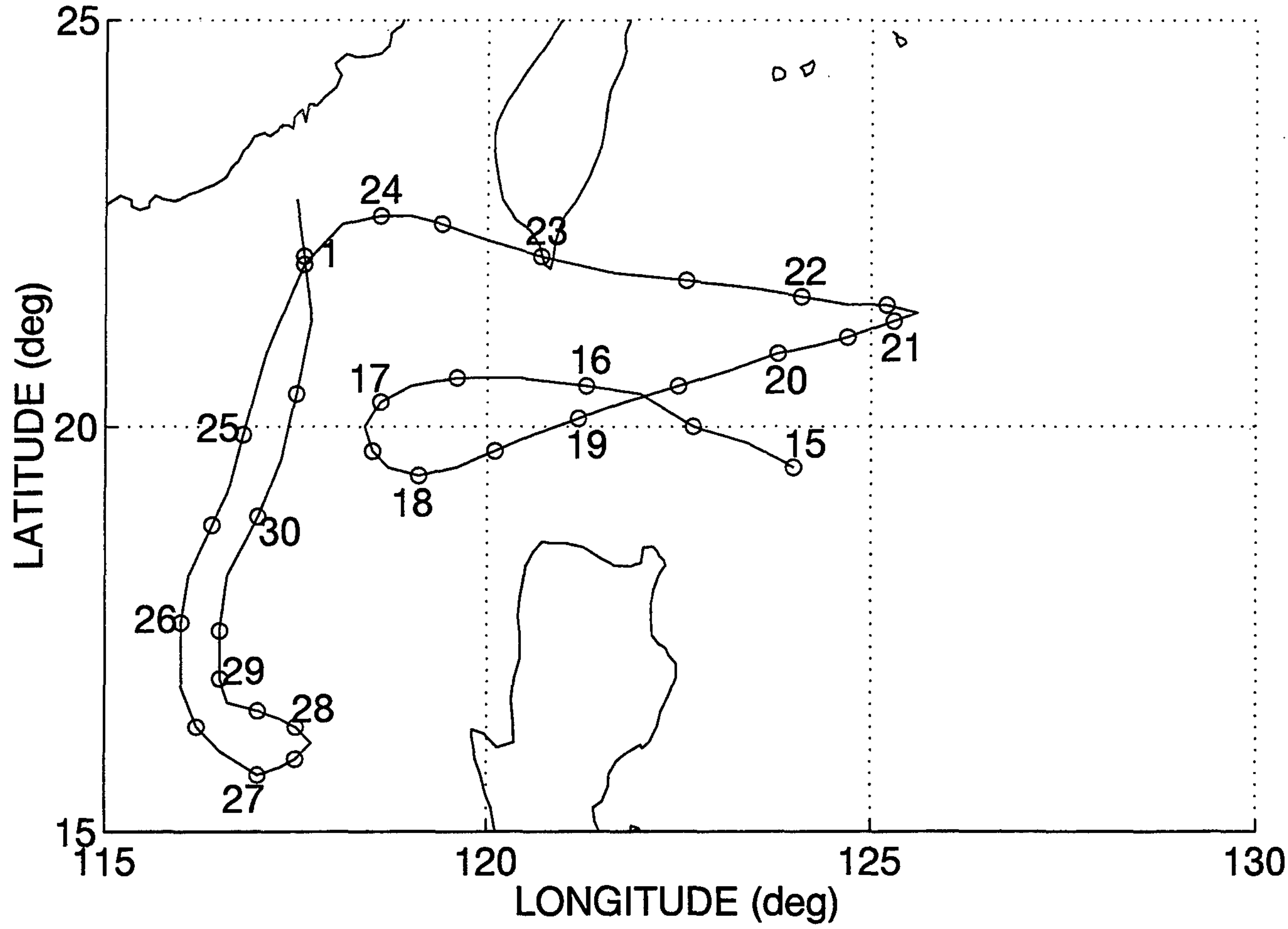
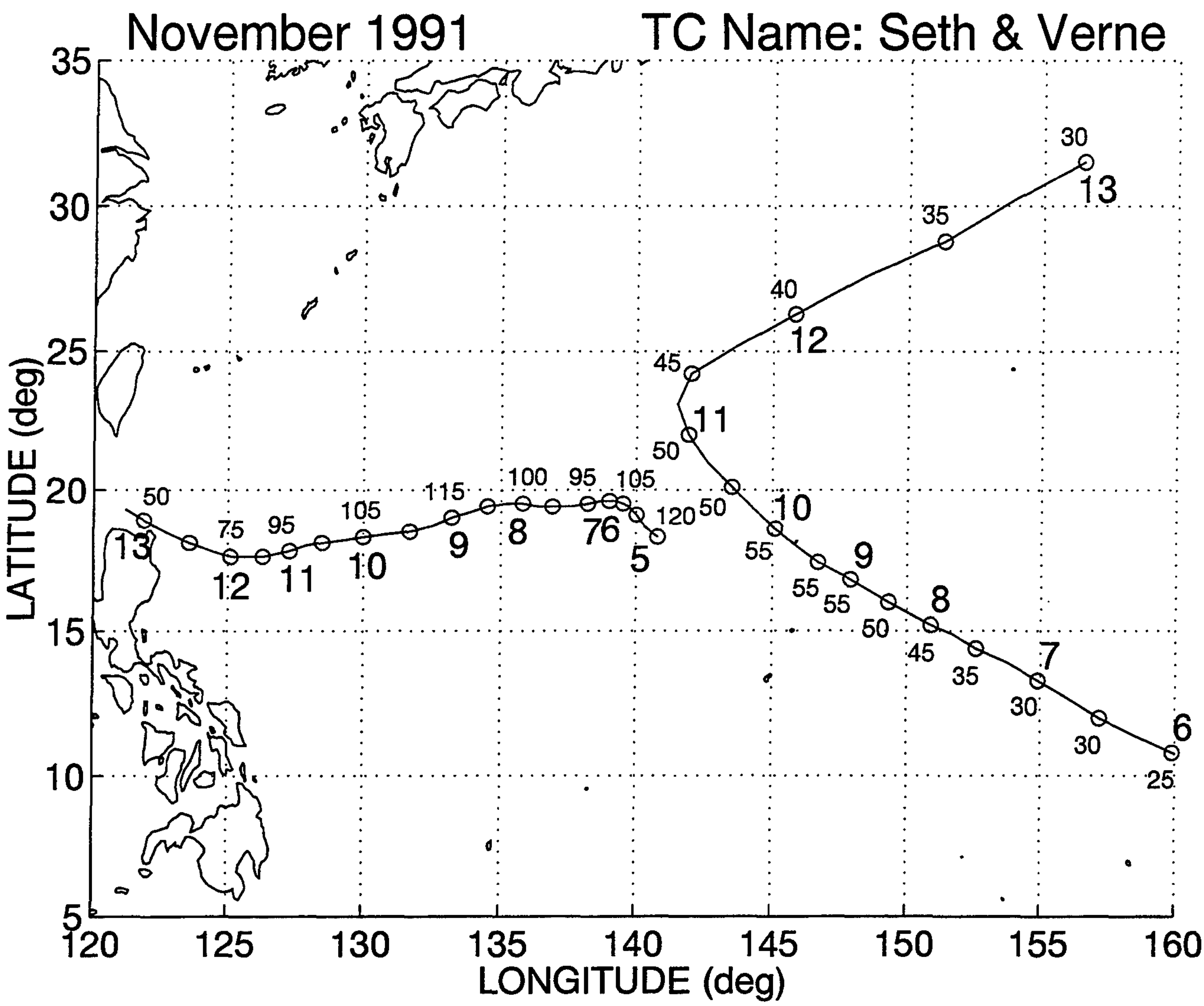
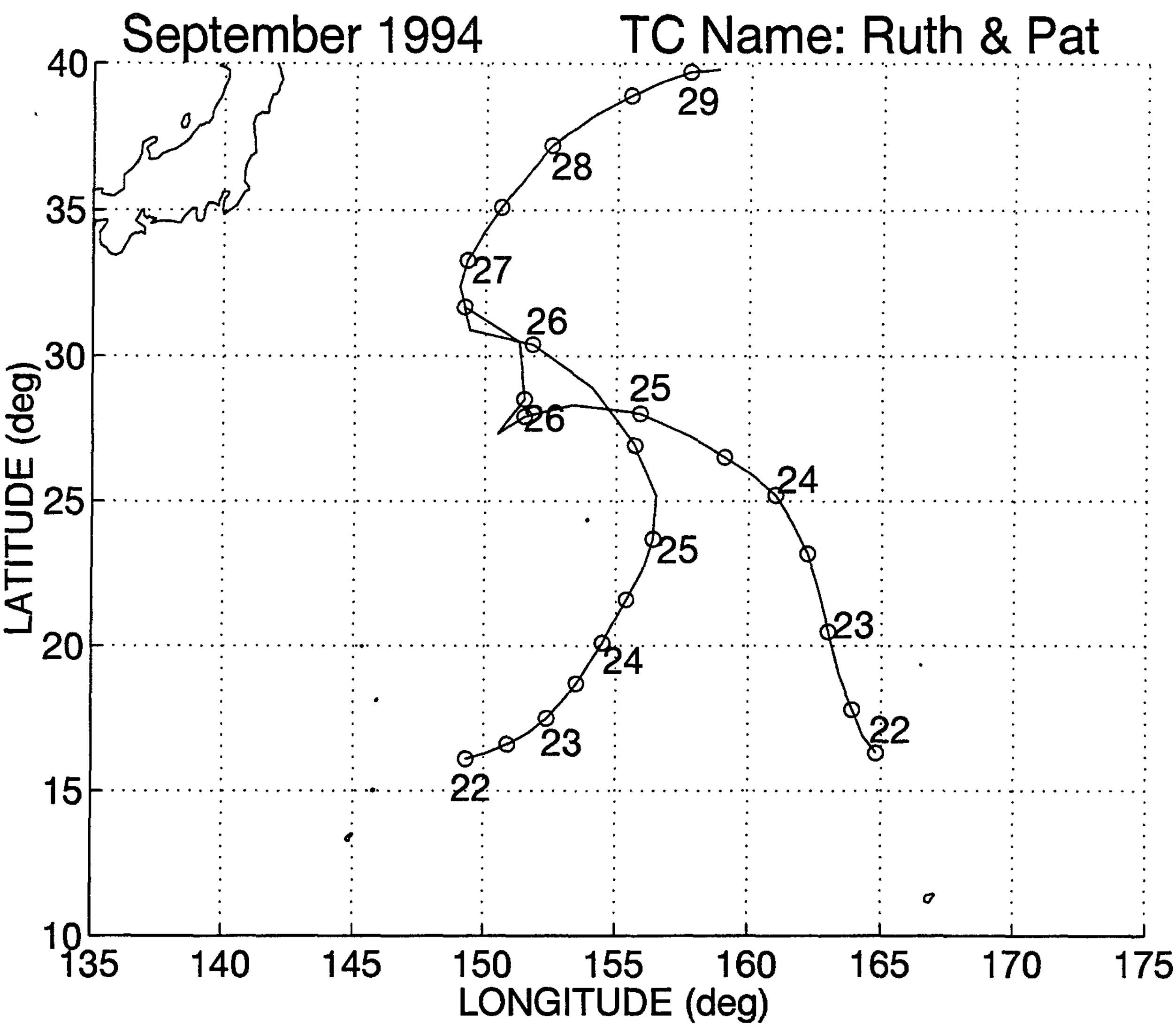
16
45

September 1991 TC Name: Nat





November 1991
TC Name: Seth & Verne
LATITUDE (deg)
LONGITUDE (deg)


September 1994
TC Name: Ruth & Pat
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LATITUDE (deg)
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LONGITUDE (deg)
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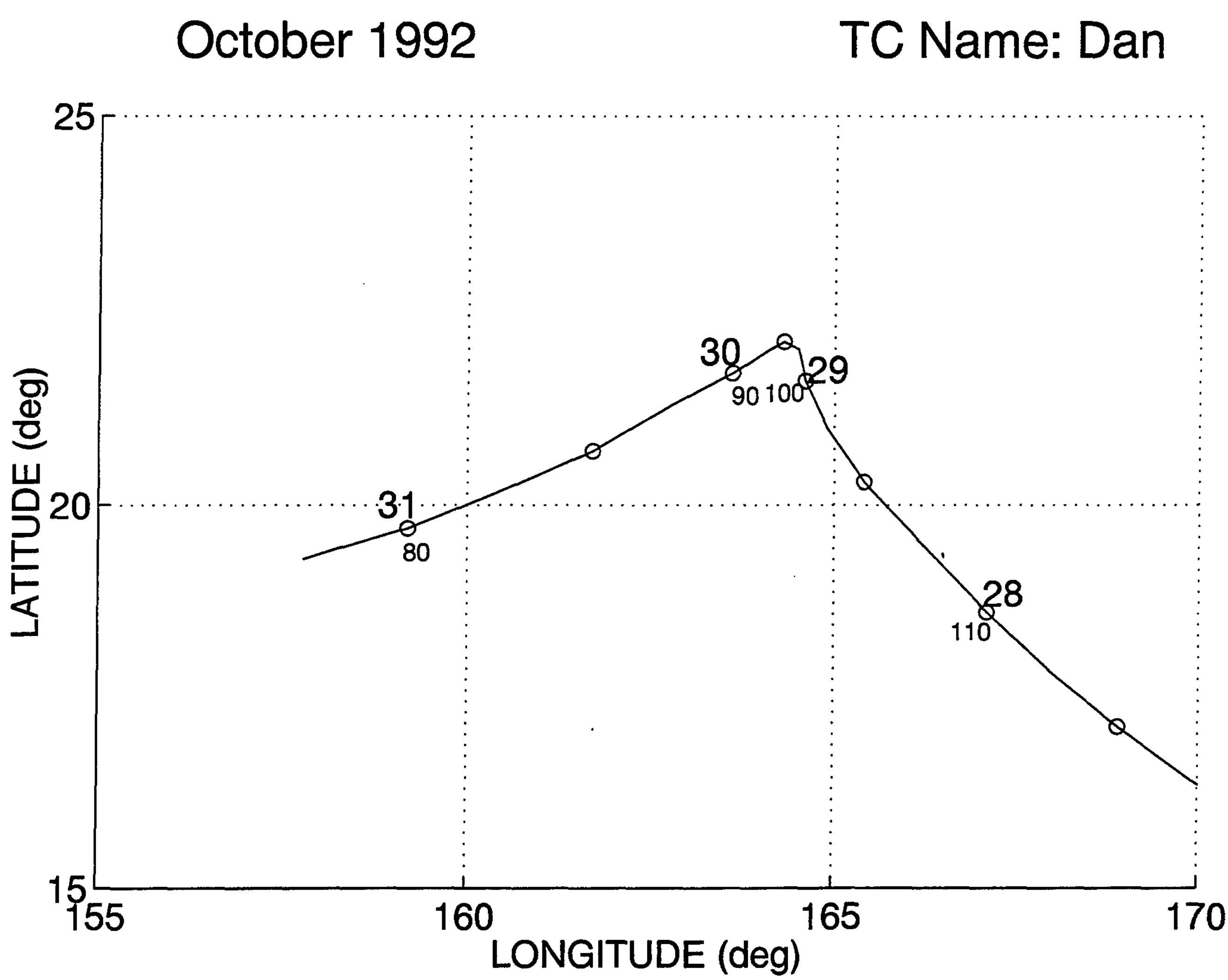

October 1992
TC Name: Dan
LATITUDE (deg)
LONGITUDE (deg)
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100
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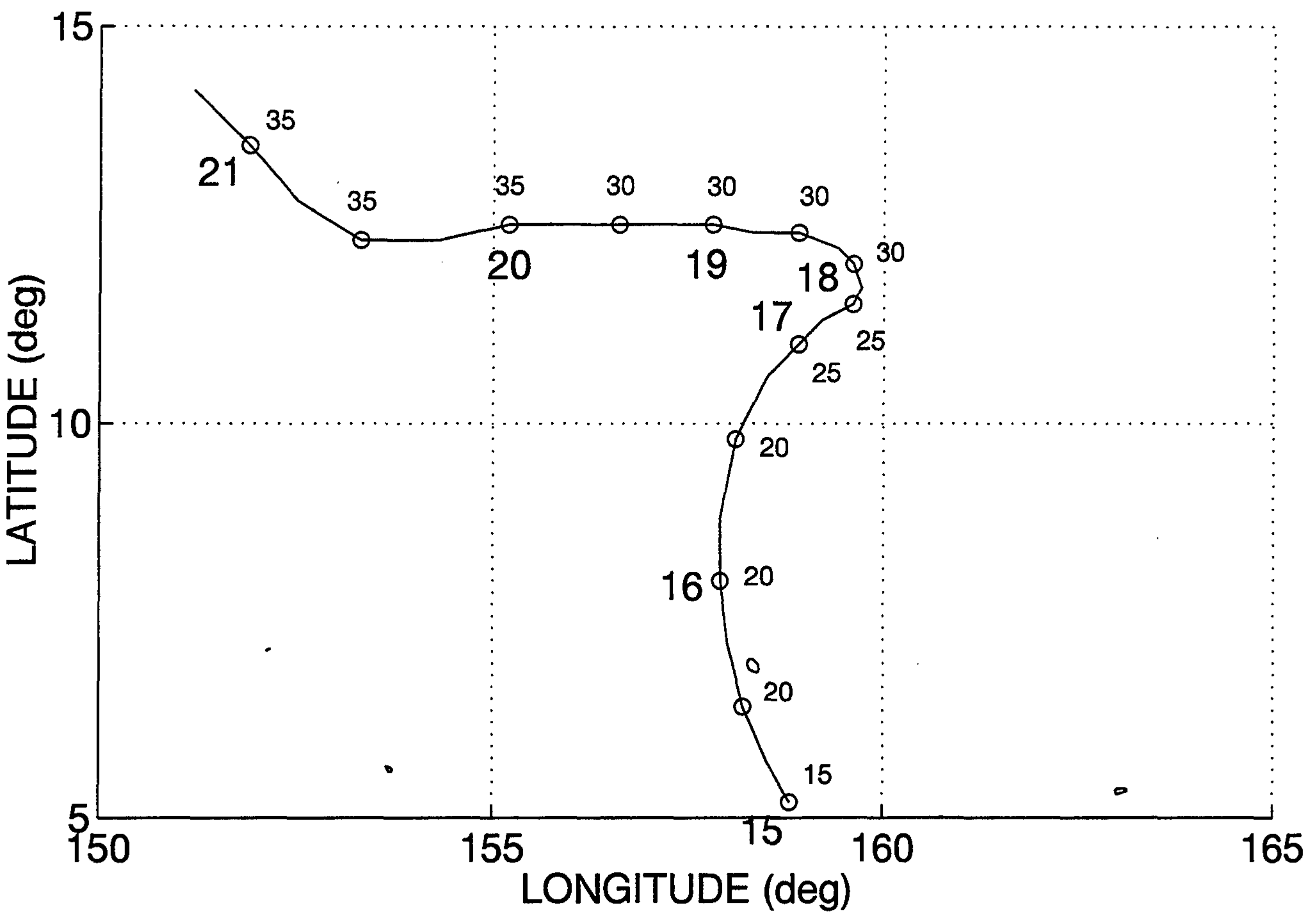
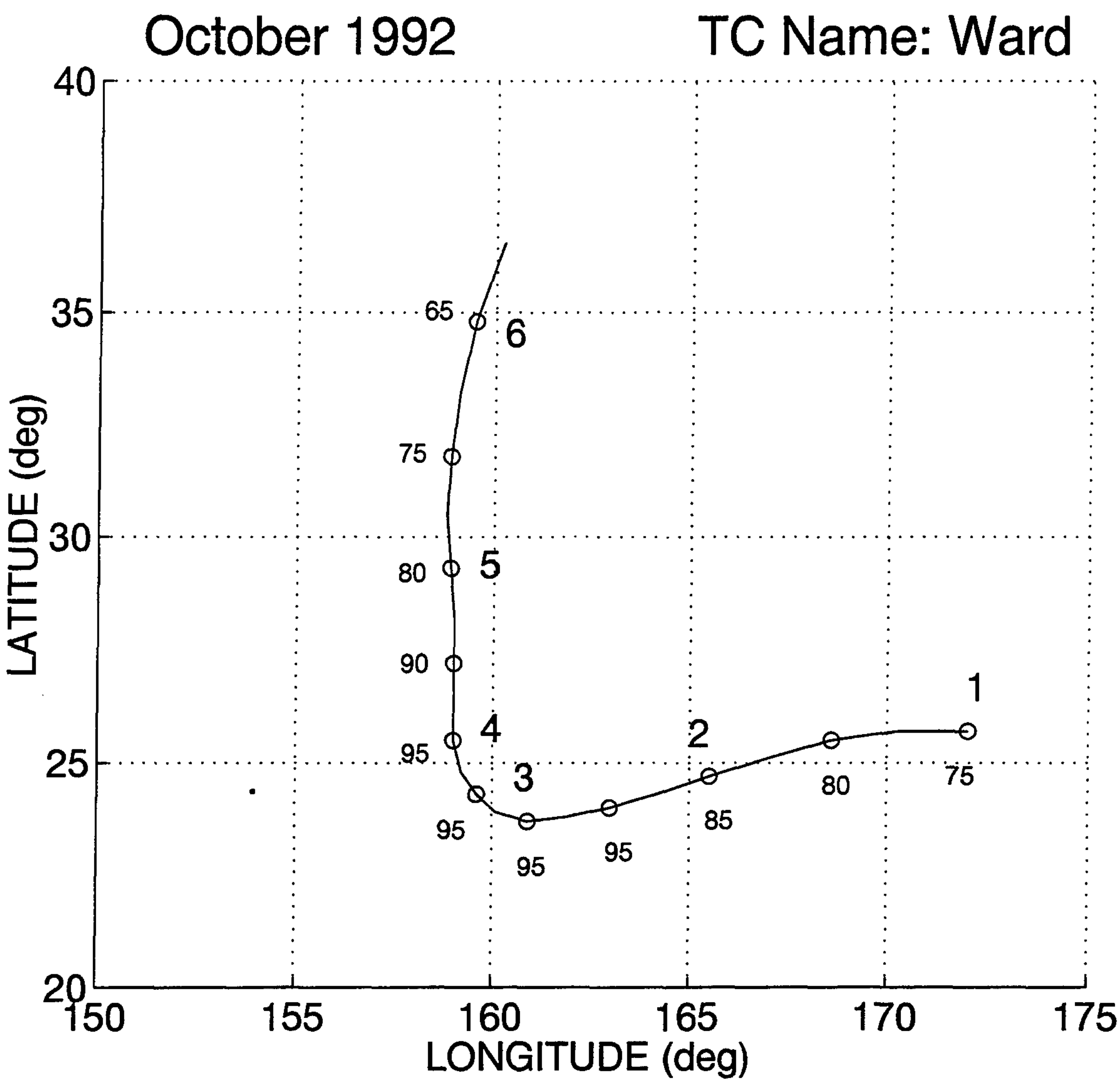
110

October 1993 TC Name: Jack

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TC Name: Ward
LATITUDE (deg)
LONGITUDE (deg)
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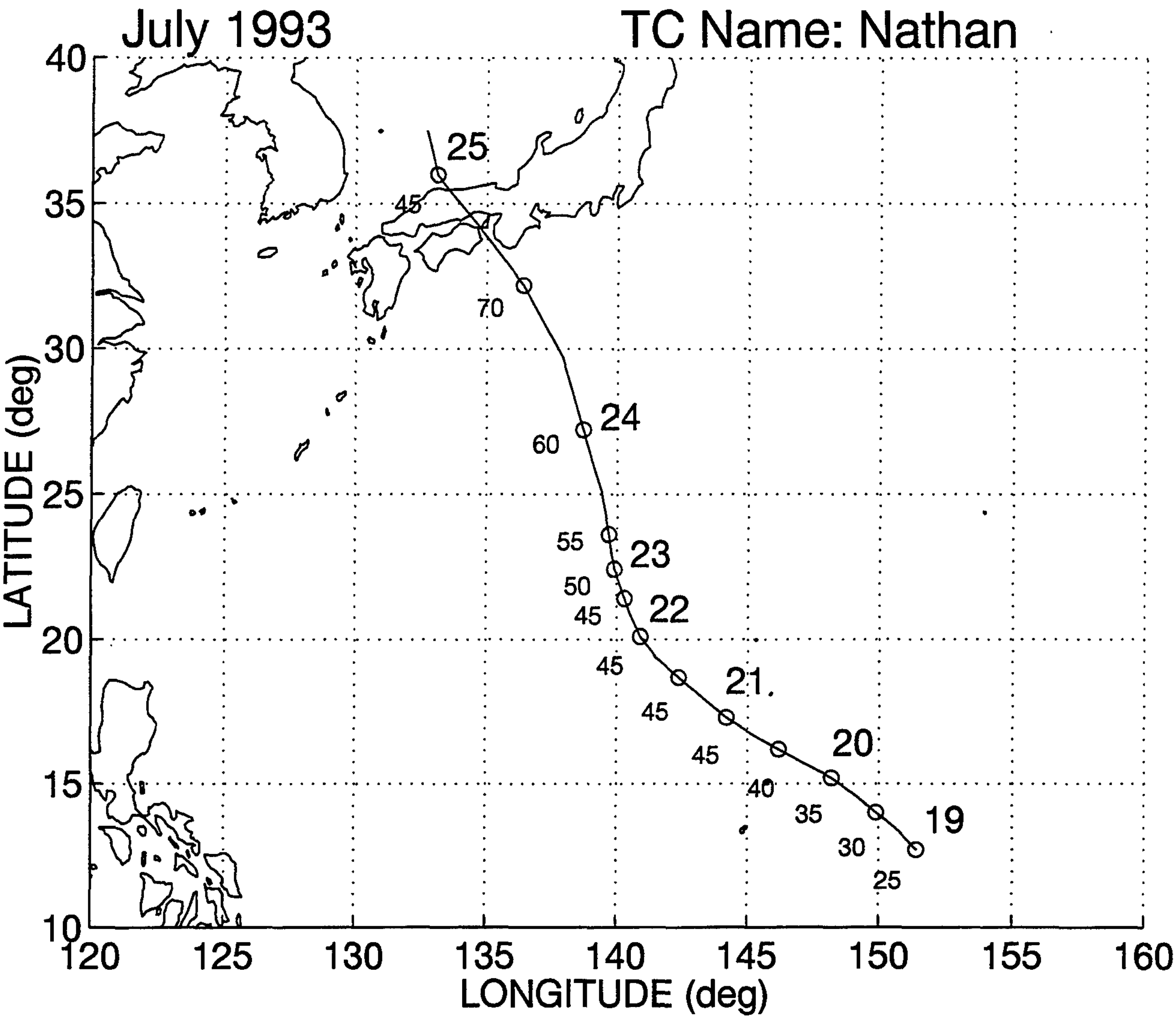

July 1993
TC Name: Nathan
LATITUDE (deg)
LONGITUDE (deg)
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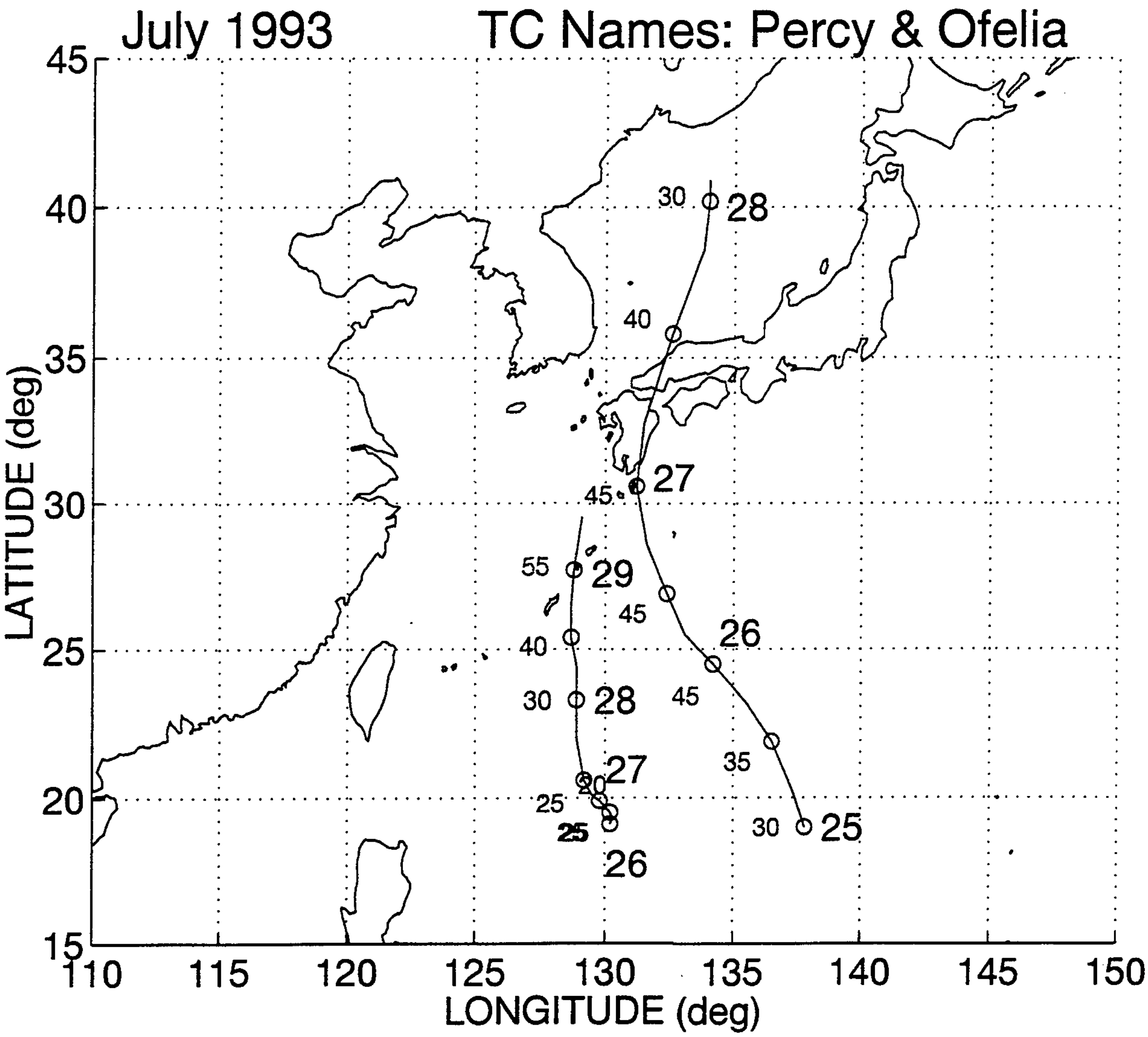
July 1993
TC Names: Percy & Ofelia
LATITUDE (deg)
LONGITUDE (deg)
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