NPS-MR-00-001

NAVAL POSTGRADUATE SCHOOL
Monterey, California

Condensed and Updated Version of the Systematic Approach Meteorological Knowledge Base Southern Hemisphere

by

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December 1999

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Prepared for: Office of Naval Research, Code 322MM, Arlington, VA 22217
SPAWARSYSCOM, Code PMW 185, San Diego, CA 92110

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Provost

This report was prepared for the Joint Typhoon Warning Center (JTWC) at the Naval Pacific Meteorology and Oceanography Center (NPMOC), Pearl Harbor, Hawaii. Funding was provided by the Office of Naval Research Marine Meteorology Program, and the Space and Naval Warfare Command (PWM 185), San Diego, California.

REPORT DOCUMENTATION PAGE

Form approved

OMB No 0704-0188

AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	December 1999	Interim 1/99 - 12/99

TITLE AND SUBTITLE
Condensed and Updated Version of the Systematic Approach Meteorological Knowledge Base
ıuthern Hemisphere

5. FUNDING
N0003900WRDF203

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8. PERFORMING ORGANIZATION REPORT NUMBER

SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of Naval Research	SPAWARSYSCOM
Code 322 MM	Code PMW 185
800 N. Quincy St.	San Diego, CA 92110-3127
Arlington, VA 22217-5000	

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

.. 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.

.a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for Public Release; Distribution Unlimited

12b. DISTRIBUTION CODE

. ABSTRACT (Maximum 200 words.)

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

SUBJECT TERMS
pical cyclone track forecasting
ıpical cyclone motion

15. NUMBER OF PAGES
140

16. PRICE CODE

SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	

7540-01-280-5800

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std 239-18

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Acknowledgements. This research has been sponsored by the Office of Naval Research Marine Meteorology Program and by Space and Naval Warfare Systems Command. The authors gratefully acknowledge the assistance by personnel at the Naval Pacific Meteorology and Oceanography Center/Joint Typhoon Warning Center, Pearl Harbor, Hawaii. NOGAPS analyses and GFDN 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, 1998) and Reader *et al.* (1999). These applications to other basins indicated the possibility of a general applicability, so that some names were changed to allow global application.

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 Southern Hemisphere. This documentation is based on nine years (1990-91 through 1998-99), 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. 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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Bannister, A. J., M. A. Boothe, L.E. Carr, III, and R. L. Elsberry, 1997: Southern Hemisphere application of the systematic approach to tropical cyclone track forecasting. Part I. Environment structure characteristics. Tech. Rep. NPS-MR-98-001, Naval Postgraduate School, Monterey, CA 93943-5114, 96 pp.

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Reader, G., M. A. Boothe, R. L. Elsberry, and L. E. Carr, III, 1999: Southern Hemisphere application of the systematic approach to tropical cyclone track forecasting. Part III. Updated environmental structure characteristics and preliminary numerical model traits. Tech. Rep. MR-99-004, Naval Postgraduate School, Monterey, CA 93943-5114, (in press).

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.

Topic: KEY TC MOTION CONCEPTS

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

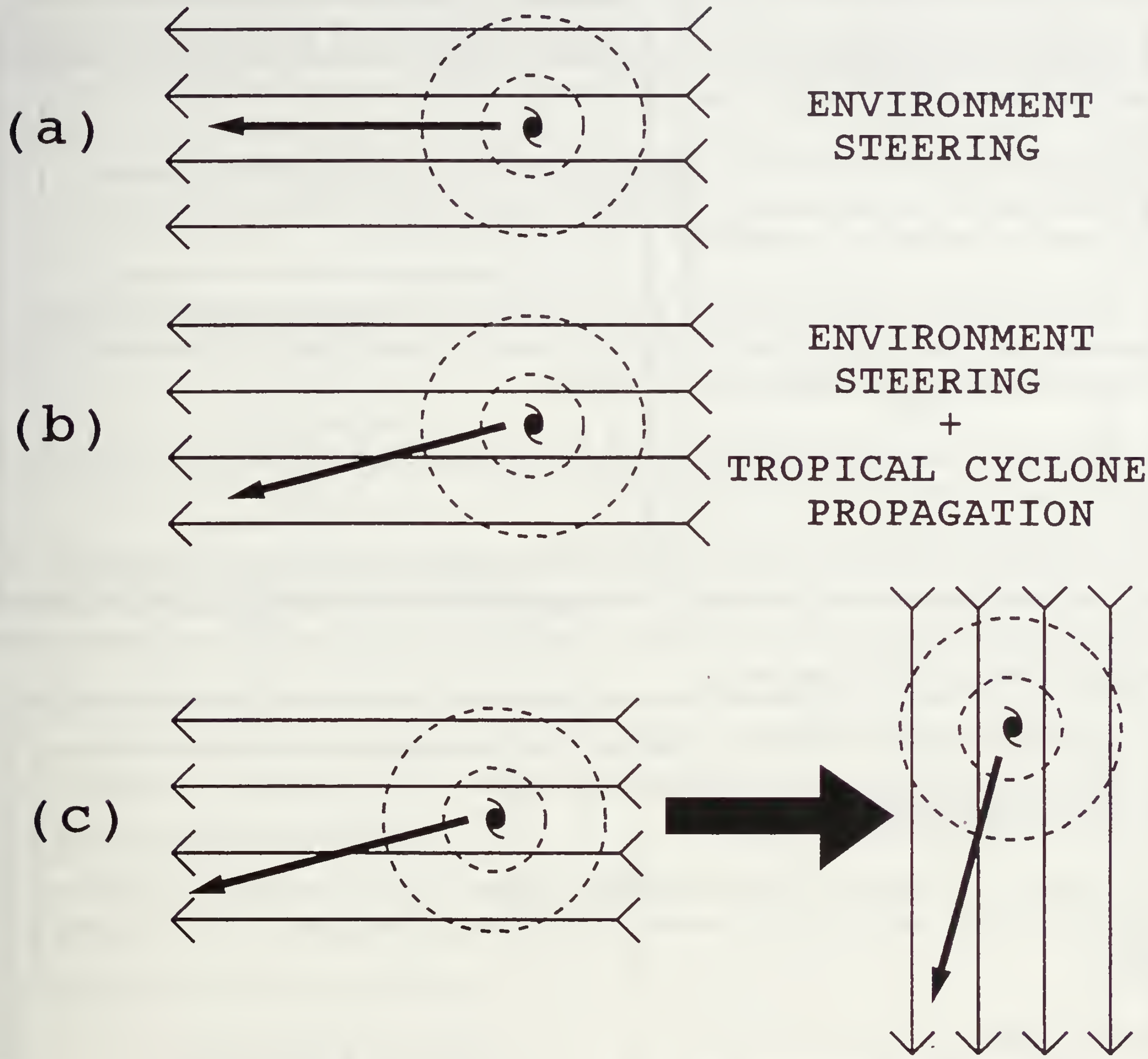
(a) ENVIRONMENTAL STEERING: To a first approximation, the TC vortex is advected by the large-scale environmental flow (i.e., the TC moves as a "cork in the stream");

(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. 19-56
Beta-effect Propagation p. 57
TC-Environment Transformations p. 57-116

KEY TC MOTION CONCEPTS



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

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.

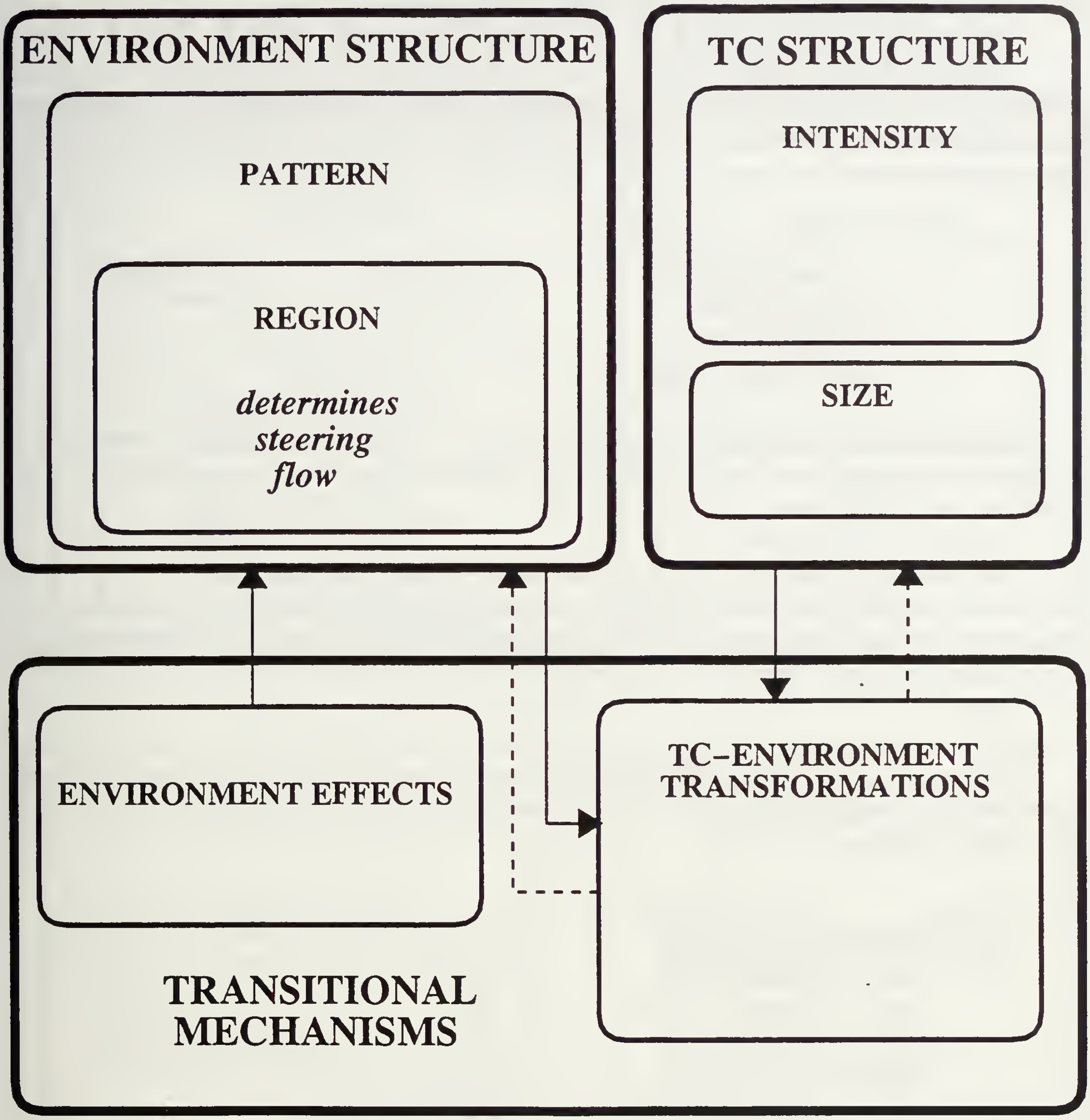
(2) ENVIRONMENT EFFECTS, which also result in changes to the structure of the environment (pattern/region) surrounding the TC, but that do not depend on, or are largely independent of, the presence of the TC.

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

Cross references:

Southern Hemisphere examples
Environment Structure p. 19-56
TC Structure p. 13-16
Transitional Mechanisms
TC-Environment Transformations, p. 57-116
Environment Effects p. 117-130

METEOROLOGICAL KNOWLEDGE BASE



Topic: SOUTHERN HEMISPHERE KNOWLEDGE BASE

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

PATTERN	REGION OPTIONS
S	EW, TE, EF, PF
P	EW, PF, EF
H	RE, EW, RP, TP
M	PF, EF, MW, ME

The HIGH-AMPLITUDE PATTERN is virtually unique to the Southern Hemisphere. The other patterns occur in other basins, but with different frequencies of occurrence from those for the Southern Hemisphere.

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 generally applicable to all basins (albeit with different titles and subdivisions), the frequency of intensity and size classifications varies from basin to basin.

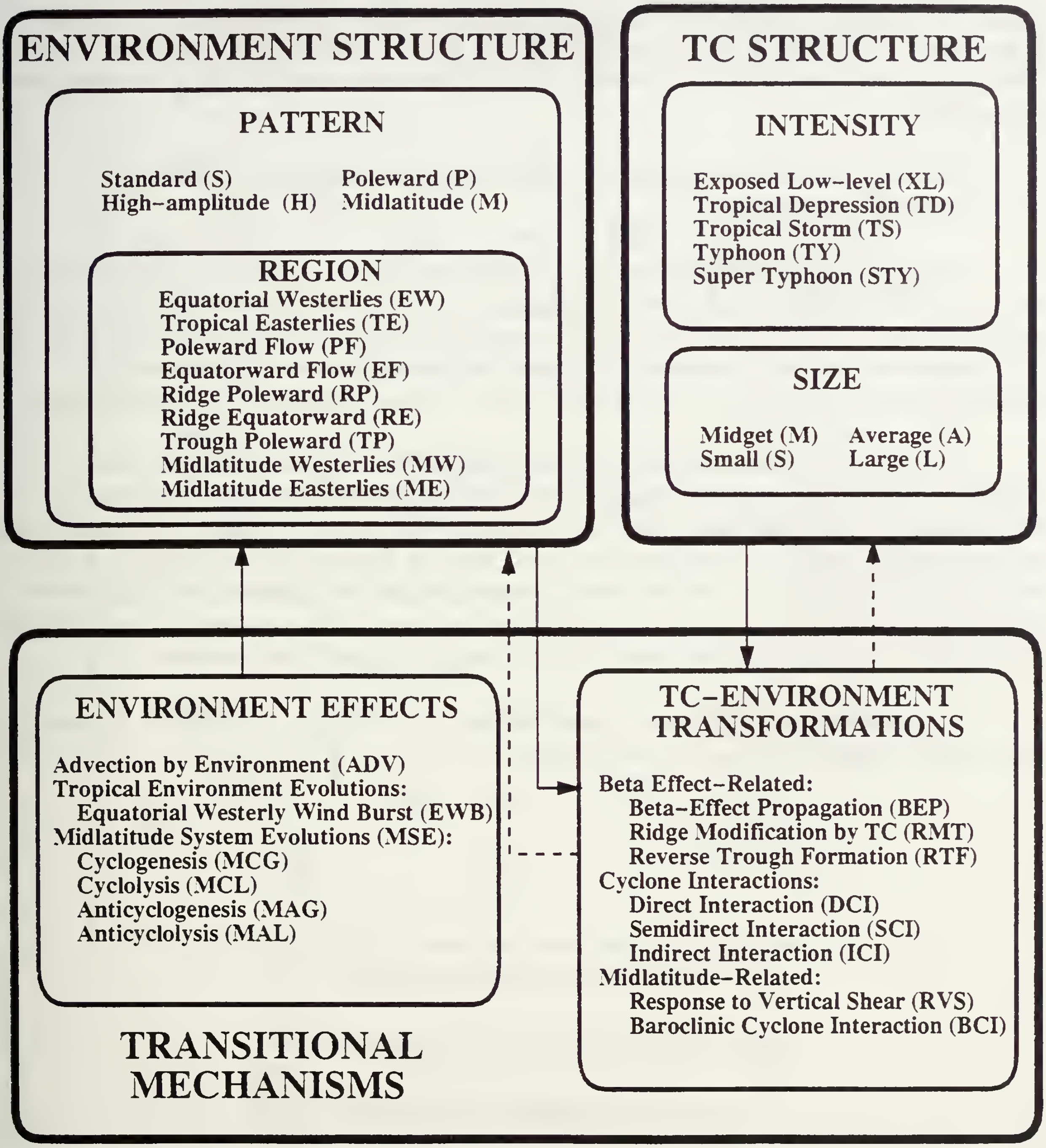
Of the TRANSITIONAL MECHANISMS, only those involving a high-amplitude trough are unique to the Southern Hemisphere. The frequency of occurrence of the others varies widely from basin to basin.

Cross-references:

Southern Hemisphere examples

S/EW	p. 25-26	H/EW	p. 43-44
S/TE	p. 25-26	H/TP	p. 43-44
S/PF	p. 27-28	H/RE	p. 45-46
S/EF	p. 27-28	H/RP	p. 45-46
P/PF	p. 35-36	M/PF	p. 53-54
P/EW	p. 35-36	M/EF	p. 53-54
P/EF	p. 35-36	M/MW	p. 53-54
TC Intensity	p. 13	M/ME	(No cases)
TC Size	p. 15		

Meteorological Knowledge Base for the Southern Hemisphere



Topic: DIAGNOSING ENVIRONMENTAL STEERING DIRECTION

As defined in the key motion concepts (p. 3), 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:

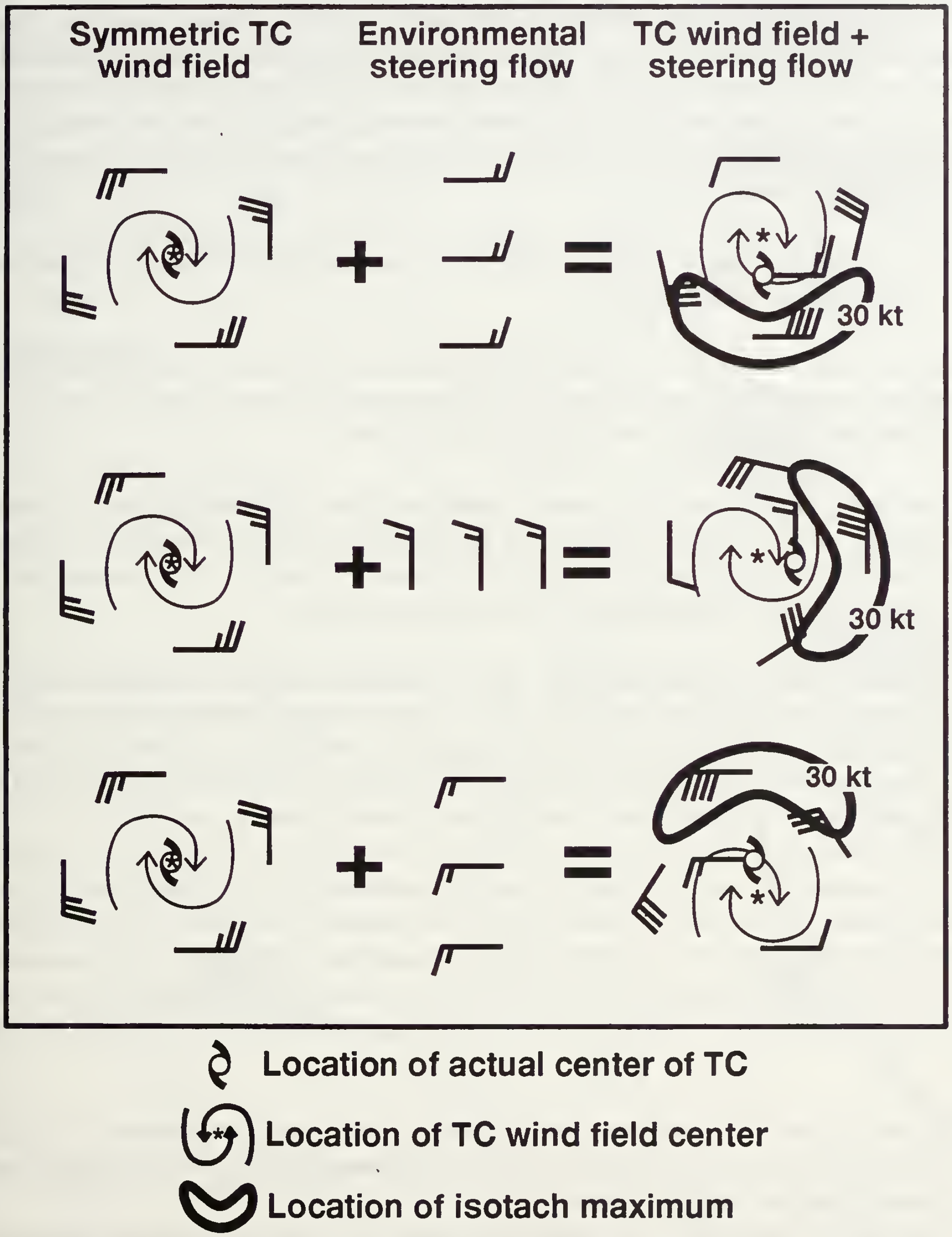
(a) a wind maximum to the left (Southern Hemisphere) of the direction of the environmental steering flow; and

(b) a displacement of the analyzed wind circulation center to the right 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 synoptic 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 page 11).

MOTION-INDUCED SHIFTING OF TC WIND FIELD CENTER CONCEPTUAL MODEL



Topic: DIAGNOSING ENVIRONMENTAL STEERING DIRECTION (cont)

The NOGAPS streamline/isotach analysis in panel b 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 right (of the direction of motion indicated by track in panel a), and the model-analyzed isotach maximum to the left. In this case, the orientation of the three positions implies that the environmental steering direction is toward the west-southwest. This direction is consistent with the recent 12-h translation direction of the TC (panel a) when the propagation effect is included.

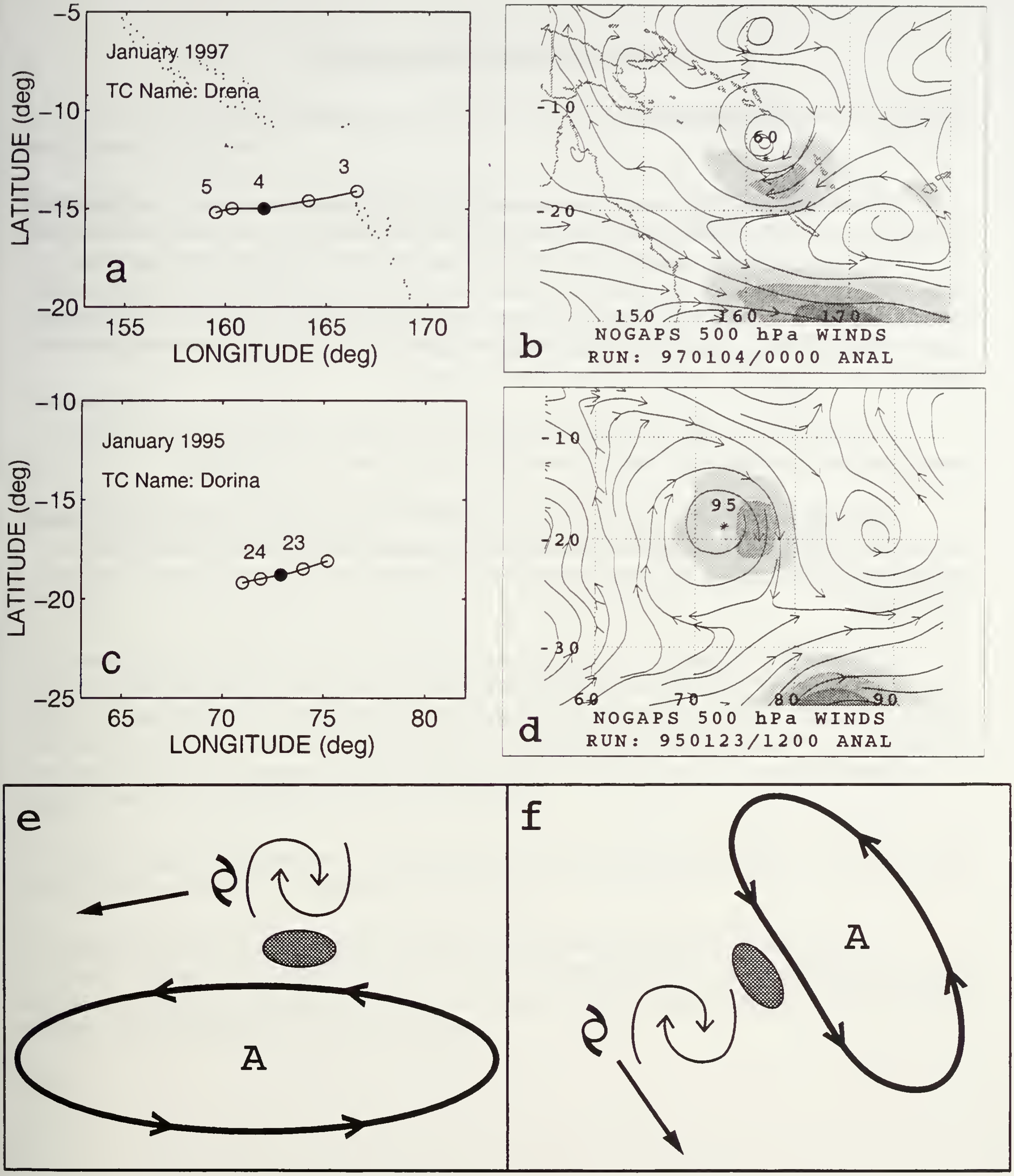
By contrast, the analysis in panel d has an inconsistent relationship among the three positions, which indicates that either:

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

Notice that the recent west-southwestward translation direction of the TC (panel c) disagrees with the steering direction inferred from NOGAPS streamline/isotach maximum. This strongly sugggests that the NOGAPS analysis is in error because the position of the isotach maximum to the east would imply a storm translation to the south 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 e and f on p. 12. In these cases, either the warning position or the wind circulation center in the NOGAPS analysis is incorrect. In panel e, the warning position may be northwest (i.e., in advance and to the right) of the actual position, or the wind circulation center is southeast (i.e., behind and to the left) of the proper location. In panel f, the warning position is behind and to the right of the actual position, or the wind circulation center is east and north 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 synthetic 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.


January 1997
TC Name: Drena
5
4
3
a
LATITUDE (deg)
LONGITUDE (deg)
-5
-10
-15
-20
155
160
165
170
-10
-20
60
150
160
170
b
NOGAPS 500 hPa WINDS
RUN: 970104/0000 ANAL
January 1995
TC Name: Dorina
24
23
c
LATITUDE (deg)
LONGITUDE (deg)
-10
-15
-20
-25
65
70
75
80
-10
-20
-30
95
60
70
80
90
d
NOGAPS 500 hPa WINDS
RUN: 950123/1200 ANAL
e
A
f
A

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

The JTWC intensity definitions are given here; each Southern Hemisphere forecast center has different definitions.

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	(TC)	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 cyclone 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 south has a small horizontal scale. Conversely, a large TC may have only moderate environment modification potential if the subtropical ridge circulation to the south is very large.

Cross-reference:

Beta-effect Propagation p. 57ff

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_o^{850}), 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_o^{850} at a constant latitude, but also by increasing (decreasing) latitude at a constant R_o^{850}.

Since R_o^{850} 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_o^{850} (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_o^{850}.

Because neither of these size estimates will be precise, the R_o^{850} and f_o values are used to define a BEP speed in one of four broad categorizations (see previous page).

Cross-reference:

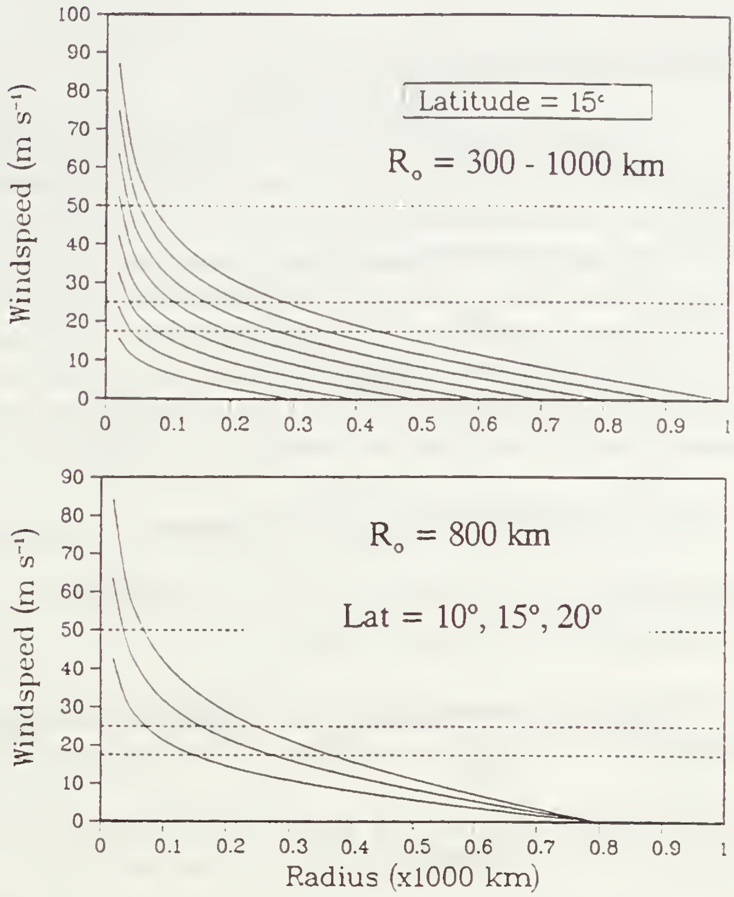
Beta-effect Propagation p. 57ff

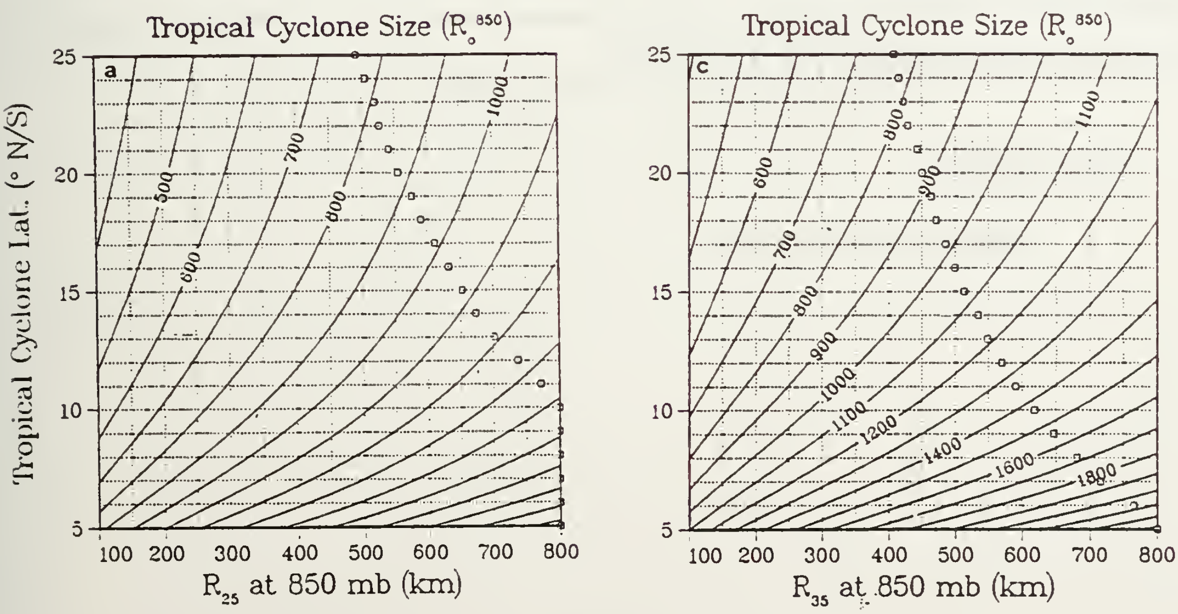
ANGULAR MOMENTUM-BASED TC WIND DISTRIBUTION MODEL

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

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

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





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 MIDLATITUDE CYCLOGENESIS (MCG), 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. In the Southern Hemisphere, 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) TROPICAL EASTERLIES (TE), 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.

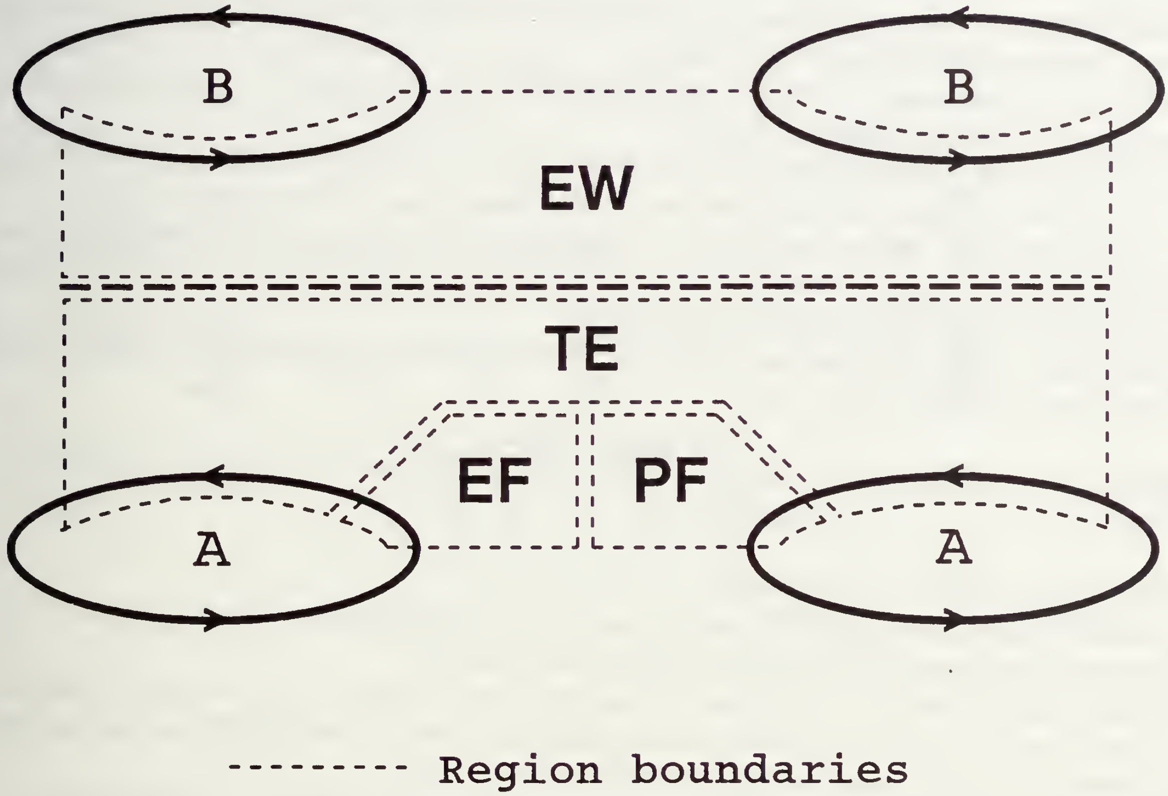
(c) POLEWARD FLOW (PF), which encompasses the area of northeasterly winds on the west-northwest quadrant of the eastern STR cell.

(d) EQUATORWARD FLOW (EF), which encompasses the area of southeasterly winds on the east-northeast quadrant of the western STR cell.

Cross-reference:

Midlatitude CycloGenesis p. 121

STANDARD (S) PATTERN



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 N to NE of the TC.
(b) In the TE region, the isotach maximum will be found SSW to SE of the TC depending on the orientation of the STR axis (sloping vs. zonal).
(c) In the PF region, the isotach maximum will be oriented from SE to E of the TC depending on the location of the TC in the region. A ridge (peripheral anticyclone) may be located NE of large Southern Hemisphere TCs. If the peripheral anticyclone becomes strong enough to shift the isotach maximum to an E to NE position, and the TC is moving strongly poleward (say < 180 deg), then the pattern/region classification is actually P/PF (see below).
(d) In the EF region, the isotach maximum will be oriented from W to WNW of the TC depending on the location of the TC in the region.

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

(1) an EASTWARD track in the EW region;
(2) a persistently westward STRAIGHT track in the TE region that may also have a small to moderate poleward component for average to large sizes of the TC;
(3) a RECURVATURE track, in which the TC changes direction from a westward track in the TE region to a more poleward track as it enters a trough-induced break in the STR (PF region) and then passes the latitude of the STR axis into the Midlatitude (M) pattern;
(4) 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 NW in the EF region and perhaps returns to the tropics in the TE region.

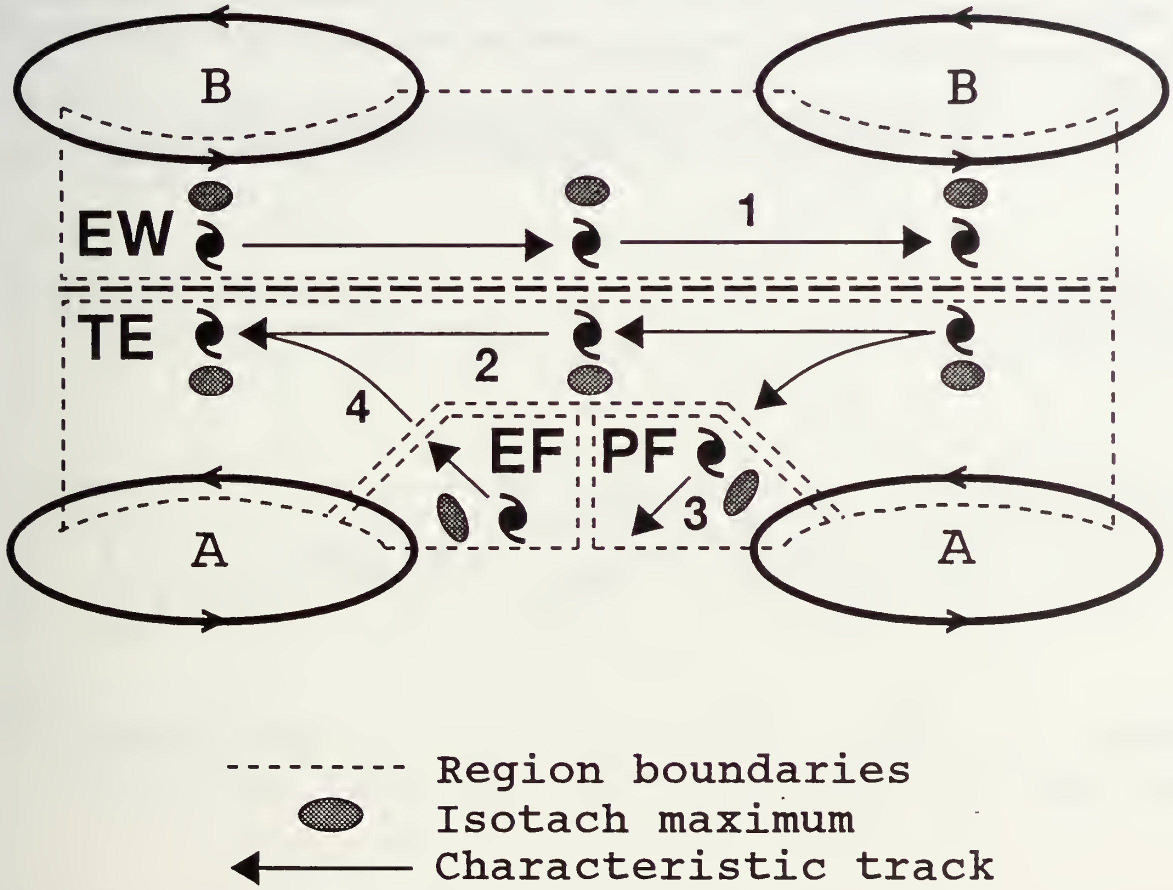
NOTES: At the bifurcation point between characteristic tracks 3 and 4, only subtle variations in TC position, STR structure, and midlatitude trough behavior may alter whether the TC "stair-steps" or "recurves."

Cross-references:

P/PF pattern/region p. 29

Midlatitude pattern p. 47

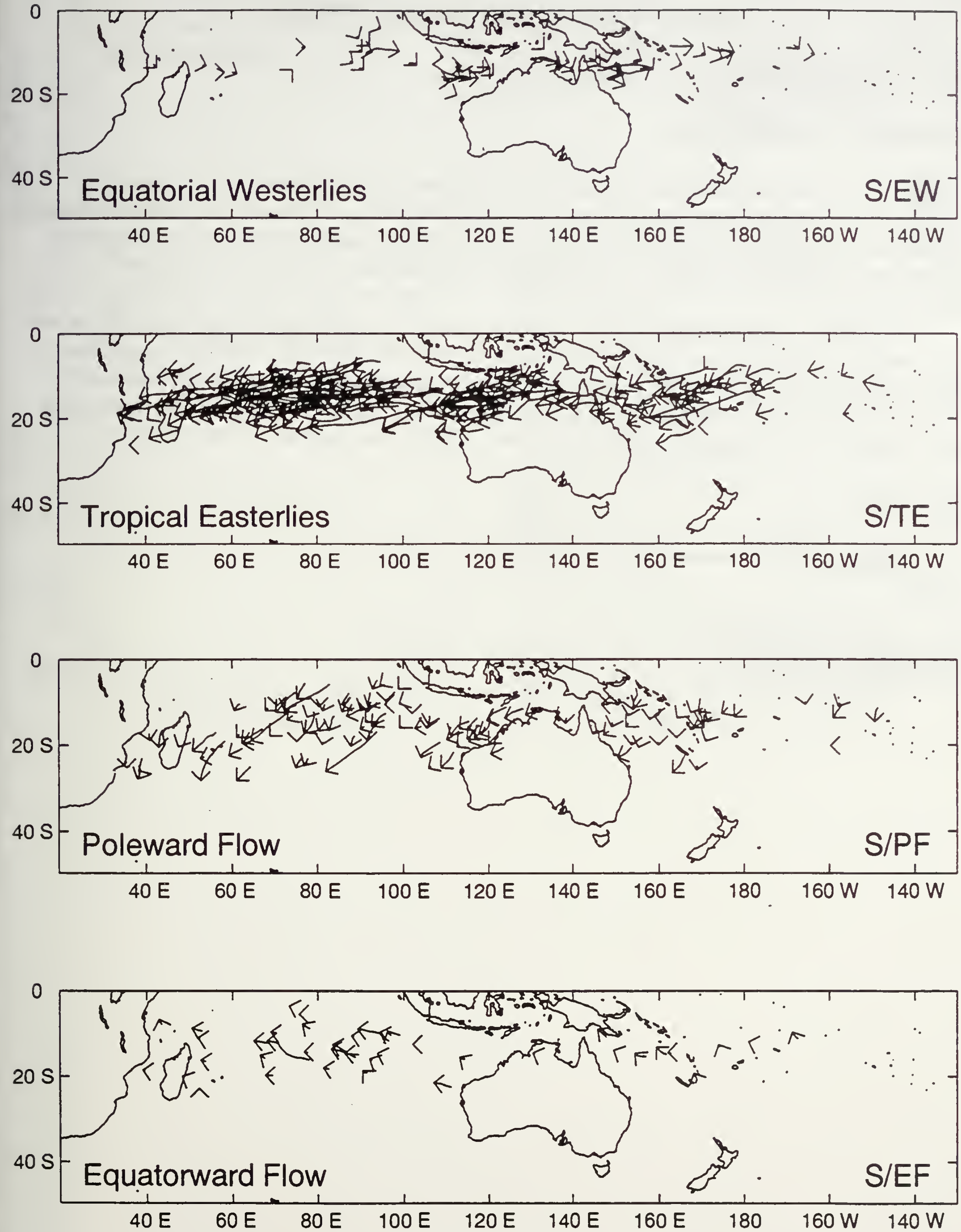
STANDARD (S) PATTERN
CHARACTERISTIC TRACKS



Topic: STANDARD (S) PATTERN (cont)

ACTUAL TRACKS

The tracks of TCs in the Southern Hemisphere during the 1990-91 through 1998-99 seasons while in the Standard (S) synoptic pattern are shown on the right. Mainly short, eastward tracks are found in the Equatorial Westerlies (EW) synoptic region. Notice the long, generally west-southwestward tracks in the Tropical Easterlies (TE) synoptic region. Track segments in the Poleward Flow (PF) synoptic region are generally poleward and are short because the TC usually does not remain in this region for very long. Equatorward and westward tracks are found in the Equatorward Flow (EF) synoptic region.


0
20 S
40 S
Equatorial Westerlies
S/EW
40 E
60 E
80 E
100 E
120 E
140 E
160 E
180
160 W
140 W
0
20 S
40 S
Tropical Easterlies
S/TE
40 E
60 E
80 E
100 E
120 E
140 E
160 E
180
160 W
140 W
0
20 S
40 S
Poleward Flow
S/PF
40 E
60 E
80 E
100 E
120 E
140 E
160 E
180
160 W
140 W
0
20 S
40 S
Equatorward Flow
S/EF
40 E
60 E
80 E
100 E
120 E
140 E
160 E
180
160 W
140 W

Topic: STANDARD (S) PATTERN (cont)

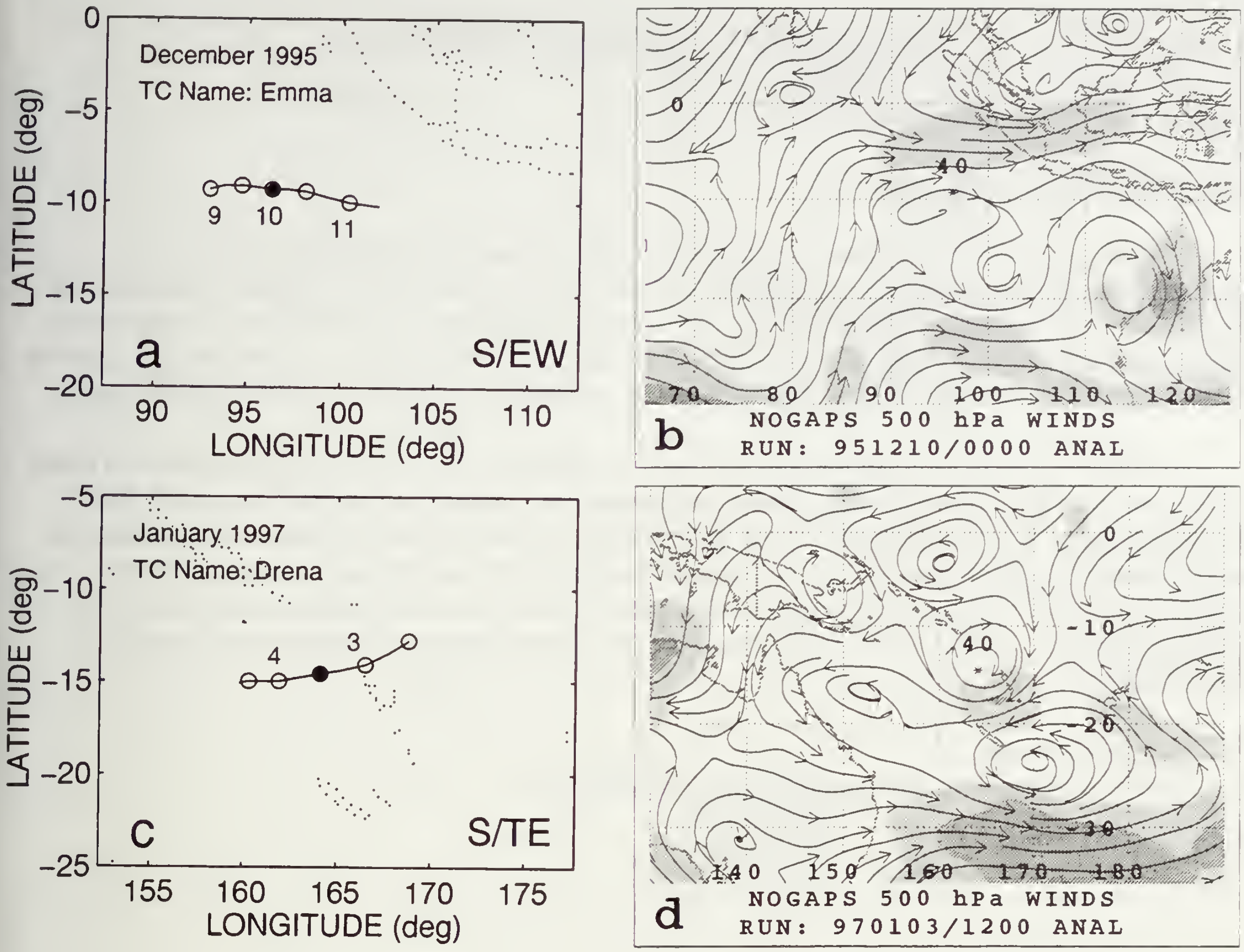
ILLUSTRATION:S/EW and S/TE

Panel a on the right indicates TC Emma is moving eastward. In panel b, the cyclonic circulation accompanying Emma (see asterisk) is not well-defined at 500 mb in the NOGAPS analysis. However, an extensive west-to-east steering flow with a 20-kt isotach maximum on the equatorial side of Emma is consistent with the Standard/Equatorial Westerlies (S/EW) pattern/region.

Panel c on the right indicates TC Drena is translating west-southwestward. In panel d, a well-defined cyclonic circulation associated with Drena is found in the NOGAPS analysis. Notice that Drena is equatorward of a moderately broad subtropical anticyclone with a more than 30-kt isotach maximum between Drena and the anticyclone. This streamline/isotach analysis and the recent track indicate Drena is in the Standard/Tropical Easterlies (S/TE) pattern/region.

Cross-reference:

Diagnosing Environmental Steering Direction p. 9


December 1995
TC Name: Emma
a
S/EW
LATITUDE (deg)
LONGITUDE (deg)
NOGAPS 500 hPa WINDS
RUN: 951210/0000 ANAL
b
January 1997
TC Name: Drena
c
S/TE
LATITUDE (deg)
LONGITUDE (deg)
NOGAPS 500 hPa WINDS
RUN: 970103/1200 ANAL
d

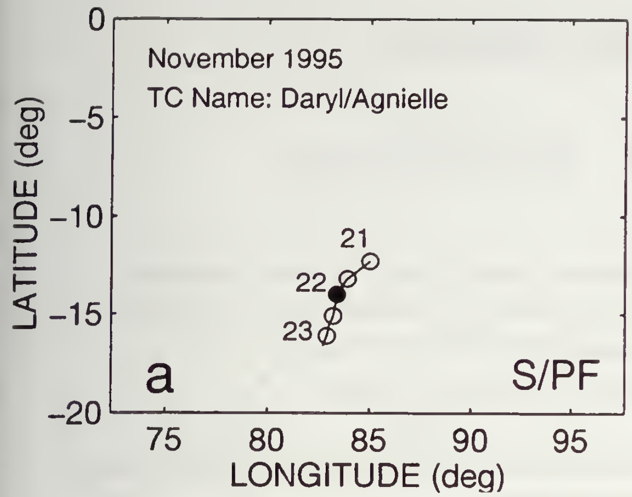
Topic: STANDARD (S) PATTERN (cont)

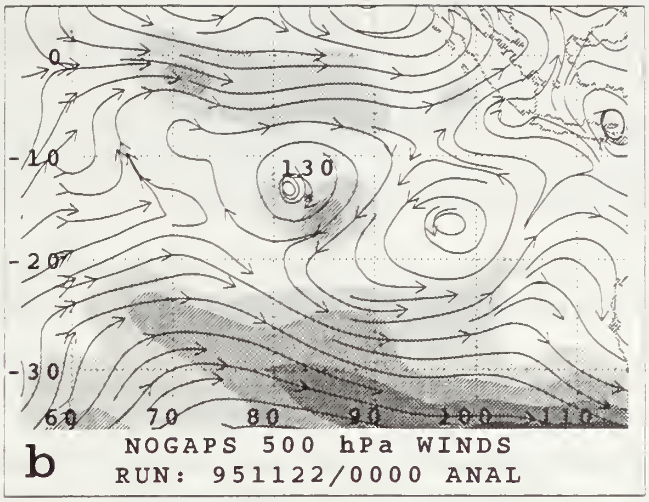
ILLUSTRATIONS: S/PF and S/EF

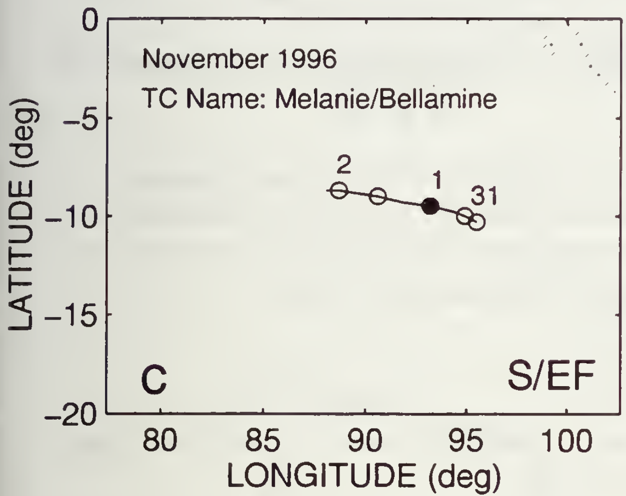
Panel a on the right indicates the track of TC Daryl/Agnielle is turning from the southwestward to south-southwestward at 0000 UTC 22 November 1995. In panel b, the expected linear relationship between the wind center, the satellite-derived center (asterisk), and the more than 30-kt isotach maximum is present in the NOGAPS streamline/isotach analysis. Thus, the TC is on the northwest flank of the subtropical anticyclone in the Standard/Poleward Flow (S/PF) pattern/region.

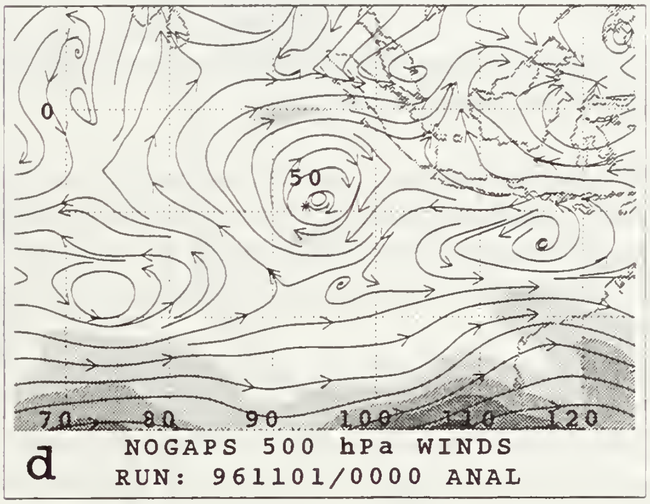
Panel c on the right indicates a west-northwest translation of TC Melanie/Bellamine. In panel d, the linear relationship of the wind center, satellite-derived center (asterisk), and the small, 20-kt isotach maximum is not as expected. That is, an isotach maximum more to the southwest would be more consistent with the motion. Given the data-sparsity in this area of the South Indian Ocean, it is likely the strength of the anticyclone to the southwest is being under-represented in the NOGAPS analysis. In that case, it would be clearer that the TC is in the Standard/Equatorward Flow (S/EF) pattern/region.

Cross-reference:
Diagnosing Environmental Steering Direction p. 9


November 1995
TC Name: Daryl/Agnielle
LATITUDE (deg)
LONGITUDE (deg)
21
22
23
a
S/PF
0
-5
-10
-15
-20
75
80
85
90
95


0
-10
-20
-30
60
70
80
90
100
110
130
b
NOGAPS 500 hPa WINDS
RUN: 951122/0000 ANAL


November 1996
TC Name: Melanie/Bellamine
LATITUDE (deg)
LONGITUDE (deg)
2
1
31
c
S/EF
0
-5
-10
-15
-20
80
85
90
95
100


0
50
70
80
90
100
110
120
d
NOGAPS 500 hPa WINDS
RUN: 961101/0000 ANAL

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 NW-to-SE axis (Southern Hemisphere) orientation, although this orientation may vary from NNW-to-SSE to WNW-to-ESE in certain scenarios; and

(c) usually produces strongly poleward steering (with either a eastward or westward 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 SE of the poleward-oriented ridge feature.)

The synoptic REGIONS of the P pattern are:

(a) POLEWARD FLOW (PF), which encompasses the area of poleward steering west of the ridge (peripheral anticyclone) circulation that identifies the pattern as P.

(b) EQUATORIAL WESTERLIES (EW), which encompasses the area of eastward steering flow between the monsoon trough and an associated anticyclone (buffer) circulation near the equator that then blends into the peripheral anticyclone.

(c) EQUATORWARD FLOW (EF), which is an equatorward steering associated with the peripheral anticyclone. NOTE: This region applies to a separate TC than the TC in the PF region, and is related to the Indirect Cyclone Interaction (ICI).

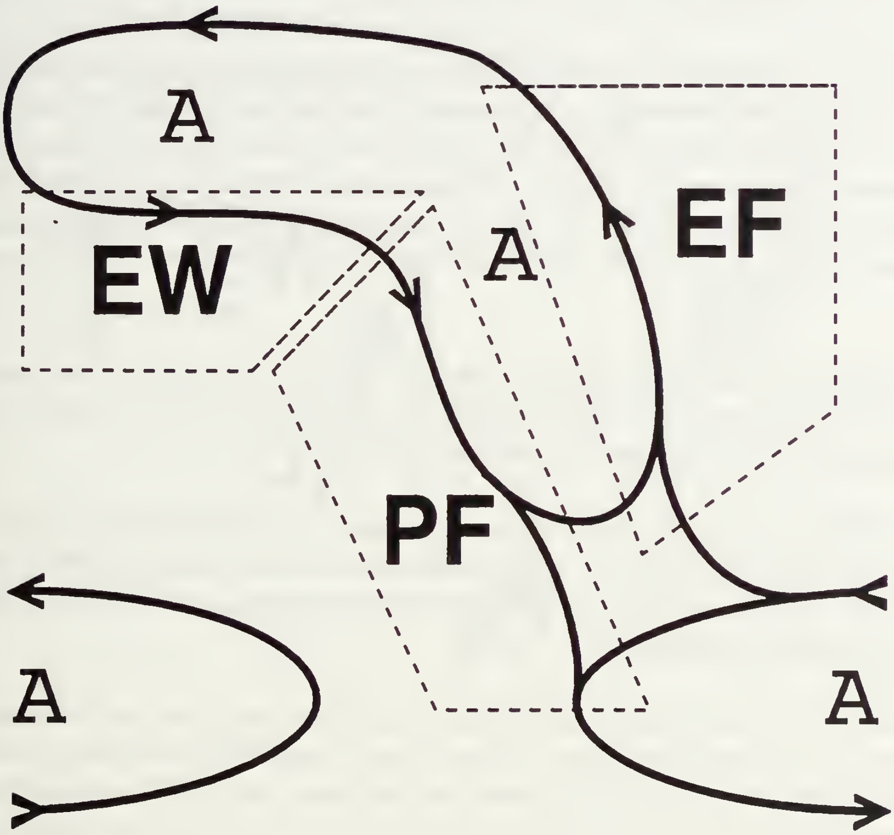
Cross-references:

Ridge Modification by a TC (RMT) p. 67

Reverse Trough Formation (RTF) p. 75

Indirect Cyclone Interaction (ICI) p. 79

POLEWARD (P) PATTERN



-------- Region boundaries

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 FLOW (PF) 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 south, 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/TE (see S Pattern summary). There is usually no break in the STR to the south of the TC when this situation occurs.

(b) In the EQUATORIAL WESTERLIES (EW) region, the motion-related isotach maximum will be from N to NE 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.

(c) In the EQUATORWARD FLOW (EF) region, the separate TC (indicated by open TC symbol for clarity) is under the steering influence of the peripheral anticyclone associated with another TC (solid symbol in PF region), or more generally, a cyclone to the southwest, which is the Indirect Cyclone Interaction (ICI) transitional mechanism.

If the P pattern persists, a TC in the PF region 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/TE pattern/region with a westward track.

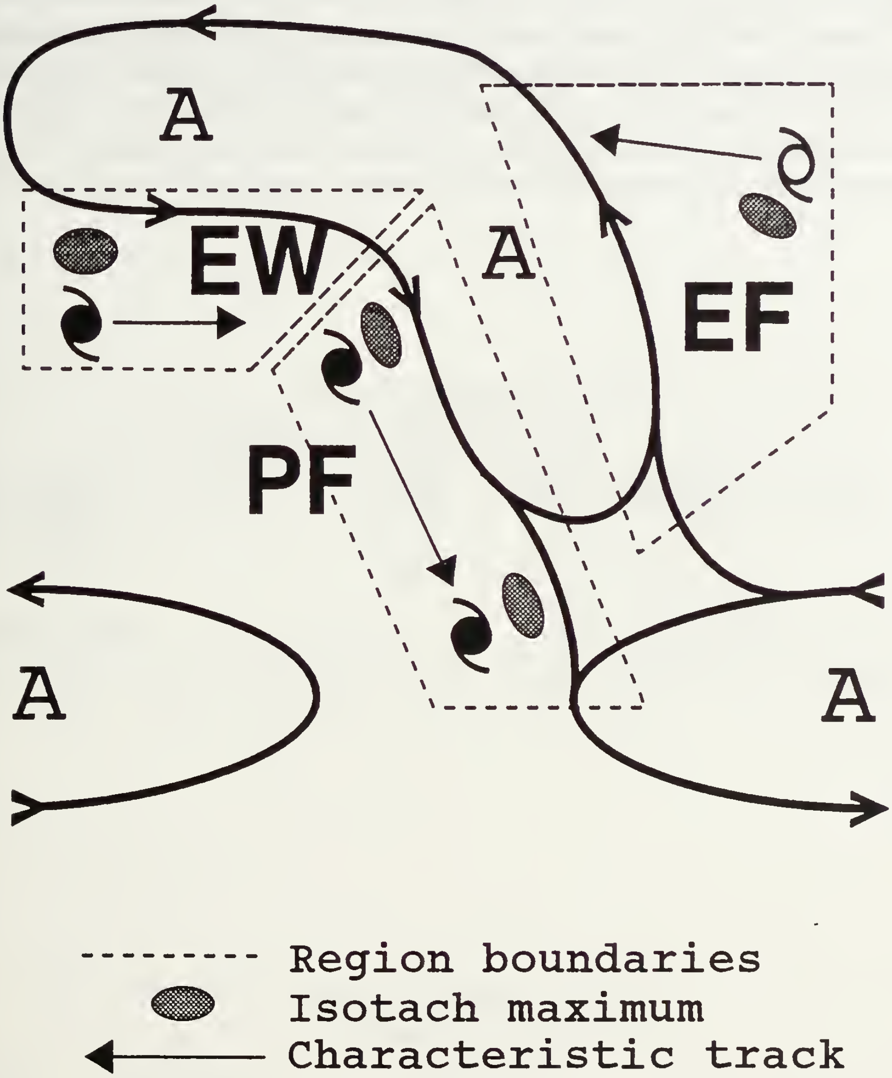
Cross references:

Diagnosing Environmental Steering Direction p. 9

Standard pattern p. 19

Indirect Cyclone Interaction p. 79

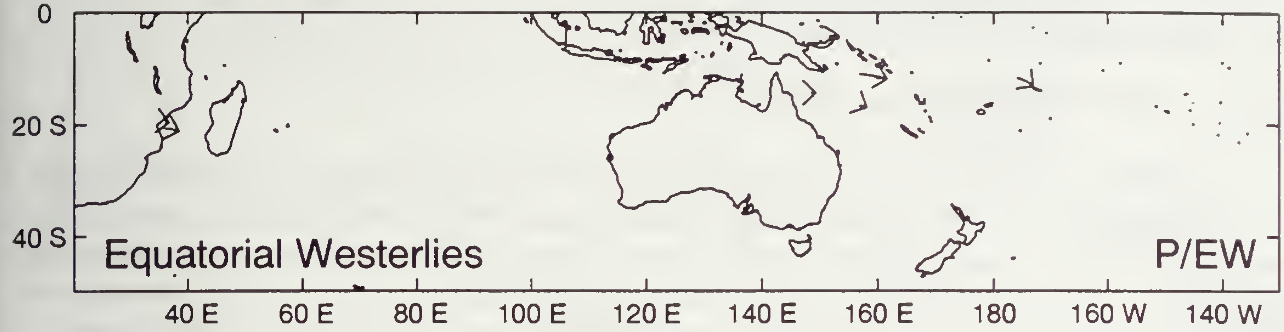
POLEWARD (P) PATTERN
CHARACTERISTIC TRACKS

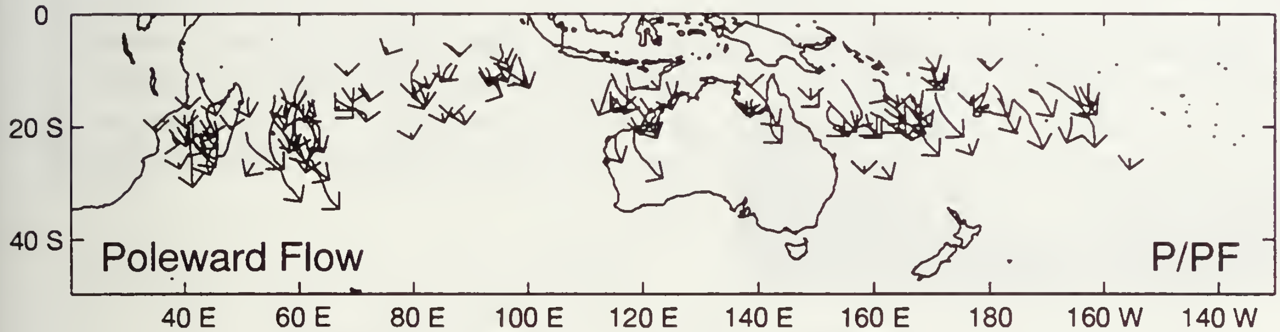


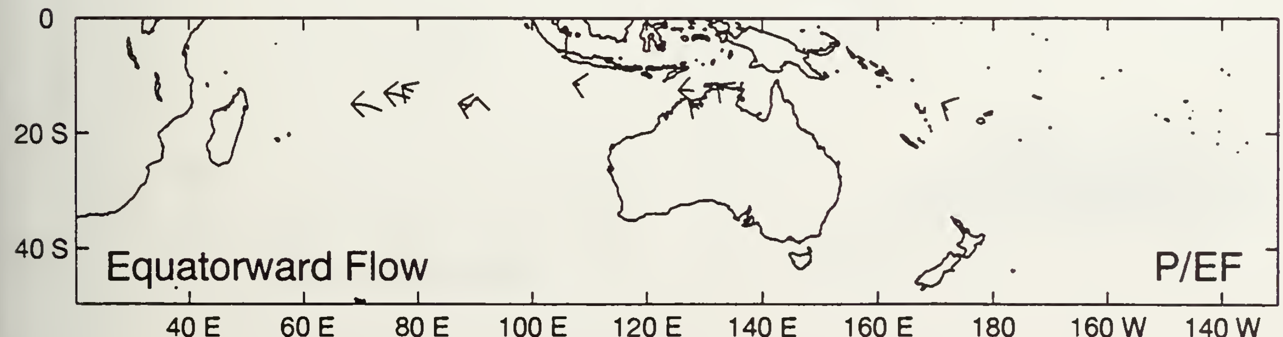
Topic: POLEWARD (P) PATTERN (cont)

ACTUAL TRACKS

The tracks of TCs in the Southern Hemisphere during the 1990-91 through 1998-99 seasons while in the Poleward (P) synoptic pattern are shown to the right. Whereas the tracks are generally poleward in the Poleward Flow (PF) synoptic region, a large variety of track directions and lengths exist. Only four TC tracks occurred in the Equatorial Westerlies (EW) synoptic region with only a short eastward track. With the presence of a peripheral anticyclone to the east that may translate poleward with the TC, a continued poleward track will be favored in the PF region. Those TCs to the east of the peripheral anticyclone in the Equatorward Flow (EF) region generally have only short track segments.


0
20 S
40 S
Equatorial Westerlies
P/EW
40 E
60 E
80 E
100 E
120 E
140 E
160 E
180
160 W
140 W


0
20 S
40 S
Poleward Flow
P/PF
40 E
60 E
80 E
100 E
120 E
140 E
160 E
180
160 W
140 W


0
20 S
40 S
Equatorward Flow
P/EF
40 E
60 E
80 E
100 E
120 E
140 E
160 E
180
160 W
140 W

Topic: POLEWARD (P) PATTERN (cont)

ILLUSTRATIONS: P/EW, P/PF, and P/EF

In panel a on the right, the eastward track of TC Usha will become more east-southeast in the next 24 h. In panel b, the satellite-derived center (asterisk near 11°S, 159°E) is slightly in advance (to the southeast) of the line connecting the wind circulation center and the main isotach maximum on the poleward side of the equatorial buffer zone circulation. Nevertheless, it is clear that TC Usha is in the Poleward/Equatorial Westerlies (P/EW) pattern/region because the overall pattern is polar-oriented with the trough (associated with South Pacific Convergence Zone) to the southeast.

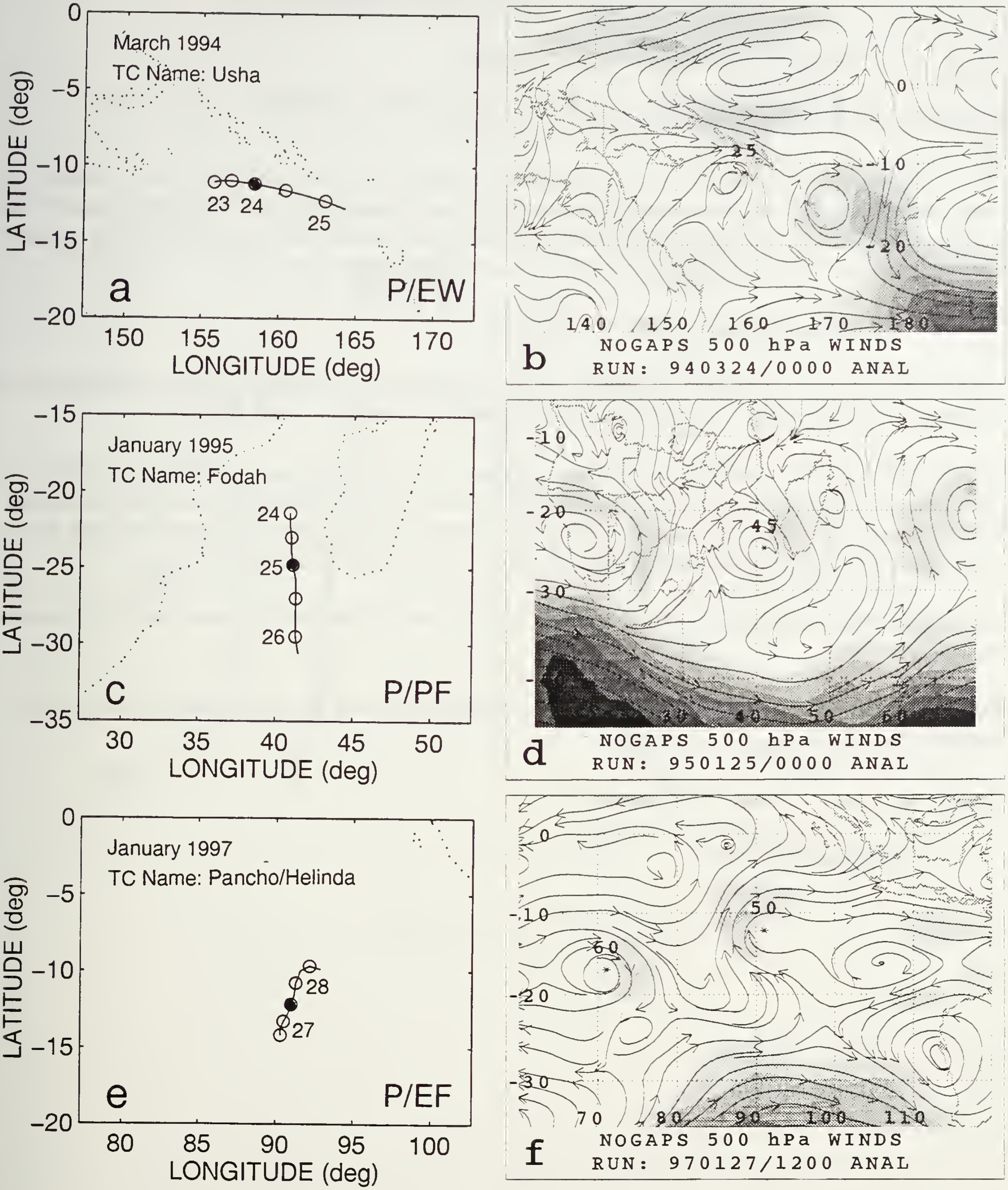
In panel c, TC Fodah is translating poleward. The corresponding NOGAPS analysis in panel d has a well-defined peripheral anticyclone to the northeast of the TC, and a 20-kt isotach maximum between the TC and that peripheral anticyclone. Thus, Fodah is in the Poleward/Poleward Flow (P/PF) pattern/region.

In panel e, a north-northeastward translation of TC Pancho/Helinda is indicated. In panel f, TC Pancho/Helinda is the eastern TC near 12°S, 91°E, which is in an equatorward steering flow established by the peripheral anticyclone of the western TC near 16°S, 72°E. Thus, TC Pancho/ Helinda is being affected by the Indirect Cyclone Interaction - East transition mechanism, and is in the Poleward/Equatorward Flow (P/EF) pattern/region.

Cross-references:

Diagnosing Environmental Steering Direction p. 9

Indirect Cyclone Interaction p. 79



March 1994
TC Name: Usha
LATITUDE (deg)
LONGITUDE (deg)
a
P/EW
NOGAPS 500 hPa WINDS
RUN: 940324/0000 ANAL
b
January 1995
TC Name: Fodah
c
P/PF
NOGAPS 500 hPa WINDS
RUN: 950125/0000 ANAL
d
January 1997
TC Name: Pancho/Helinda
e
P/EF
NOGAPS 500 hPa WINDS
RUN: 970127/1200 ANAL
f

ENVIRONMENTAL STRUCTURE DEFINITIONS

Topic: HIGH-AMPLITUDE (H) PATTERN

PATTERN/REGIONS DESCRIPTION:

The High-amplitude (H) synoptic pattern is unique to the Southern Hemisphere. Its chief characteristic is a midlatitude trough-ridge system that penetrates deeply into the tropics, even to the Equator. In the schematic on the right, only one anticyclone on the west or the east may be present. The trough may also have more of a northwest-southeast tilt than shown.

The synoptic REGIONS of the H pattern are:

(a) EQUATORIAL WESTERLIES (EW), which encompasses the area of eastward steering between the deep trough and a high pressure (buffer zone) near the equator.

(b) TROUGH POLEWARD (TP), which encompasses the area of poleward steering between the deep trough and the eastern anticyclone. NOTE: Because of the special character of the steering in the TP region, this is the only synoptic region that extends poleward from the tropics through the subtropical ridge axis, rather than having a transition to the Midlatitude (M) pattern.

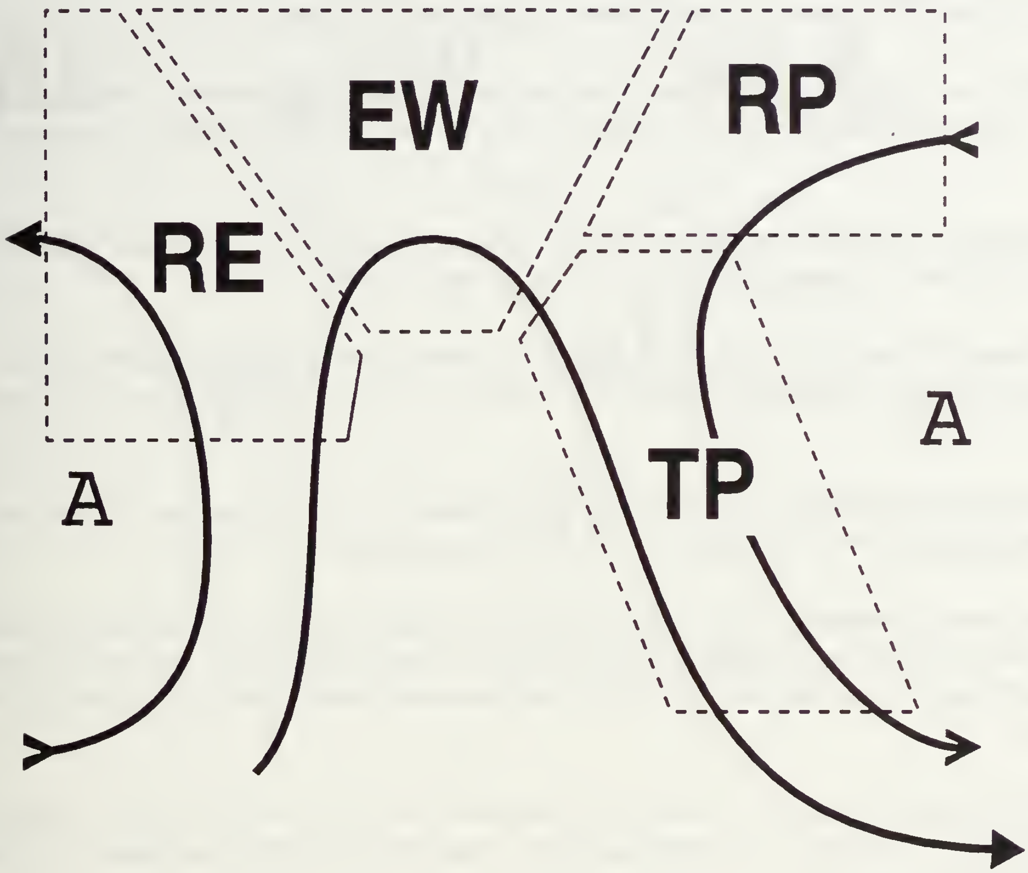
(c) RIDGE POLEWARD (RP), which encompasses the area on the northwestern flank of the eastern anticyclone.

(d) RIDGE EQUATORWARD (RE), which encompasses the area on the northeastern flank of the western anticyclone.

Cross-references:

Midlatitude (M) pattern p. 47

HIGH AMPLITUDE (H) PATTERN



-------- Region boundaries

Topic: HIGH-AMPLITUDE (H) PATTERN (cont)

CHARACTERISTIC TC LOCATIONS AND TRACKS

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

(a) In the TP synoptic region, the isotach maximum that indicates the direction of environmental steering will be positioned approximately between the TC and the anticyclone to the east of the deep trough.

(b) In the Equatorial Westerlies (EW) region, the motion-related isotach maximum will be oriented from N to NE of the TC depending on the location of the TC in the region.

(c) In the Ridge Poleward (RP) region, the isotach maximum that indicates the direction of environmental steering will be approximately between the TC and the anticyclone circulation to the east.

(d) In the Ridge-Equatorward (RE) region, the isotach maximum that indicates the direction of environmental steering will be between the TC and the anticyclone to the west.

One formation sequence is that the TC forms in the EW region and then moves around the equatorward side of the deep trough into the TP region. Another formation sequence is that the TC forms in the RP region and translates around the northwestern flank of the eastern anticyclone into the TP region.

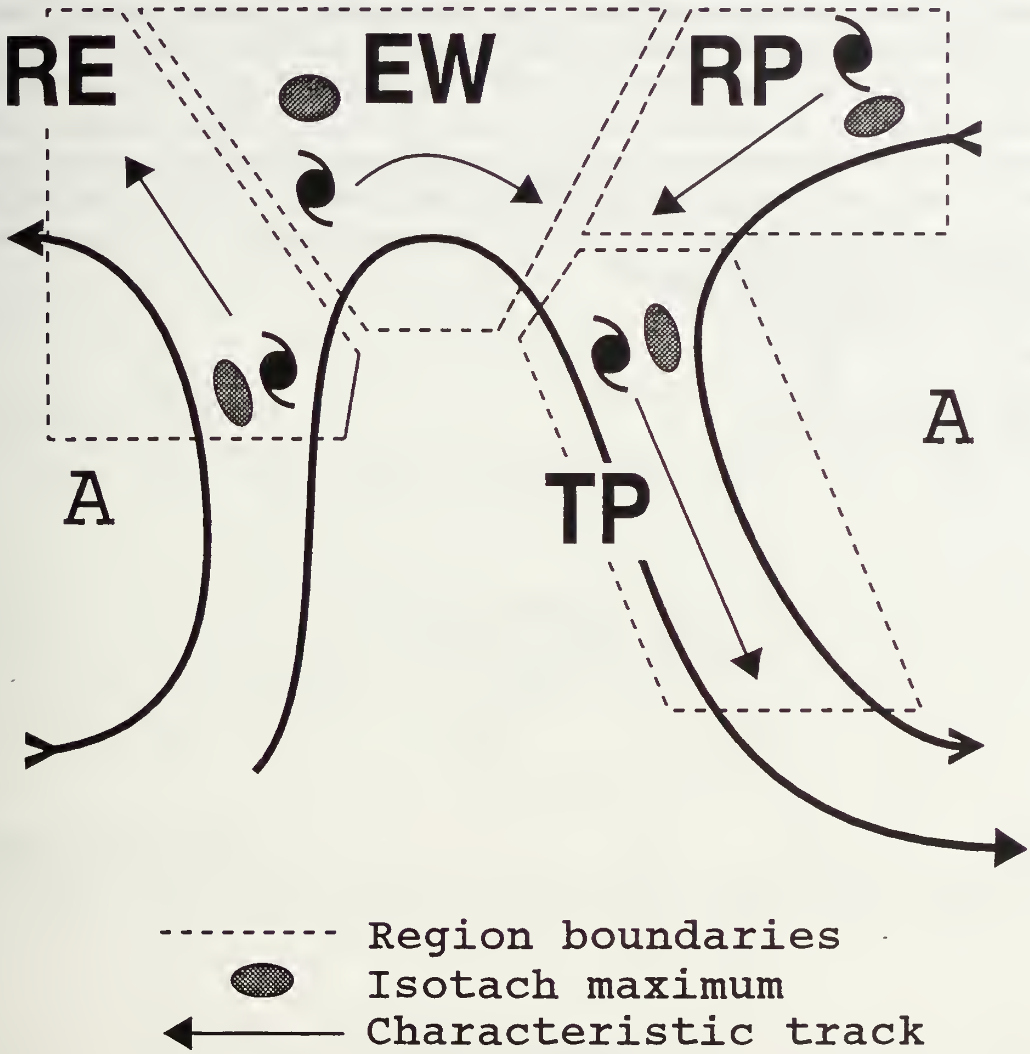
A TC in the RE region may continue equatorward and move into a Standard/Tropical Easterlies (S/TE) pattern/region. An alternate path is around the northwestern flank of the deep trough into the EW region.

Cross-references:

Diagnosing Environmental Steering Direction p. 9

Standard (S) pattern p. 19

HIGH AMPLITUDE (H) PATTERN
CHARACTERISTIC TRACKS



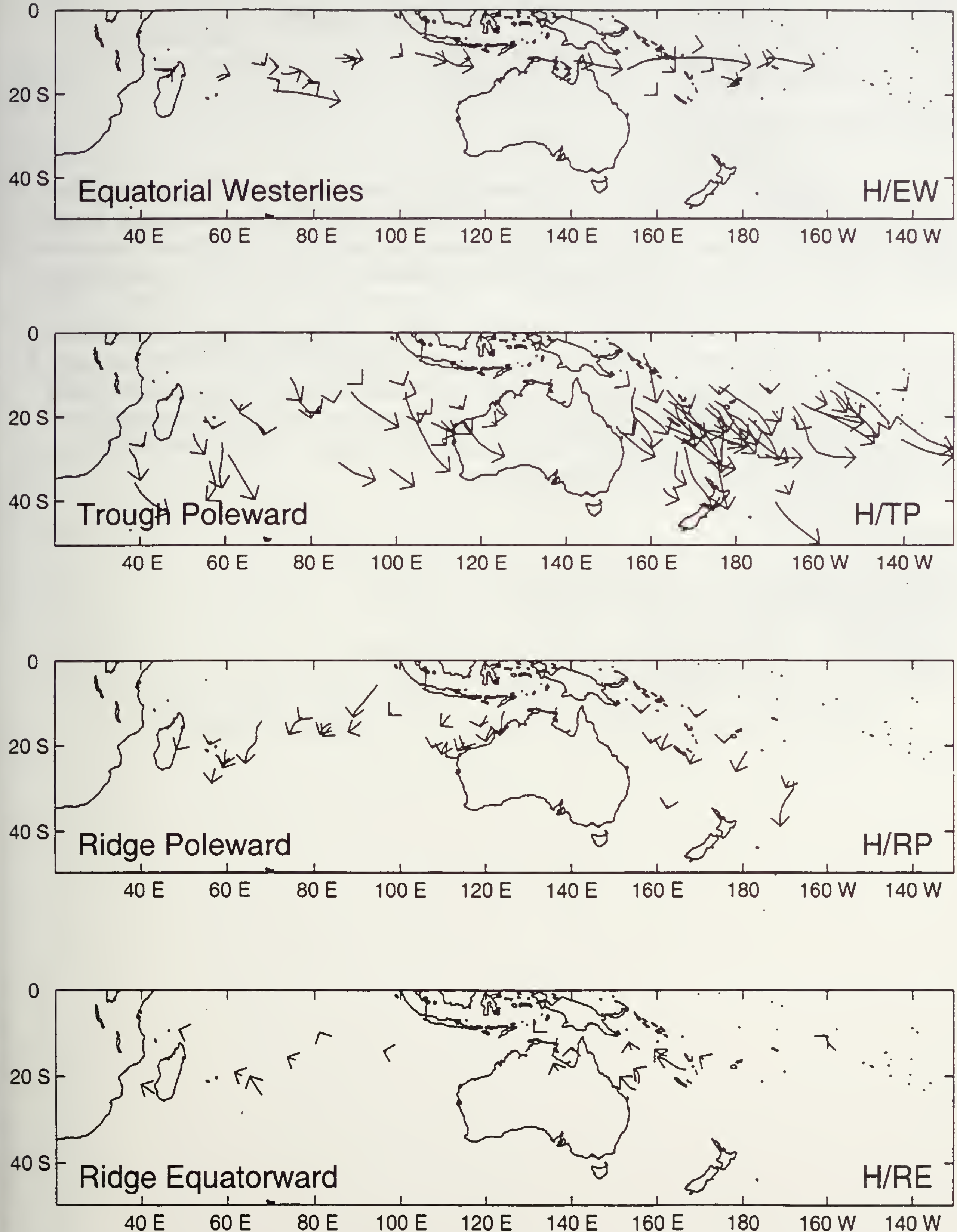
Topic: HIGH-AMPLITUDE (H) PATTERN (cont)

ACTUAL TRACKS

In the 1990-91 through 1998-99 sample of Southern Hemisphere TCs, the High-amplitude (H) synoptic pattern was more common in the South Pacific Ocean than in the South Indian Ocean. Some TCs first move toward the east after forming in the EW region, and then curve poleward around the eastern side of the deep trough. One characteristic of the tracks in the Trough Poleward (TP) synoptic region is a cyclonic turning at low latitudes and then an anticyclonic turn in higher latitudes. A bifurcation point may exist for the equatorward moving tracks in the RE region. If the western anticyclone extends eastward, the TC may continue into the Standard/Tropical Easterlies (S/TE) pattern/region on the equatorward side, and thus turn more westward. An alternate transition is into the H/EW synoptic pattern/region, and the TC will turn eastward.

Cross reference:

Standard (S) pattern p. 19


0
20 S
40 S
Equatorial Westerlies
H/EW
40 E
60 E
80 E
100 E
120 E
140 E
160 E
180
160 W
140 W
0
20 S
40 S
Trough Poleward
H/TP
40 E
60 E
80 E
100 E
120 E
140 E
160 E
180
160 W
140 W
0
20 S
40 S
Ridge Poleward
H/RP
40 E
60 E
80 E
100 E
120 E
140 E
160 E
180
160 W
140 W
0
20 S
40 S
Ridge Equatorward
H/RE
40 E
60 E
80 E
100 E
120 E
140 E
160 E
180
160 W
140 W

Topic: HIGH-AMPLITUDE (H) PATTERN (cont)

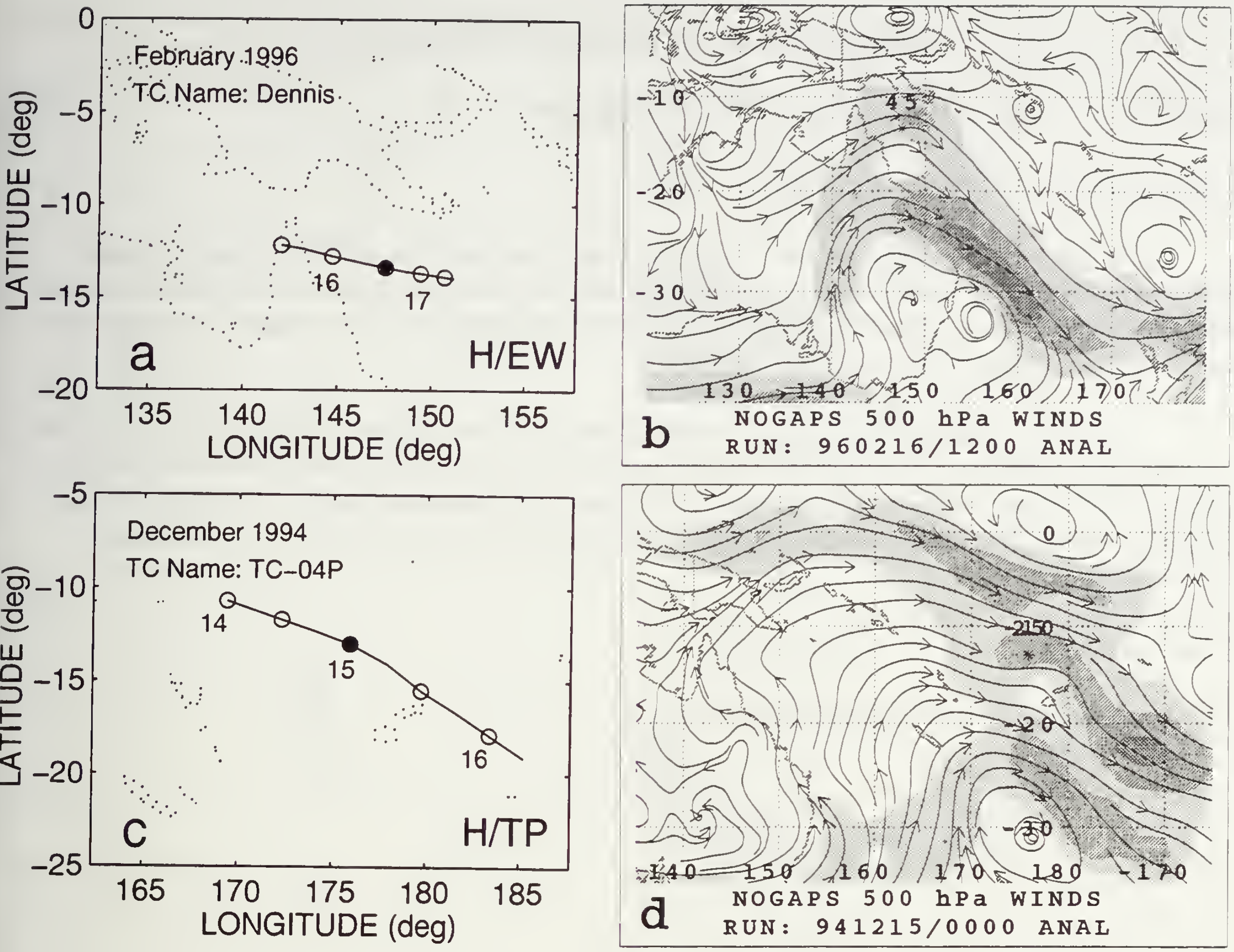
ILLUSTRATIONS: H/EW and H/TP

In panel a on the right, the track of TC Dennis is slightly south of eastward. In panel b, the TC (near 14°S, 146°E) is at the equatorward end of a midlatitude trough that has penetrated deeply into the tropics. Eastward steering flow is indicated between the trough and the buffer circulation on the Equator. Thus, TC Dennis is in the High-amplitude/Equatorial Westerlies (H/EW) pattern/region.

In panel c, the track of TC-04P has been toward the southeast and is turning more poleward over the next 24 h. Whereas the TC is near 14°S, 175°E, the NOGAPS analysis at 500 mb in panel d has an open trough farther to the southeast. The dominant circulation feature is the extremely deep midlatitude trough that extends to the Equator, and the TC is embedded in the southeastward flow between this trough and the anticyclone to the east (mainly off the figure). Thus, the TC is in the High-amplitude/Trough Poleward (H/TP) pattern/region.

Cross-reference:

Diagnosing Environmental Steering Direction p. 9


February 1996
TC Name: Dennis
LATITUDE (deg)
LONGITUDE (deg)
16
17
a
H/EW
NOGAPS 500 hPa WINDS
RUN: 960216/1200 ANAL
b
December 1994
TC Name: TC-04P
14
15
16
c
H/TP
NOGAPS 500 hPa WINDS
RUN: 941215/0000 ANAL
d

TOPIC: HIGH-AMPLITUDE (H) PATTERN (Cont.)

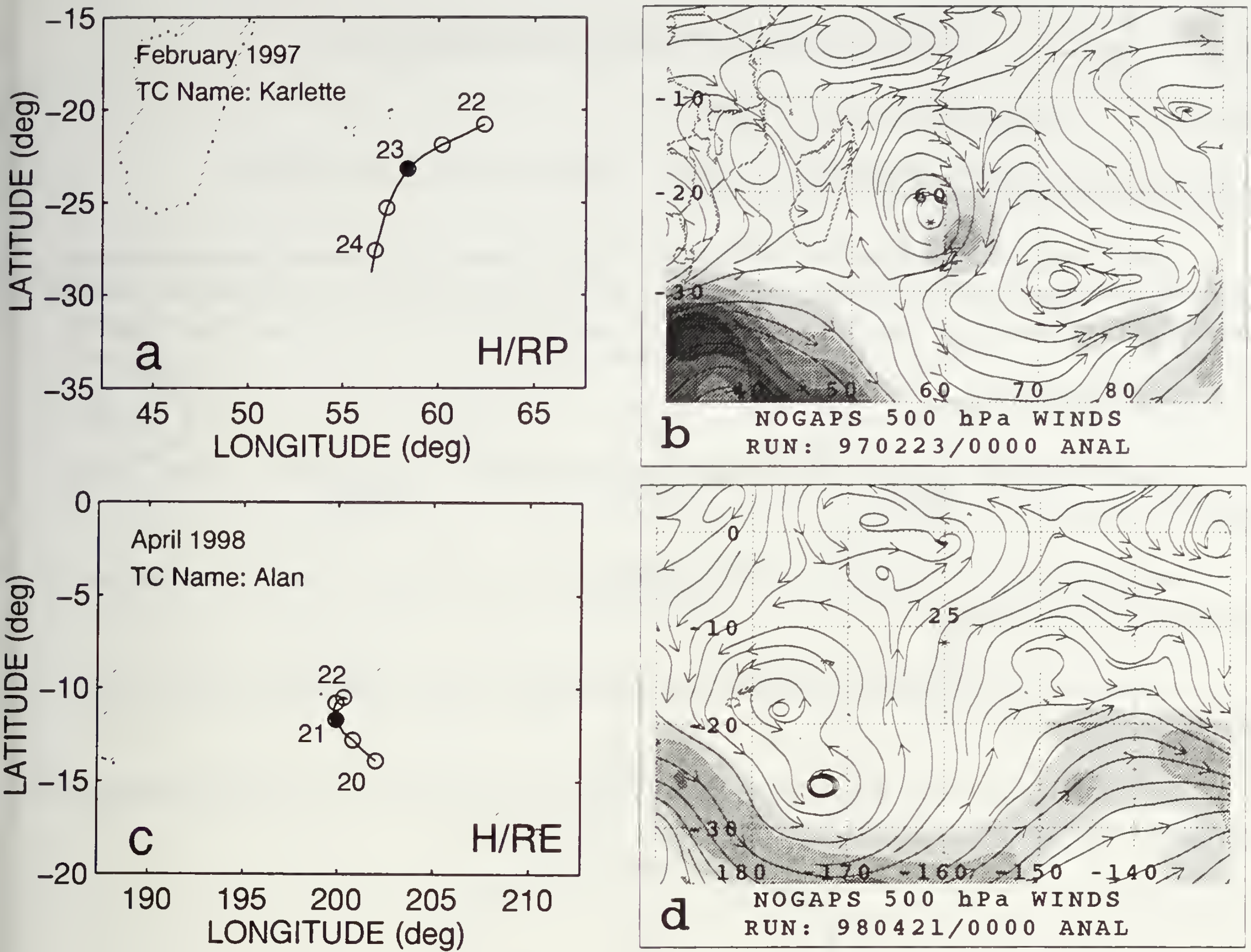
ILLUSTRATIONS: H/RP and H/RE

In panel a on the right, the track of TC Karlette is turning from southwestward to south-southwestward over the next 24 h. In panel b, Karlette is on the northwestern flank of the eastern anticyclone of a High-amplitude (H) synoptic pattern that is defined by the trough to the west, and Karlette is in the Ridge Poleward (RP) region.

In panel c, TC Alan has a highly anomalous track to the north-northwest and will turn to the northeast during the next 24 h. The corresponding NOGAPS analysis in panel d indicates the TC is on the western (back) side of a deep trough. With the highly meridional nature of the ridge to the west and the trough to the east, this is a High-amplitude (H) pattern and Alan is in the Ridge Equatorward (RE) region.

Cross-reference:

Diagnosing Environmental Steering Direction p. 9



February 1997
TC Name: Karlette
22
23
24
a
H/RP
LATITUDE (deg)
LONGITUDE (deg)
-15
-20
-25
-30
-35
45
50
55
60
65
-10
-20
-30
60
70
80
b
NOGAPS 500 hPa WINDS
RUN: 970223/0000 ANAL
April 1998
TC Name: Alan
22
21
20
c
H/RE
LATITUDE (deg)
LONGITUDE (deg)
0
-5
-10
-15
-20
190
195
200
205
210
0
-10
25
-20
-30
180
-170
-160
-150
-140
d
NOGAPS 500 hPa WINDS
RUN: 980421/0000 ANAL

ENVIRONMENT STRUCTURE DEFINITIONS

Topic: MIDLATITUDE (M) PATTERN

PATTERN/REGIONS DESCRIPTIONS

Except in the Trough Poleward (TP) region of the H pattern, a TC moving poleward across the subtropical ridge (anticyclone) axis will have a transition into the MIDLATITUDE (M) synoptic pattern. With this exception, all TCs poleward of the subtropical ridge axis will be in the M pattern.

The REGIONS are:

(1) a POLEWARD FLOW (PF) synoptic region is on the southwestern flank of the subtropical anticyclone.

(2) a MIDLATITUDE WESTERLIES (MW) synoptic region is on the southern quadrant of the subtropical anticyclone.

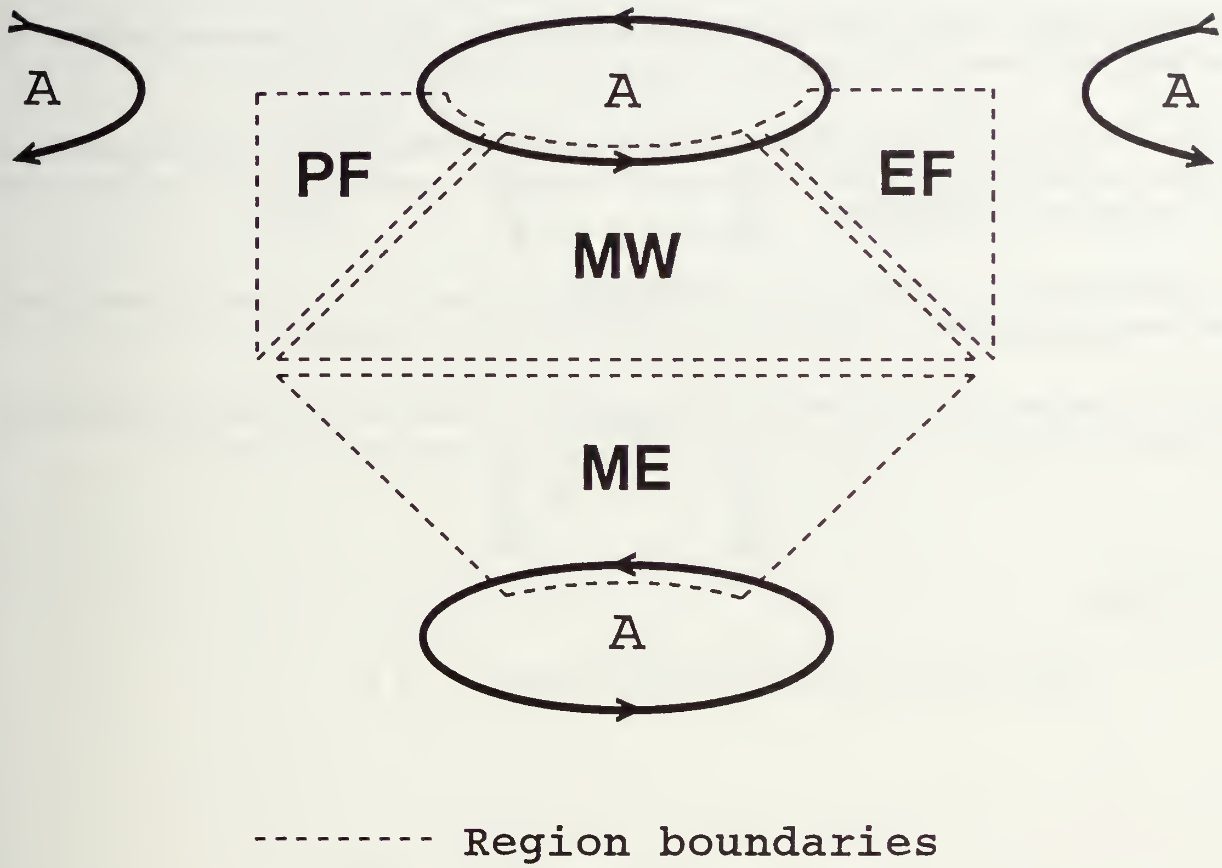
(3) an EQUATORWARD FLOW (EF) synoptic region is on the southeastern flank of the subtropical anticyclone.

(4) a MIDLATITUDE EASTERLIES (ME) synoptic region is poleward of the MW region in the region equatorward of a midlatitude anticyclone (when it exists).

Cross-reference:

High-amplitude (H) synoptic pattern p. 37

MIDLATITUDE (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 circulation to the east.

(b) In the MW region, the isotach maximum that indicates the direction of environmental steering will be between north-northeast and north-northwest depending on the position of the TC relative to the subtropical anticyclone to the north.

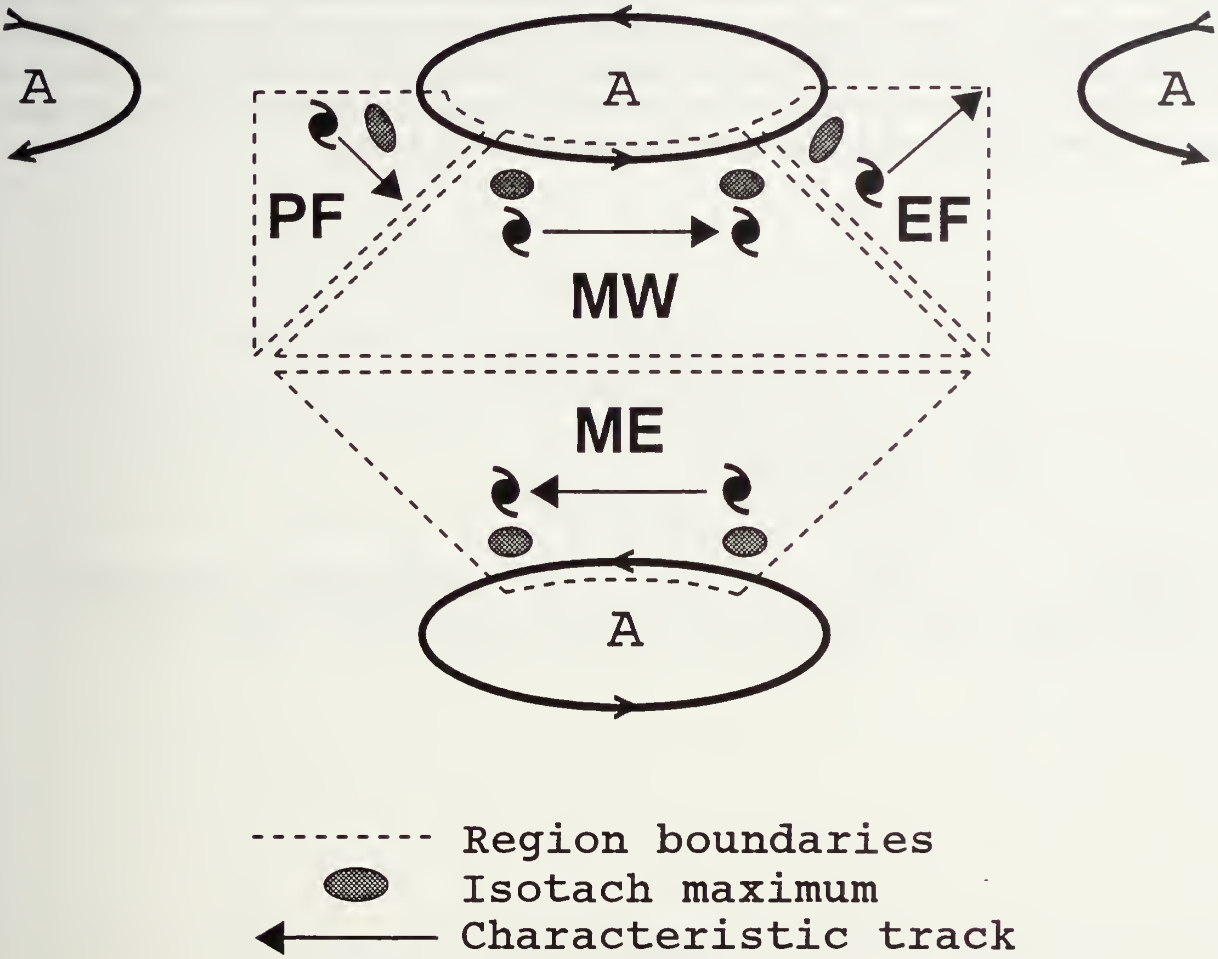
(c) In the EF region, the isotach maximum that indicates the direction of environmental steering will be positioned approximately between the TC and the STR feature to the west.

(d) In the ME region, the isotach maximum that indicates the direction of environmental steering will generally be to the south between the TC and the midlatitude anticyclone to the south.

Cross-reference:

Diagnosing Environmental Steering Direction p. 9

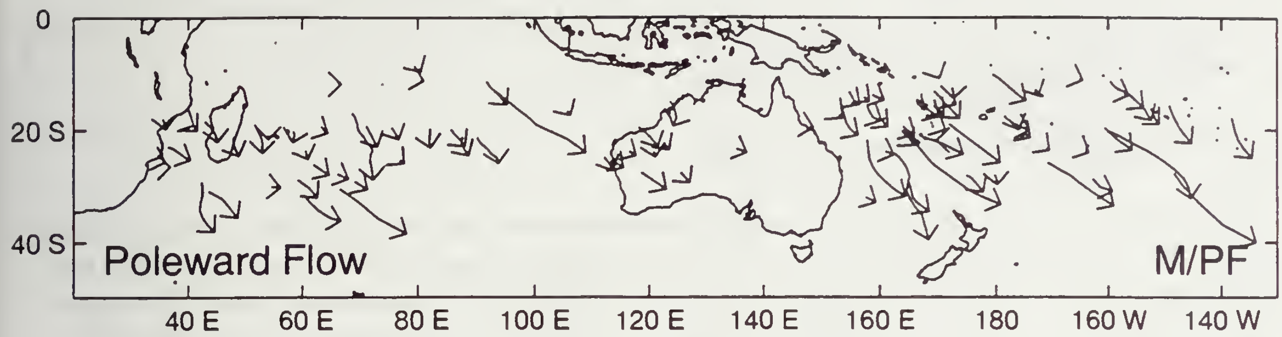
MIDLATITUDE (M) PATTERN
CHARACTERISTIC TRACKS

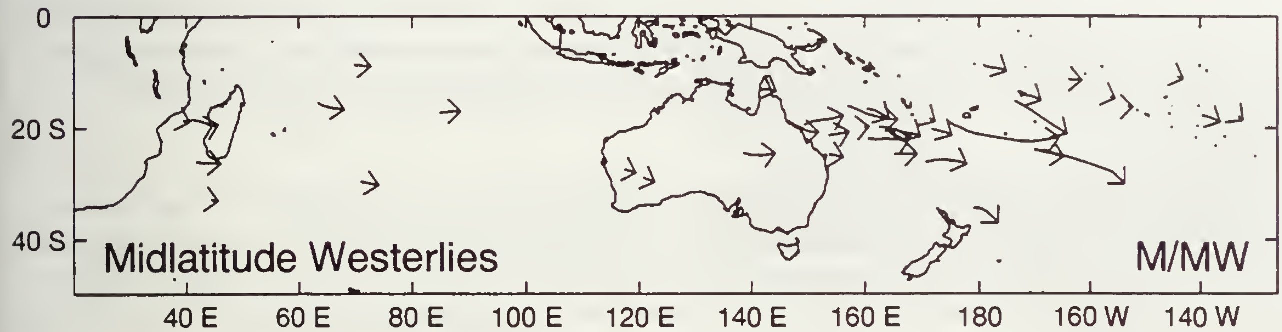


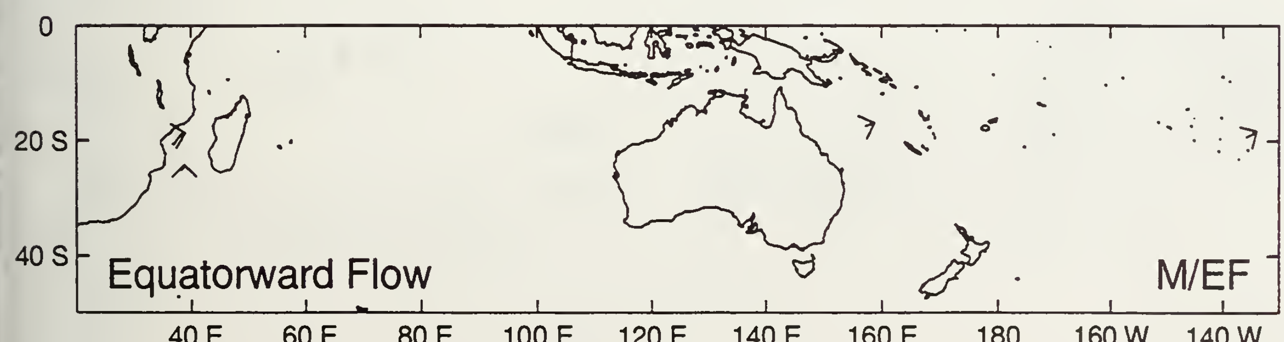
Topic: MIDLATITUDE TC (M) PATTERN (cont)

ACTUAL TRACKS

The tracks of TCs in the Southern Hemisphere during 1990-91 through 1998-99 seasons while in the Midlatitude (M) synoptic pattern are shown on the right. In the Poleward Flow (PF) synoptic region, the TC tracks are toward the southeast. In the Midlatitude Westerlies (MW) region, the tracks are generally eastward. Although many of these track segments are short because the TC dissipates in the westerly vertical wind shear, some cases at relatively low latitudes in the South Pacific Ocean persist longer. The four TC tracks in the Equatorward Flow (EF) synoptic region are very short. No cases of TCs in the Midlatitude Easterlies (ME) region were present in this sample.


0
20 S
40 S
Poleward Flow
M/PF
40 E
60 E
80 E
100 E
120 E
140 E
160 E
180
160 W
140 W


0
20 S
40 S
Midlatitude Westerlies
M/MW
40 E
60 E
80 E
100 E
120 E
140 E
160 E
180
160 W
140 W


0
20 S
40 S
Equatorward Flow
M/EF
40 E
60 E
80 E
100 E
120 E
140 E
160 E
180
160 W
140 W

Topic: MIDLATITUDE (M) PATTERN (Cont.)

ILLUSTRATIONS: M/PF, M/MW, AND M/EF

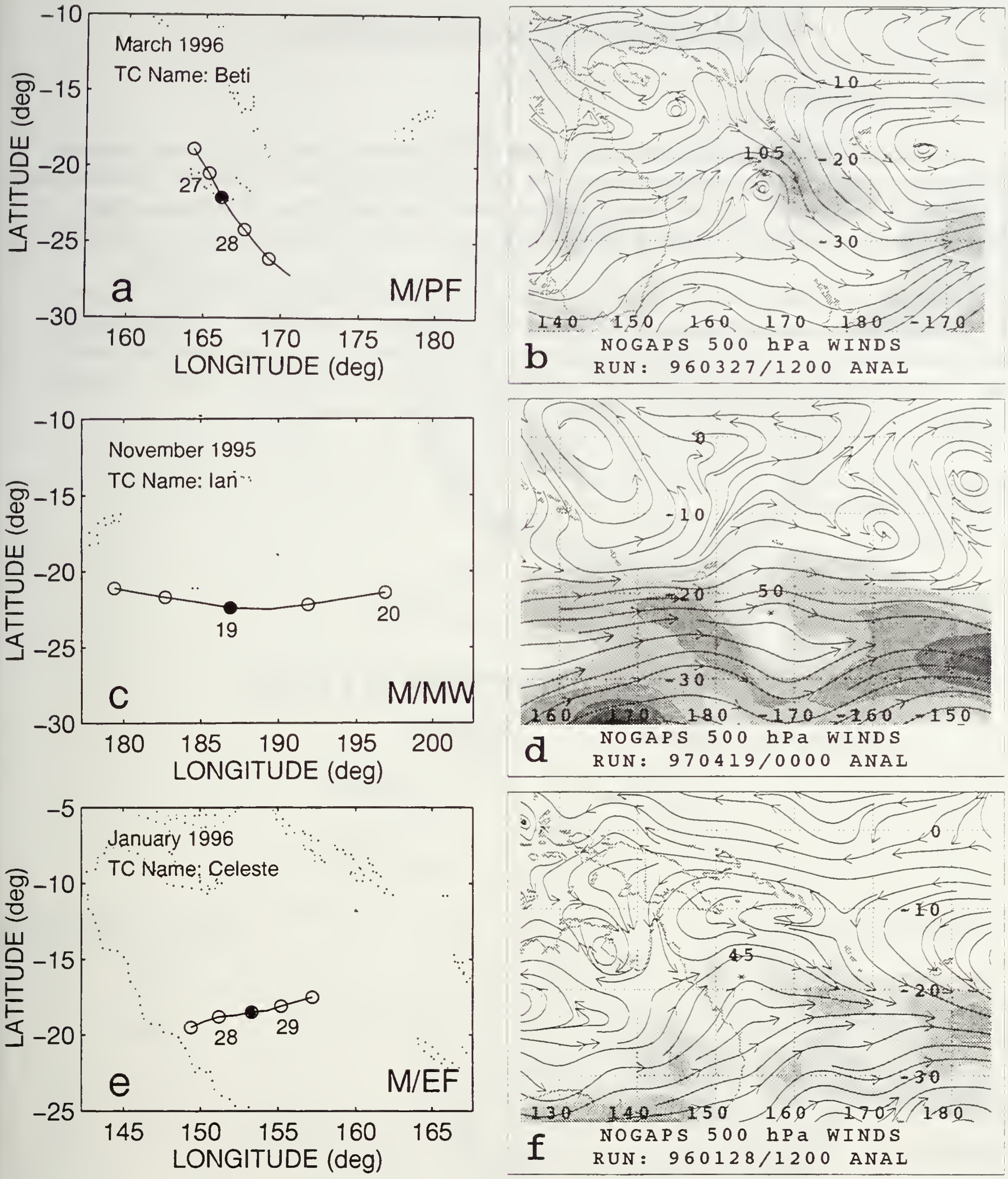
In panel a on the right, TC Beti is moving southeastward and will accelerate in the next 24 h. In panel b, the corresponding NOGAPS analysis has a cyclonic circulation associated with Beti that has a more than 30-kt isotach to the east. Notice that the subtropical anticyclone axis to the east is around 19°S, so that Beti is now poleward of that axis, and thus is by definition in the Midlatitude (M) pattern (unless it is in the H/TP pattern/region). Although the double midlatitude short waves have created a wide break between the subtropical anticyclone cells to the east and west (off the figure), the overall pattern is more zonally oriented rather than meridionally oriented as in the H pattern. Given the track direction in panel a and that Beti has just passed through the subtropical anticyclone axis, Beti is in the Midlatitude/Poleward Flow (M/PF) pattern/region.

In panel c, TC Ian is translating eastward very rapidly. Notice that the only reflection of Ian in the 500-mb streamline/isotach analysis (panel d) is a weak short wave embedded in zonally oriented midlatitude westerlies. Thus, Ian is clearly in the Midlatitude/Midlatitude Westerlies (M/MW) pattern/region.

In panel e, TC Celeste is undergoing an unusual north of east track deflection. Only a weak short-wave trough at 500 mb (panel f) is associated with Celeste. Notice the 20-kt isotach maximum is to the west of Celeste, which is consistent with the equatorward track deflection (panel e). Since Celeste is well poleward of the subtropical anticyclone axis, it is in the Midlatitude/Equatorward Flow (M/EF) pattern/region.

Cross-reference:

High-amplitude (H) pattern p. 37


March 1996
TC Name: Beti
27
28
a
M/PF
LATITUDE (deg)
LONGITUDE (deg)
-10
-15
-20
-25
-30
160
165
170
175
180
-10
-20
-30
105
140
150
160
170
180
-170
b
NOGAPS 500 hPa WINDS
RUN: 960327/1200 ANAL
November 1995
TC Name: Ian
19
20
c
M/MW
LATITUDE (deg)
LONGITUDE (deg)
-10
-15
-20
-25
-30
180
185
190
195
200
0
-10
-20
50
-30
160
170
180
-170
-160
-150
d
NOGAPS 500 hPa WINDS
RUN: 970419/0000 ANAL
January 1996
TC Name: Celeste
28
29
e
M/EF
LATITUDE (deg)
LONGITUDE (deg)
-5
-10
-15
-20
-25
145
150
155
160
165
0
-10
45
-20
-30
130
140
150
160
170
180
f
NOGAPS 500 hPa WINDS
RUN: 960128/1200 ANAL

ENVIRONMENT STRUCTURE DEFINITIONS

PATTERN CLIMATOLOGY

A total of 2731 characterizations were made of the synoptic patterns relative to Southern Hemisphere tropical cyclones each 12 h during the 1990-91 through 1998-99 seasons. The Standard (S) pattern was involved in 54% of these characterizations. The distribution of S cases is quite different between the South Indian and South Pacific Oceans with 63.6% and 35.1%, respectively.

An opposite-type distribution occurs for the High-amplitude (H) pattern with 11.3% and 27.0% of the cases in the South Indian and South Pacific Oceans, respectively. A similar unequal distribution occurs for the Midlatitude (M) pattern with 7.5% and 22.1% in the South Indian and South Pacific Oceans, respectively. A nearly equal percentage of Poleward (P) patterns exists with 17.6% and 15.8% in the South Indian and South Pacific Oceans, respectively.

Cross-references:

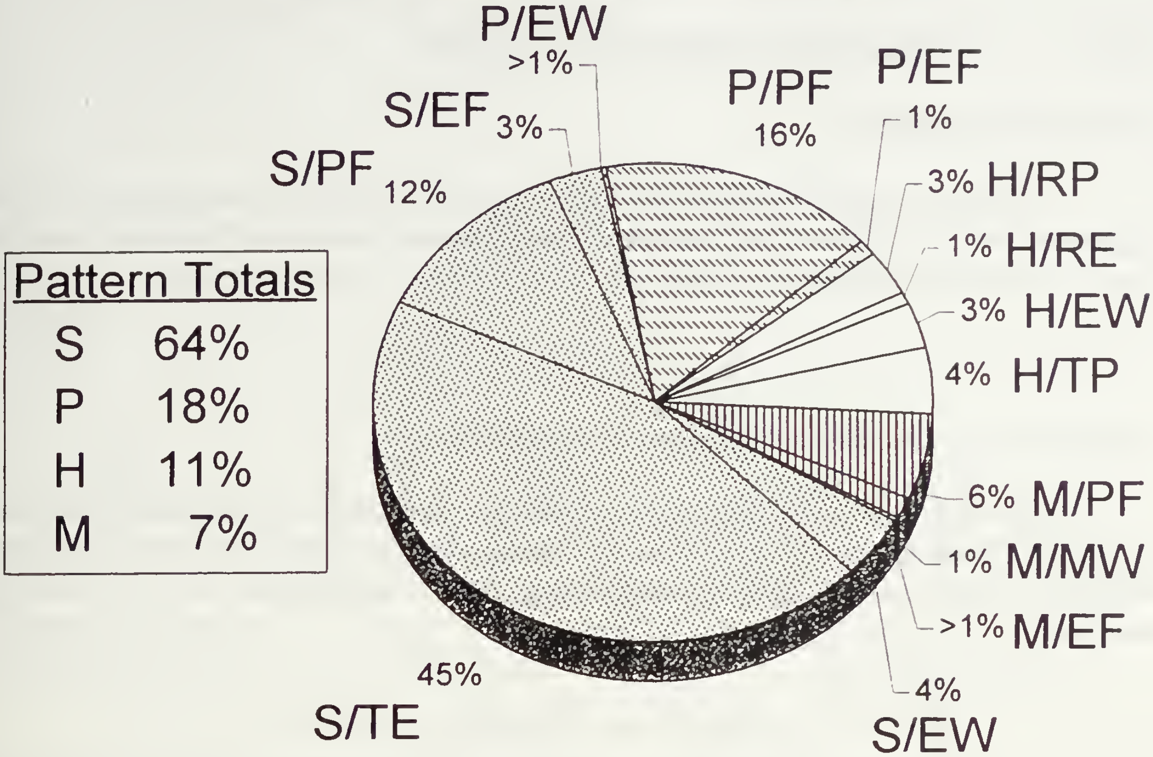
Standard (S) Pattern p. 19

Poleward (P) Pattern p. 29

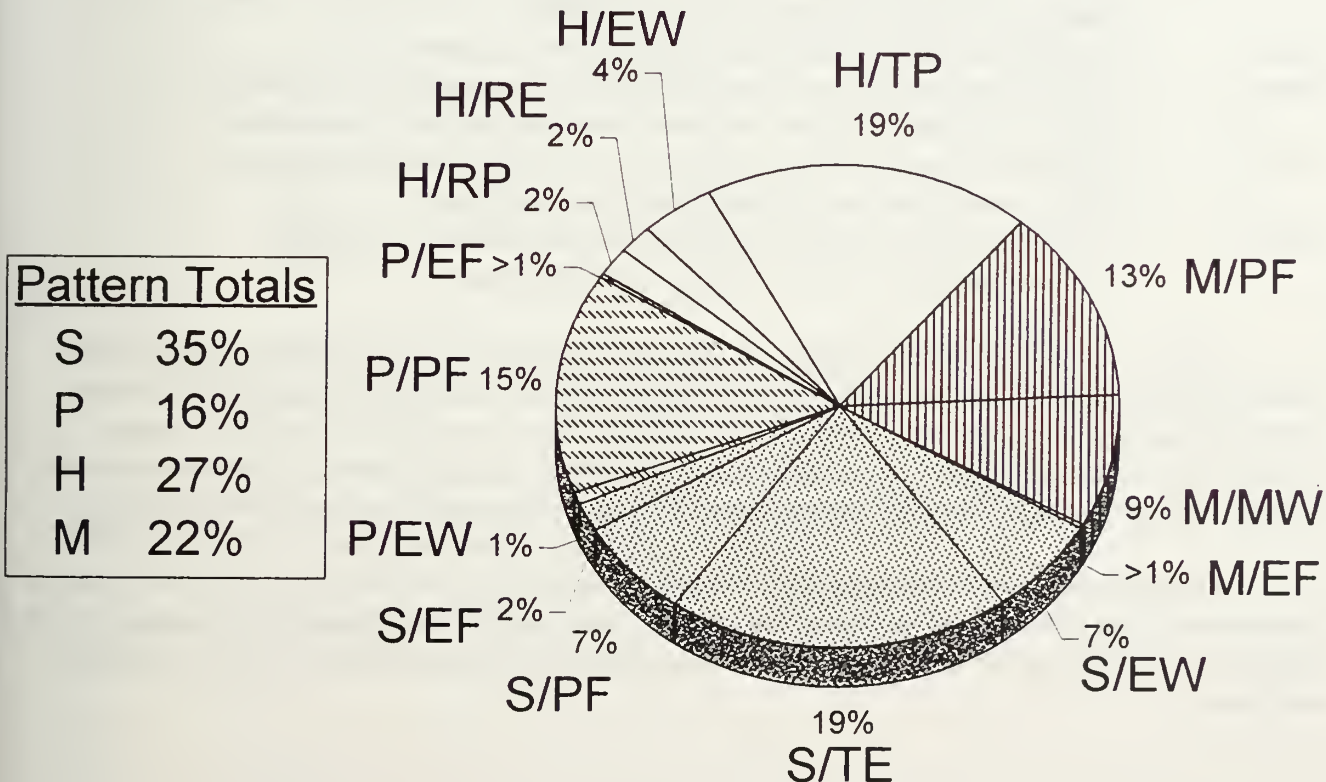
High-amplitude (H) Pattern p. 37

Midlatitude (M) Pattern p. 47

SOUTH INDIAN OCEAN



SOUTH PACIFIC OCEAN



Topic: BETA-EFFECT PROPAGATION (BEP)

DYNAMICAL BASIS

The non-divergent, barotropic modeling provides the simplest description of why a tropical cyclone will have a poleward and westward track deflection relative to the environmental steering flow. With the assumption of non-divergence, the vorticity equation becomes

$$\frac{\partial \zeta}{\partial t} = -\mathbf{V} \bullet \nabla \zeta - \beta v$$

where beta (β) is the latitudinal gradient of the Coriolis.

It is convenient to divide the tropical cyclone circulation into symmetric (S) and asymmetric (A) parts. Wavenumber one is the most important part of the asymmetry. After thus partitioning both the advecting velocity field and the vorticity, and discarding small terms, the vorticity equation becomes

$$\underbrace{\frac{\partial \zeta}{\partial t}}_{\text{Term 1}} = - \underbrace{\mathbf{V}_A \bullet \nabla \zeta_S}_{\text{Term 2}} - \underbrace{\mathbf{V}_S \bullet \nabla \zeta_A}_{\text{Term 3}} - \underbrace{\beta v}_{\text{Term 4}}$$

Meaning (1st line) and effect (2nd line) of terms

Term 1: Time rate change of relative vorticity (response to terms 2 - 4).

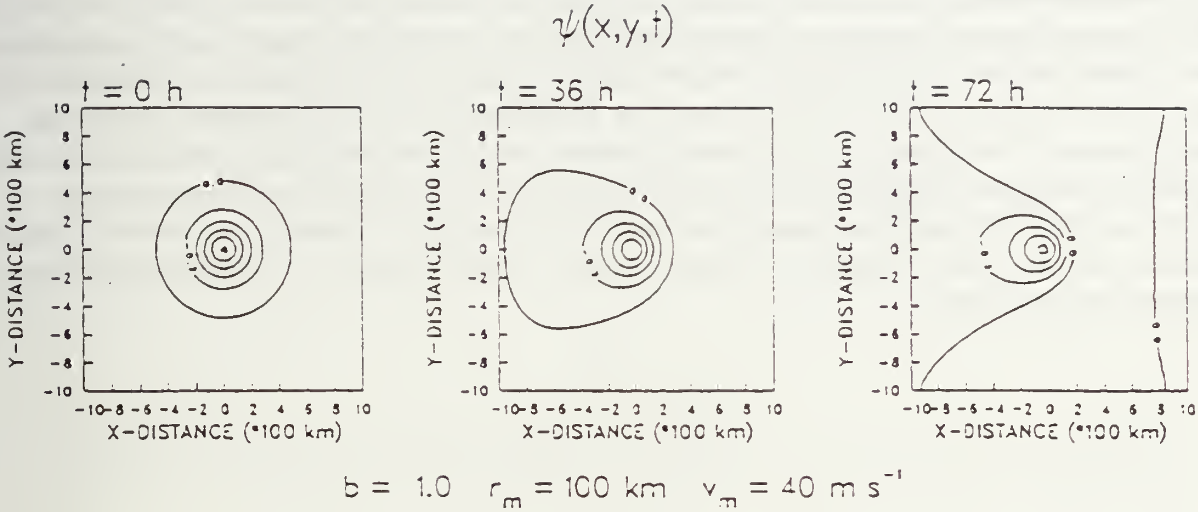
Term 2: Advection of symmetric vortex component by asymmetric component.
Results in motion of vortex relative to environment (aka: propagation).

Term 3: Advection of asymmetric vortex component by symmetric component.
Acts to stabilize vortex to dispersive influence of term 4.

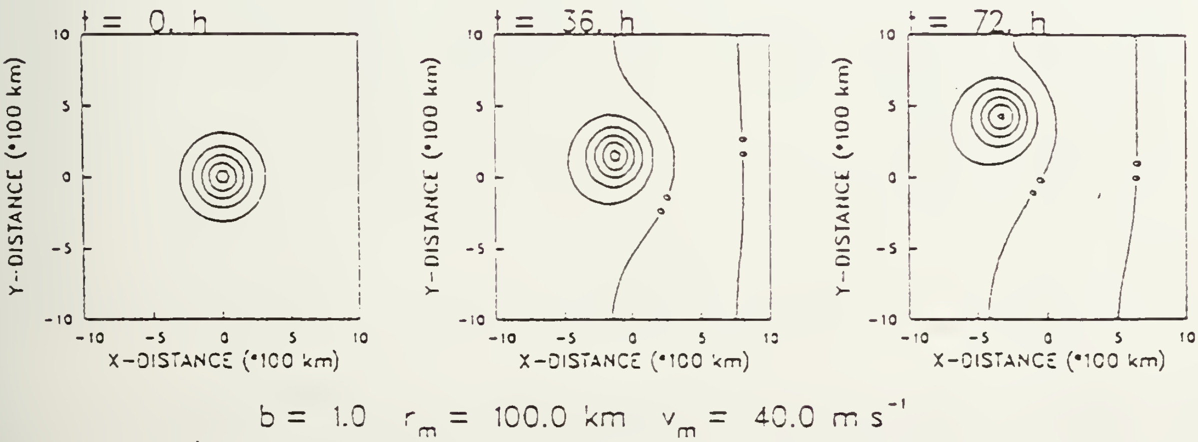
Term 4: Advection of earth vorticity by vortex meridional wind component.
Acts to disperse vortex via radiation of Rossby waves.

In the top sequence of streamfunction diagrams from the Chan and Williams (1987) model without environmental flow, and with only the linear (βv) term, the initial circular vortex becomes stretched significantly to the west. Whereas the westward drift of the center is small, the outer envelope propagates at a larger rate and results in a distorted vortex. When the nonlinear advection terms 2 and 4 are included, the advection tendency is for a poleward advection of the vortex.

The lower sequence of streamfunction predictions indicates the nonlinear beta effect leads to the westward and poleward advection of the vortex. This is a Northern Hemisphere example, so the deflection is toward the northwest. In the Southern Hemisphere, the deflection will be toward the southwest.



Streamfunction fields (Ψ) at 0, 36, and 72 h from the linear numerical simulation of Chan and Williams (1987) for a vortex profile with $V_m = 40$ m s^{-1}, $R_m = 100$ km, and b = 1.0. The contour interval is 0.2 x 10^6 m^{2}s^{-1}.

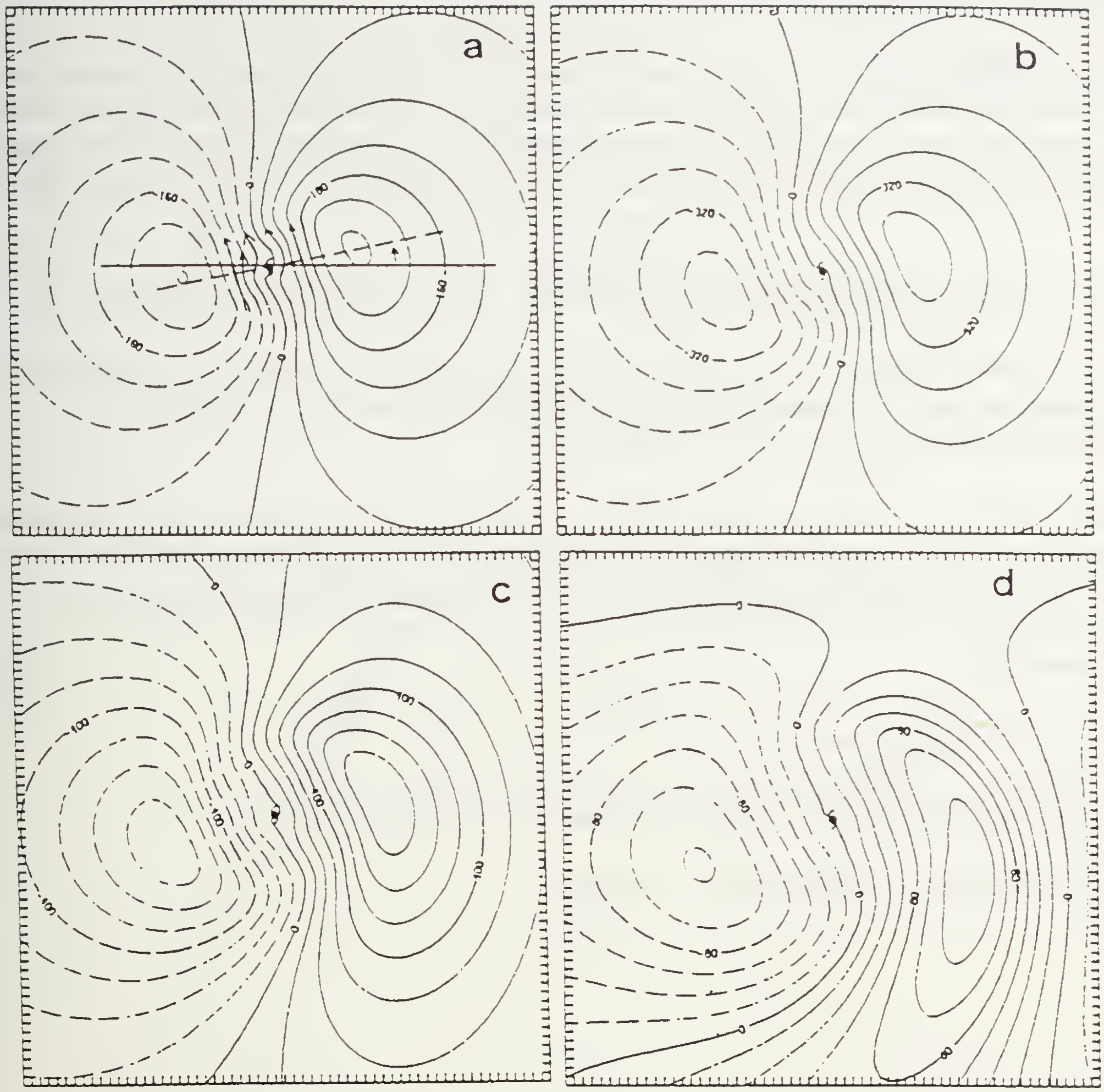


As in first panel sequence, except from a nonlinear numerical simulation of Chan and Williams (1987). The contour interval is 0.1 x 10^6 m^{2}s^{-1}.

Topic: BETA-EFFECT PROPAGATION (BEP)

MODEL DEPICTION OF BETA GYRES

The non-divergent, barotropic model of Fiorino and Elsberry without a background flow and the nonlinear beta effect terms as on page 57 simulates the formation of the beta gyres (on the right). The solid streamfunction indicates an anticyclonic gyre (Northern Hemisphere) to the east-northeast of the tropical cyclone, and the dashed streamfunction indicates a cyclonic gyre. As indicated in panel a after only 6 h, the flow between these two gyres establishes an advective component over the tropical cyclone. This advective component is toward the pole and westward, and is the source of the beta-effect propagation that exists for all cyclonic vortices. For the Southern Hemisphere, an anticyclonic gyre forms east-southeast of the tropical cyclone, and a cyclonic gyre forms to the west-northwest. The resulting advective component between these two gyres is toward the southwest (westward and poleward).



Temporal evolution of the asymmetric streamfunction ψ_a ($m^2\ s^{-1}$) at (a) 6 h; (b) 12 h; (c) 24 h; and (d) 72 h in the numerical simulation of Fiorino and Elsberry (1989). The plot domain is 61 x 61 points (with Δx = 40 km, 2400 x 2400 km) centered on the vortex. The tick marks indicate the location of the grid points. Positive (negative) values indicate anticyclonic (cyclonic) streamfunctions. Contour intervals are 4, 8, 10, and 20 (10^4), and the maximum absolute values of ψ_a are 2.5, 4, and 7 ($x10^5$), respectively.

Topic: BETA-EFFECT PROPAGATION (BEP)

BEP MAGNITUDE VERSUS TC SIZE

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

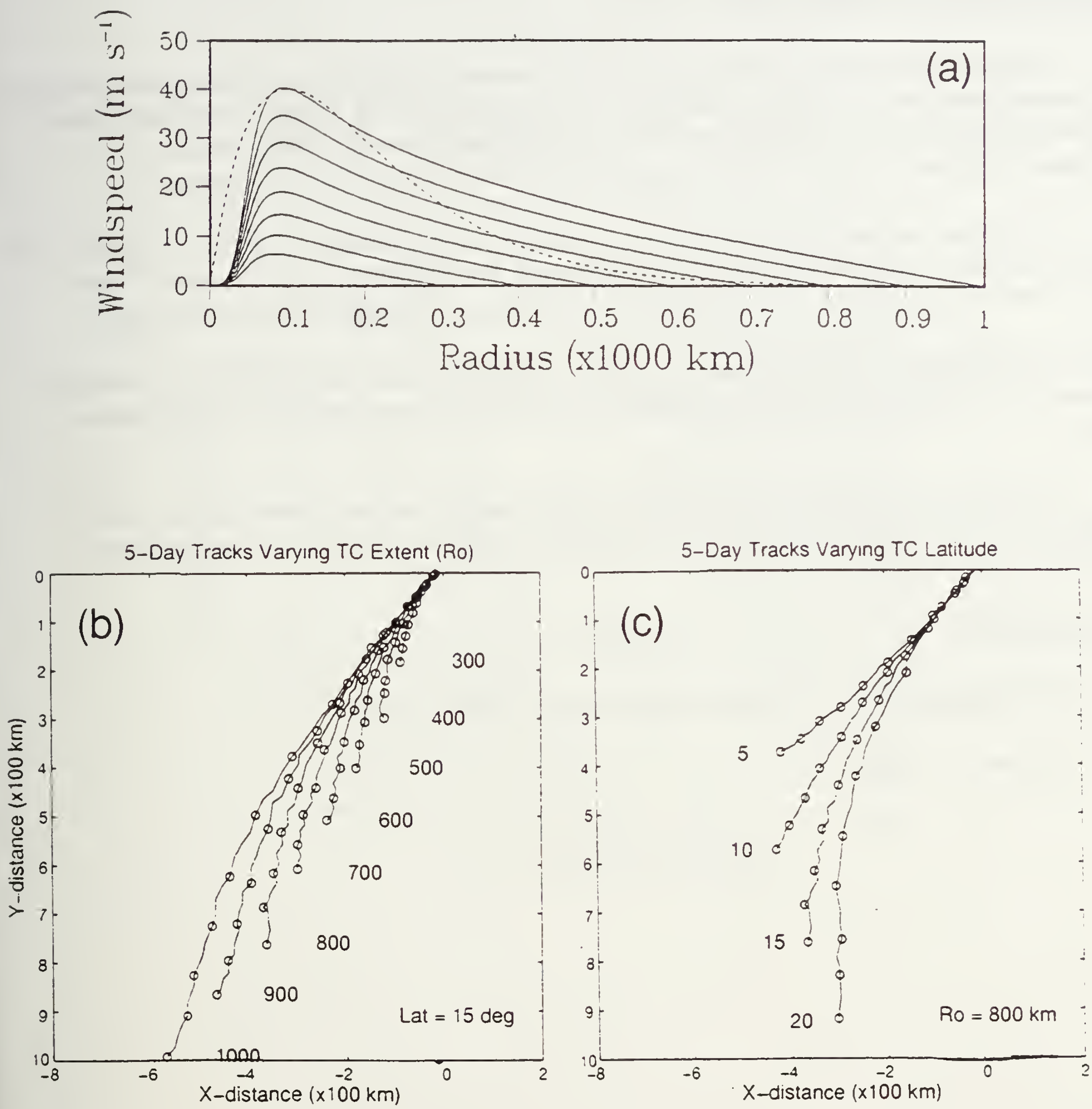
(c) the BEP direction is initially toward 225° for all profiles. At longer forecast intervals (assuming unchanging conditions), the steady southwestward track turns more poleward for the TC wind profiles representing higher latitude TCs (panel c), or for larger TCs (panel b).

Cross-references:

Key TC Motion Concepts p. 3

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

Dynamical basis for Beta-Effect Propagation p. 57


(a)
Windspeed (m s⁻¹)
Radius (x1000 km)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
10
20
30
40
50
5-Day Tracks Varying TC Extent (Ro)
(b)
300
400
500
600
700
800
900
1000
Lat = 15 deg
Y-distance (x100 km)
X-distance (x100 km)
5-Day Tracks Varying TC Latitude
(c)
5
10
15
20
Ro = 800 km
X-distance (x100 km)

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

BEP MAGNITUDE VERSUS SIZE (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_o850) 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_o850 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_o850 = 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.

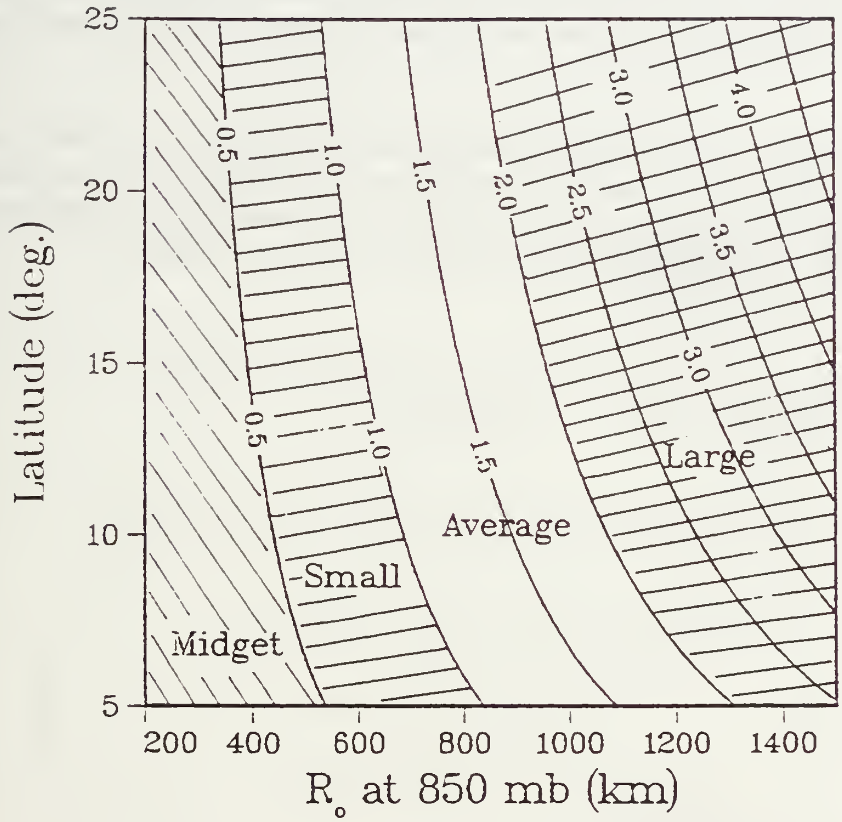
The BEP may cause a TC-Environment transformation by advecting the TC into another synoptic region within the same pattern, or contribute to a pattern transition via the peripheral anticyclone development.

Cross-references:

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

TC size p. 15

BEP Speed & TC Sizes



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

BEP TRACK DEFLECTION EXAMPLES (cont)

At latitudes north of 25° in the Southern Hemisphere, a TC may be in the easterly 10-15 kt steering associated with the TE region of a S pattern (i.e., equatorward of a zonally-oriented subtropical ridge. 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 225° (panel a) or 180° (panel b).

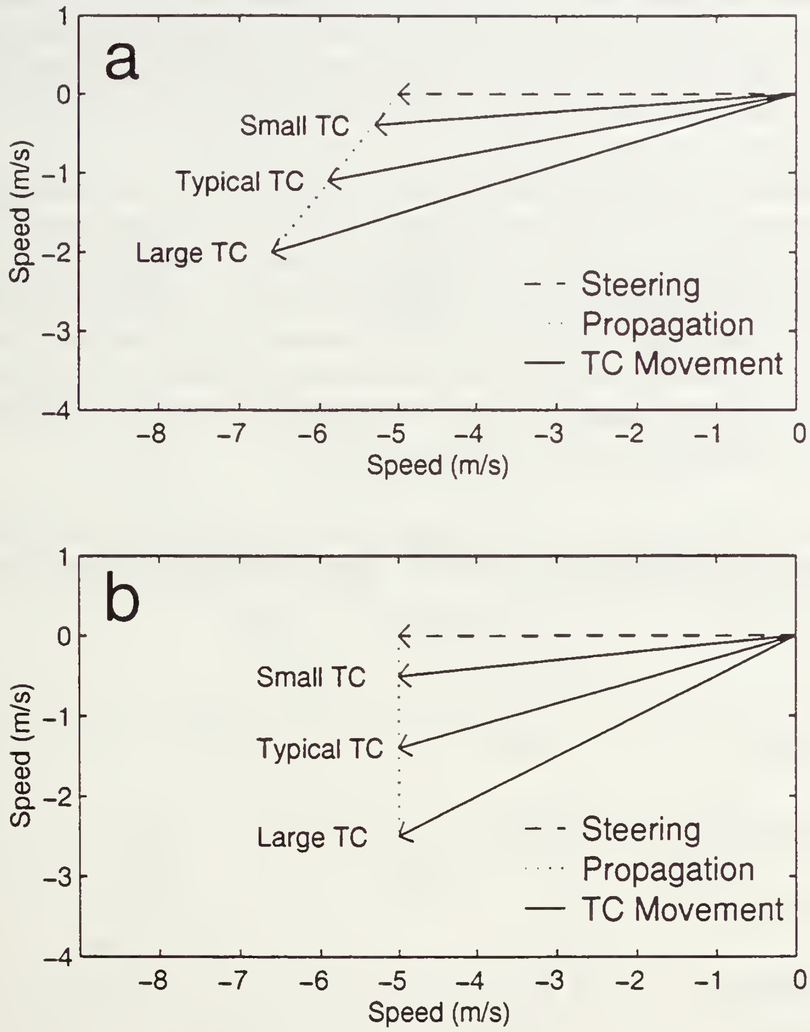
Whereas the motion of a SMALL TC departs very little (i.e., a cork in the stream) from the motion of the steering flow, the motion of an AVERAGE or LARGE TC departs quite significantly. In addition, recall from the definition of the LARGE TC that it also has a considerable potential to alter the structure 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: RIDGE MODIFICATION BY A TC (RMT)

DESCRIPTION

According to barotropic modelling results, the beta effect (latitudinal 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 anticyclonic vorticity advection that occurs in the northeastern portion of the TC circulation due to distortion of the TC windfield in association with the beta effect. Similarly, cyclonic vorticity advection occurs poleward and somewhat westward of the TC.

The development of a vigorous peripheral anticyclone as in panels b 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/TE to P/PF.

Cross-references:

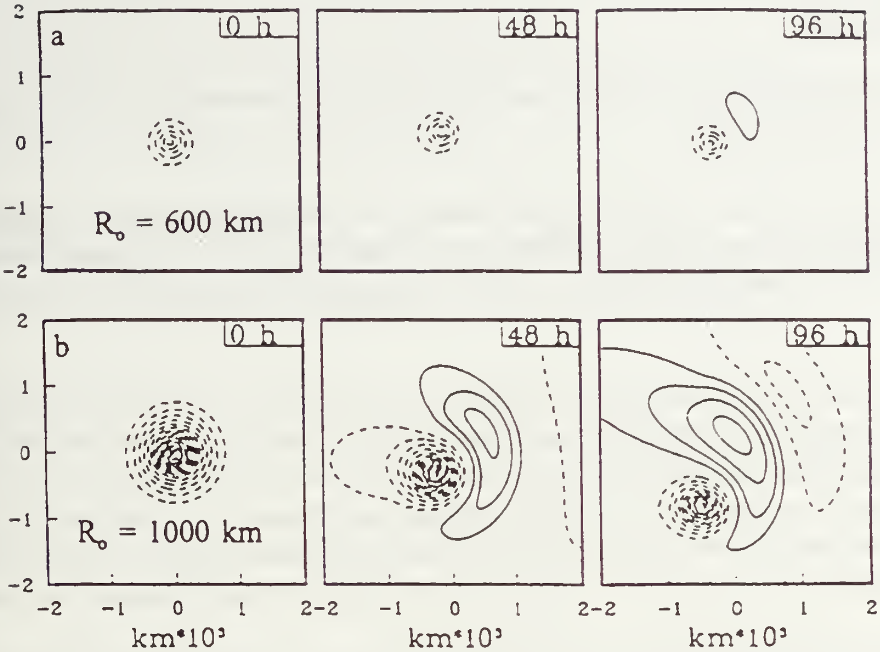
TC size p. 15

Angular Momentum TC Wind Profile p. 17

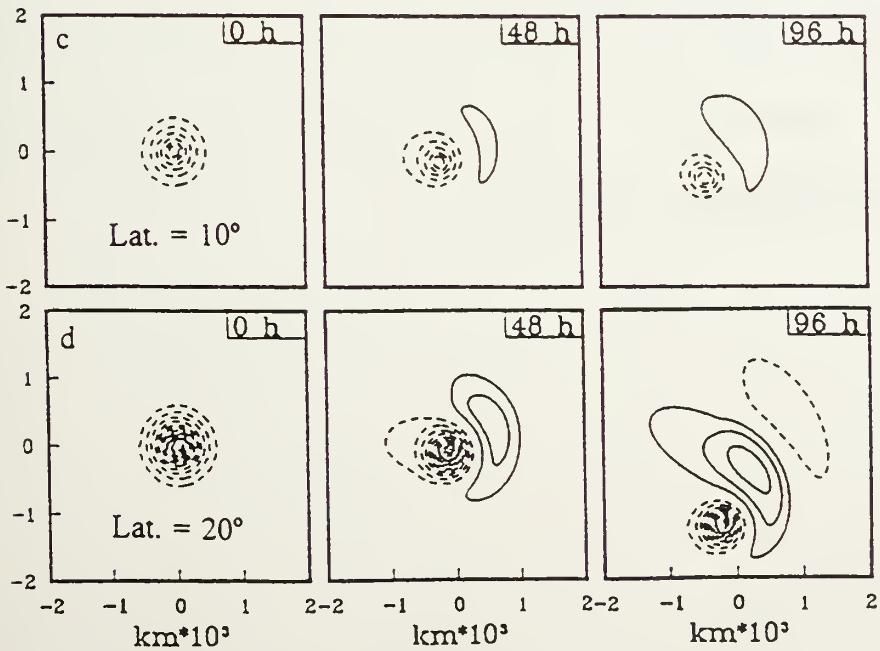
Standard (S) Pattern p. 19

Poleward (P) Pattern p. 29

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 modeling results on pp. 57-59, 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 cyclonic vorticity advection 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 cyclonic vorticity advection 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 northeast 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.

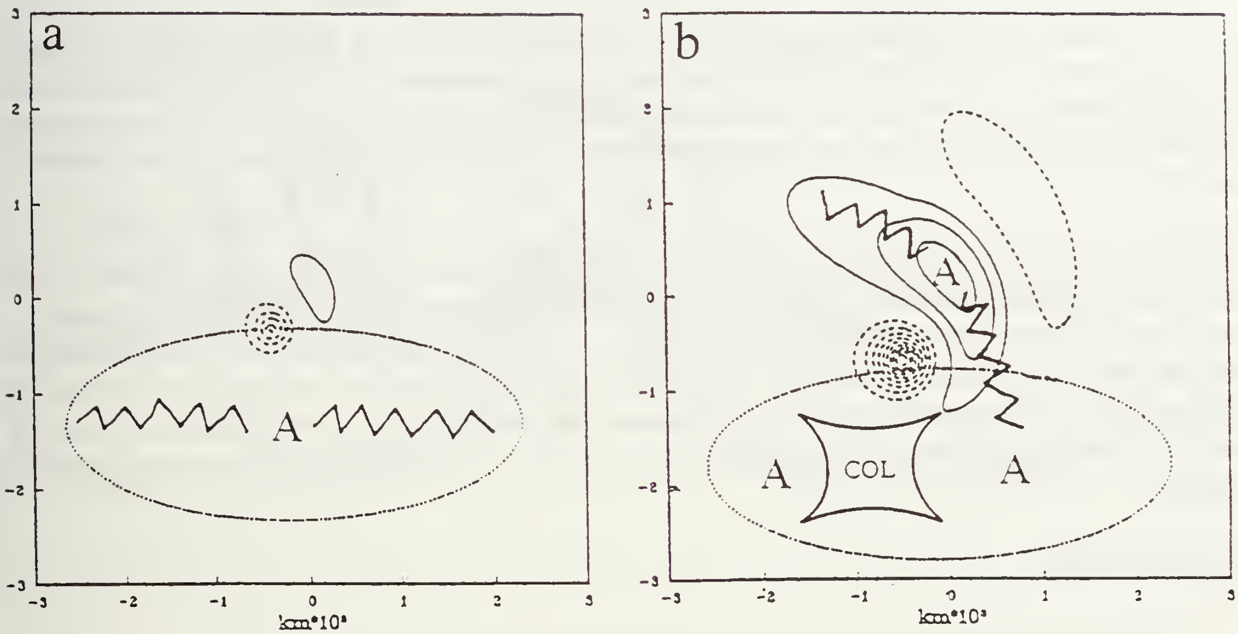
NOTE: It is the RELATIVE SIZE of the TC and its associated peripheral anticyclone in comparison with the amplitude of the STR that determines whether or not (or with what rapidity) the RMT process will result in a ridge-breaking event and a poleward turn by the TC. Thus, the relatively weak RMT process 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/TE pattern/region combination (panel a) to a P/PF 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/TE and P/PF, which makes it difficult to determine the pattern/region classification on the basis of 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/TE because the TC is moving more westward and poleward and the isotach maximum is to the south-southeast of the TC. By contrast, the environment structure in panel (b) is P/PF because the TC is moving more poleward than westward (and sometimes eastward) and the isotach maximum is to the northeast 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/TE and P/PF situation, respectively. Notice also that this implies that in general the track change associated with an S/TE to P/PF transition involving a small TC will be more severe (sharp) than for a larger TC. Such behavior has often actually been observed.

Cross-references:

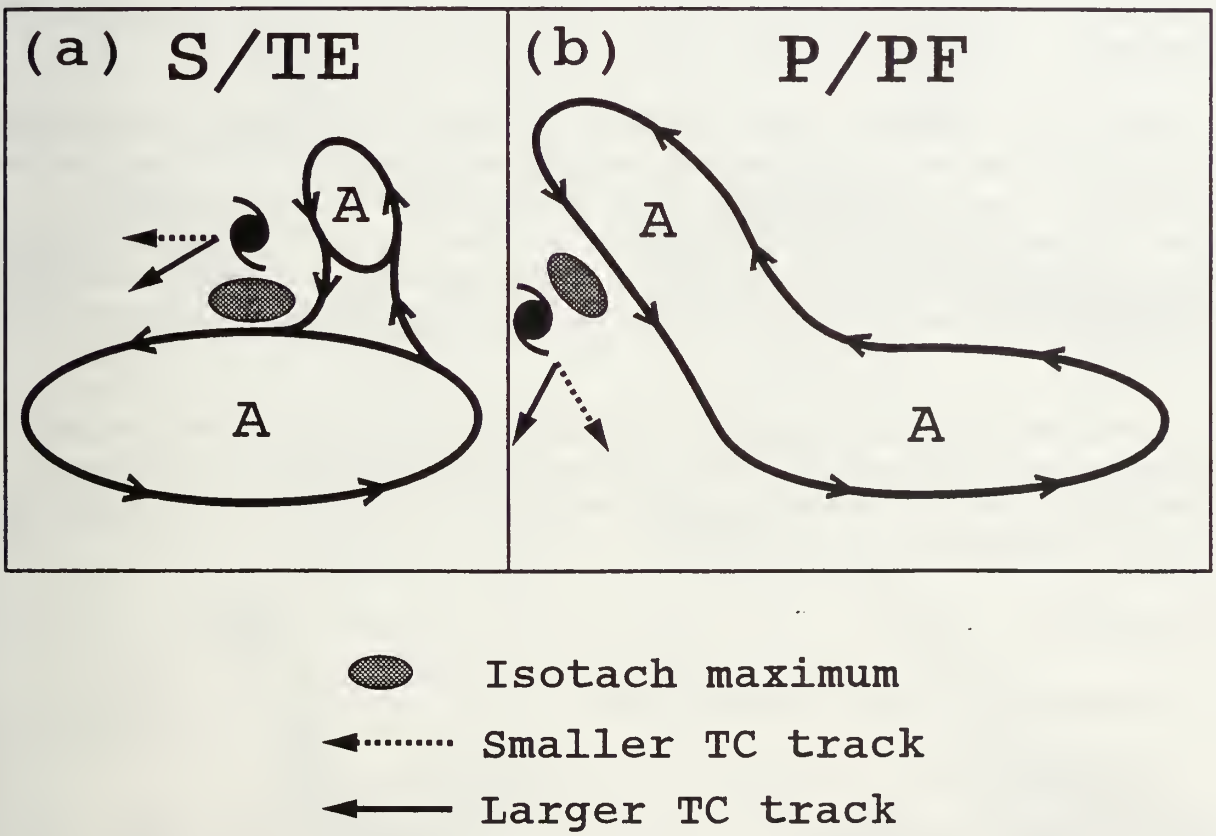
Diagnosing Environmental Steering Direction p. 9

Standard (S) Pattern p. 19

Poleward (P) Pattern p. 29

S/TE to P/PF Transition via Ridge Modification by TC (RMT)

Before: After:



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

RMT SCENARIO ILLUSTRATION

During 13 to 17 February 1994, the track of TC Ivy turned from west-southwestward to a sinuous poleward motion (panel a on right). In the NOGAPS analysis at 0000 UTC 13 February (panel b), Ivy (northeastern TC) is equatorward of a prominent subtropical anticyclone that has an east-northeast to west-southwest orientation. The isotach maximum in the south through east quadrant indicates a steering flow toward the southwest. Thus, Ivy is in the Standard/Tropical Easterlies (S/TE) pattern/region.

At 0000 UTC 14 February (panel c), the isotach maximum has shifted to the eastern semicircle, and a peripheral anticyclone is evident to the northeast. By 0000 UTC 15 February (panel d), the isotach maximum is to the northeast of Ivy, and the translation speed has decreased prior to a poleward turn.

By 000 UTC 16 February (panel e), Ivy is moving poleward in response to the steering flow associated with the peripheral anticyclone to the northeast, which is indicated by the isotach maximum to the northeast. Thus, the transition to the Poleward/Poleward Flow (P/PF) pattern/region is complete. This pattern/region continues at 0000 UTC 17 February (panel f). Notice that Ivy has intensified from 60 kt to 90 kt during the past 24 h. Such an intensification is not uncommon in the P/PF pattern/region because the TC is still at relatively low latitudes equatorward of the subtropical anticyclone.

Note: In panels d-f, the cyclone/trough located to the south of Ivy should not be misinterpreted as a midlatitude feature, in which case a H pattern might reasonably be assigned for the environment structure of Ivy. Rather, this cyclone/trough is the remnants of TC Hollanda, which appears as the southwest TC (asterisk) in panels b and c.

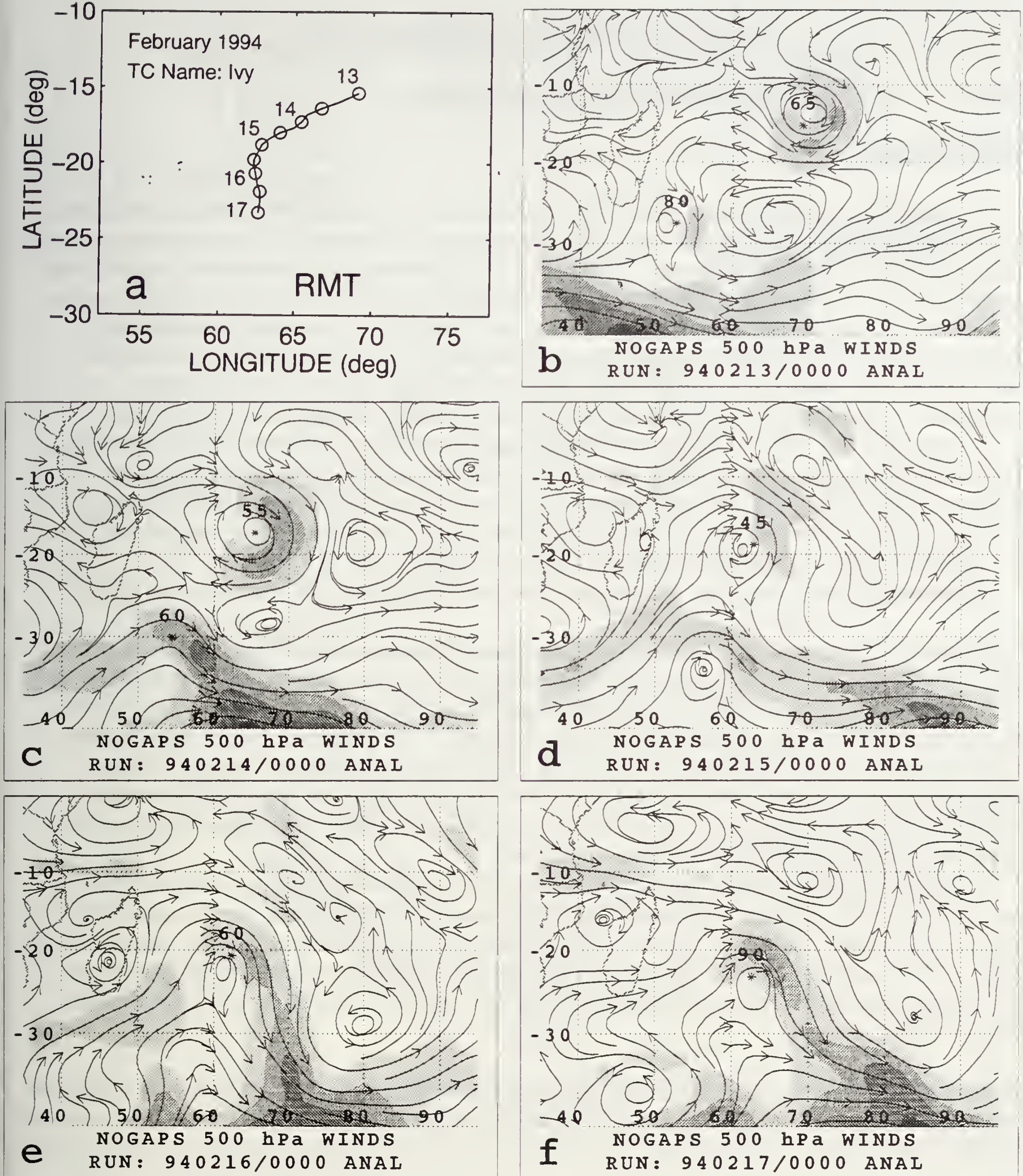
Cross-references:

Diagnosing Environmental Steering Direction p. 9

Standard (S) Pattern p. 19

Poleward (P) Pattern p. 29

High-amplitude (H) Pattern p. 37


February 1994
TC Name: Ivy
a
RMT
LATITUDE (deg)
LONGITUDE (deg)
b
NOGAPS 500 hPa WINDS
RUN: 940213/0000 ANAL
c
NOGAPS 500 hPa WINDS
RUN: 940214/0000 ANAL
d
NOGAPS 500 hPa WINDS
RUN: 940215/0000 ANAL
e
NOGAPS 500 hPa WINDS
RUN: 940216/0000 ANAL
f
NOGAPS 500 hPa WINDS
RUN: 940217/0000 ANAL

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 northeast 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 southeast, 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 southwest 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 southeast of the anticyclone;
- keep the western TC peripheral anticyclone from forming at all; or
- constrain the formation of the anticyclone to be more north 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 Semi-direct Cyclone Interaction (SCI) transition mechanism is temporarily established. As the eastern TC moves poleward of the western TC, the development of the peripheral anticyclone to the northeast 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.

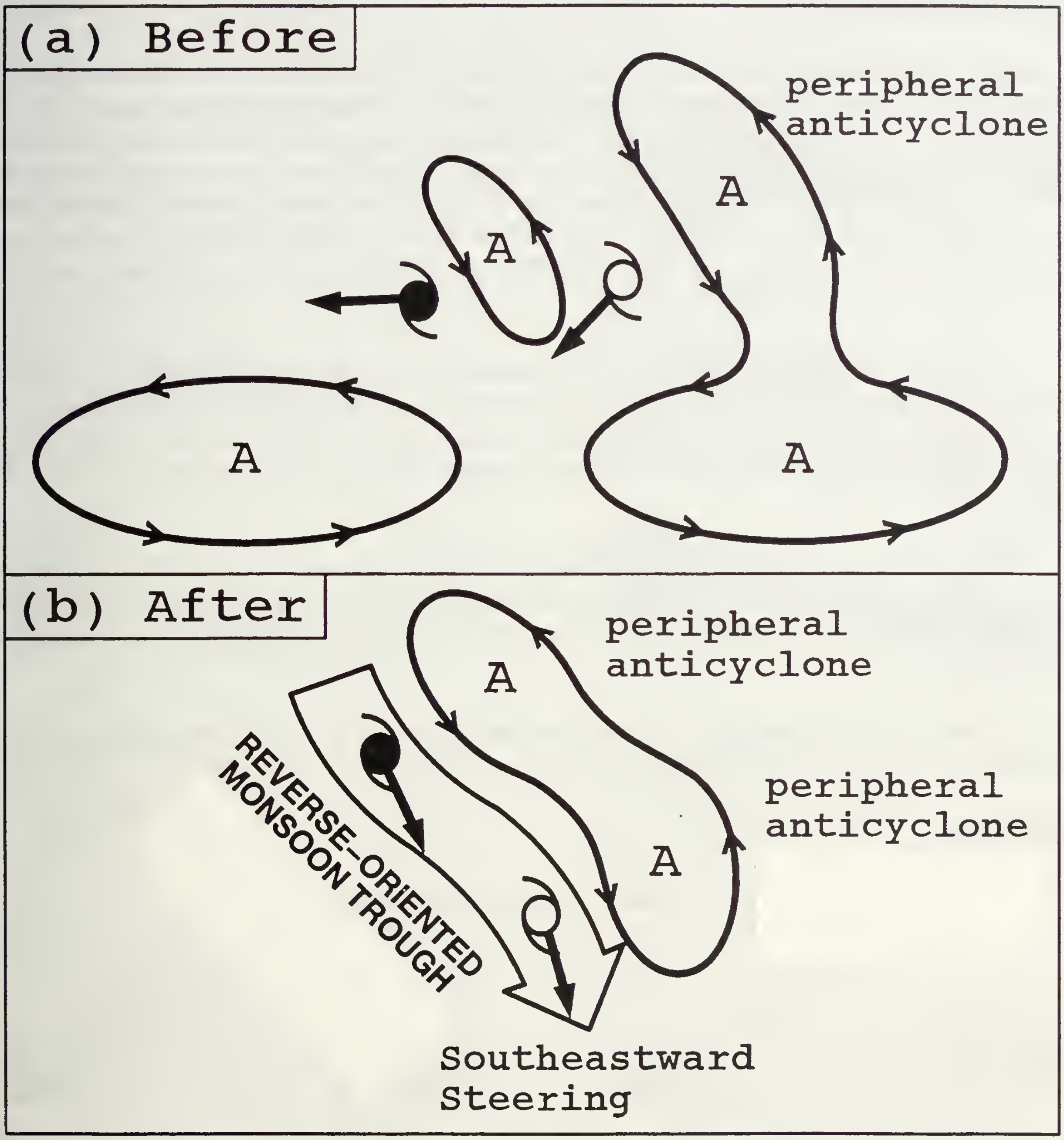
If the contribution of the western TC to the growth of its associated peripheral anticyclone exceeds the damping effect on the eastern TC, the impact of the steering flow on the eastern TC will cause an equatorward deflection, which will be described later as an Indirect Cyclone Interaction-East (ICIE). 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, which is ICI-West or ICIW.

Note: Especially in the region of the South Pacific Convergence Zone, two cyclones may form in an orientation as in panel b, and as their peripheral anticyclones grow and merge, this will also be labeled as RTF.

Cross-references:

Ridge Modification by a TC (RMT) p. 67
Semidirect Cyclone Interaction (SCI) p. 91
Indirect Cyclone Interaction (ICI) p. 79

REVERSE TROUGH FORMATION (RTF) CONCEPTUAL MODEL



Topic: REVERSE TROUGH FORMATION (RTF) (cont)

SCENARIO ILLUSTRATION

In panel a on the right, the tracks of three TCs that turned poleward almost simultaneously are displayed. Notice that the western (Pete) and central (Olinda) TCs had been near-stationary until after the eastern (Dani) TC began moving poleward. Although both Olinda and Dani are equatorward of the subtropical anticyclone axis on 1200 UTC 19 January 1999 (panel b), they are in a weak steering flow -- notice the isotach maximum wraps around Dani. By 1200 UTC 20 January (panel c), Dani has begun to move poleward -- notice the more than 30-kt isotach to the east. Olinda is starting to drift eastward with a 20-kt isotach maximum to the north, and Pete is just beginning to form farther west in the monsoon trough.

At 1200 UTC 21 January (panel d), Dani is beginning to accelerate southeastward. Notice the peripheral anticyclone to the northeast and the isotach maximum to the east, so that Dani is now in the P/PF pattern/region. Similarly, Olinda has an isotach maximum to the northeast and has turned to a more poleward track (panel a). Finally, Pete has now formed and is moving eastward in the P/EW pattern/region.

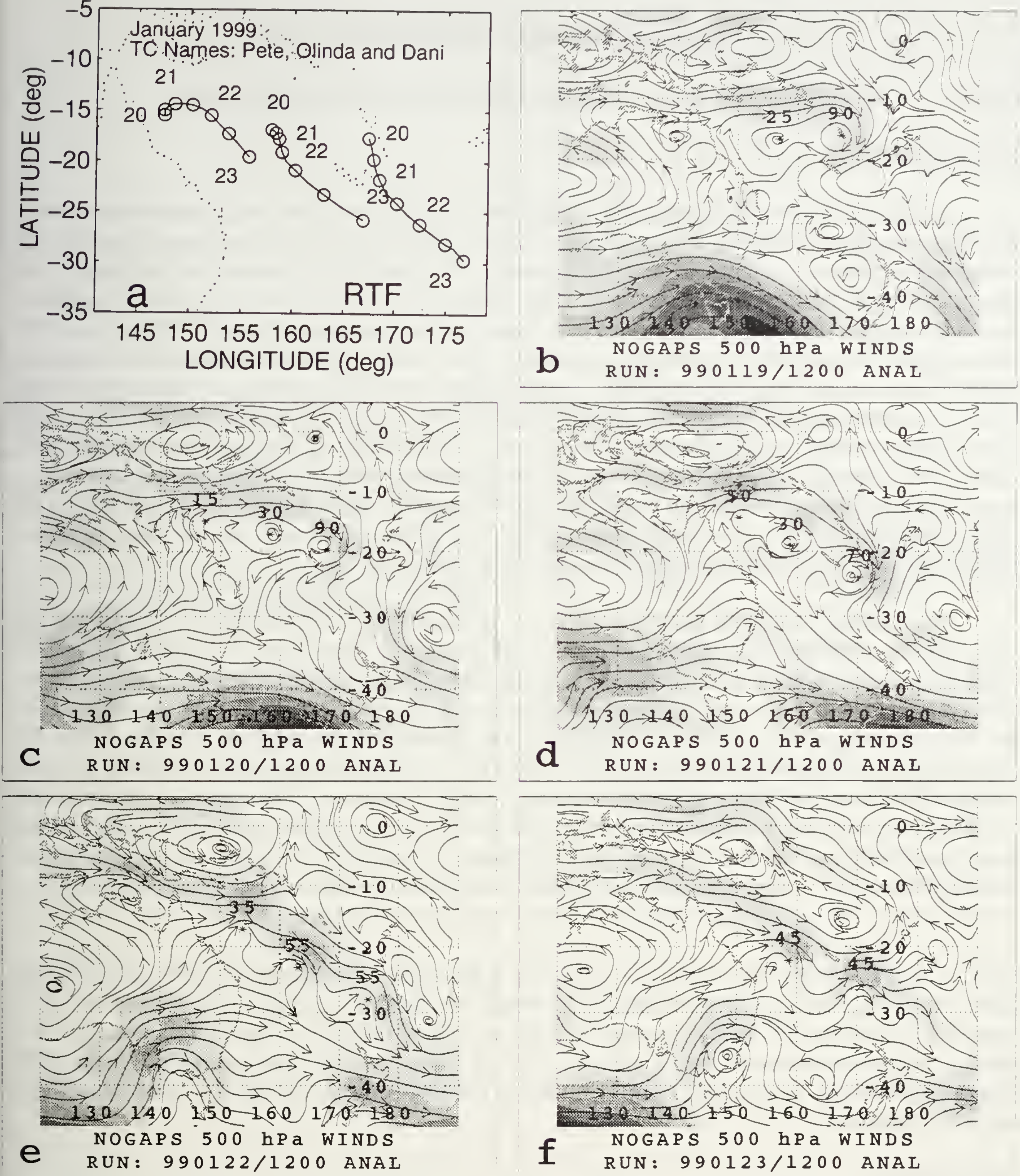
The establishment of a P pattern for all three TCs is even more evident at 1200 UTC 22 January (panel e). Notice that the peripheral anticyclones of the three TCs have combined, and the three TCs are in a reverse-oriented monsoon trough. This is the Reverse Trough Formation (RTF) transitional mechanism.

By 1200 UTC 23 January (panel f), Dani is only an open wave at 500 mb. However, both Olinda and Pete are in a P pattern with a combined peripheral anticyclone to the northeast.

Cross-reference:

Ridge Modification by a TC, Peripheral Anticyclone Development p. 67

Poleward (P) pattern p. 29


January 1999
TC Names: Pete, Olinda and Dani
LATITUDE (deg)
LONGITUDE (deg)
a
RTF
NOGAPS 500 hPa WINDS
RUN: 990119/1200 ANAL
b
NOGAPS 500 hPa WINDS
RUN: 990120/1200 ANAL
c
NOGAPS 500 hPa WINDS
RUN: 990121/1200 ANAL
d
NOGAPS 500 hPa WINDS
RUN: 990122/1200 ANAL
e
NOGAPS 500 hPa WINDS
RUN: 990123/1200 ANAL
f

Topic: INDIRECT CYCLONE INTERACTION ON EASTERN TC (ICIE)

DESCRIPTION

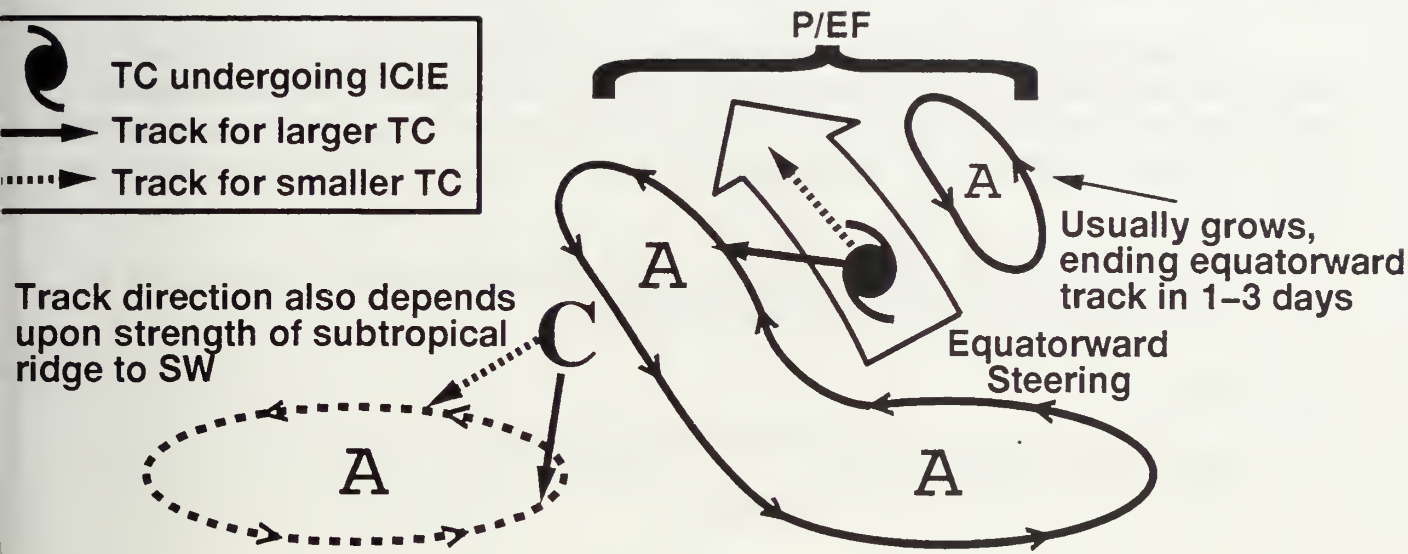
An Indirect Cyclone Interaction East (ICIE) involves a TC on the east and a cyclone to the west. The separation distance may be about 15° long. or more. The cyclone to the west may be another TC, a monsoon depression, an upper-tropospheric trough, or a midlatitude trough. As indicated in the schematic at right, the western cyclone in an ICIE scenario has a peripheral anticyclone of significant scale and strength, and appears connected or "linked" to the subtropical ridge (STR) as in a P/PF pattern/region. By contrast, the eastern TC presently has a weaker peripheral anticyclone. Although two ICI variations may occur simultaneously, in the ICI-East (or ICIE) variation, the track of the eastern TC may be significantly affected by the peripheral anticyclone of the western cyclone without the track of the western cyclone being affected by the presence of the eastern TC. As a result, the significant equatorward steering of the peripheral anticyclone associated with the western cyclone is able to temporarily turn the eastern TC from the typical WSW direction of motion expected equatorward of the STR to a more westward or even north of west direction of motion. During the period when the eastern TC track is deflected equatorward, an ICIE is said to be occurring.

The duration of ICIE is usually limited to 1-3 days for the following reason. Notice that the northeastward orientation of the western cyclone, 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 peripheral anticyclone associated with the western cyclone suggests that the eastern TC formation may be indirectly aided by the western cyclone. 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 equatorward steering effect of the western peripheral anticyclone and will turn to an increasingly poleward track. A slow transition to an environment structure of P/PF often, but not always, results.

NOTE: The environment of a single TC undergoing ICIE would be classified as a S/PF pattern/region. If the western cyclone is a TC, the eastern TC would be classified in a P/EF environment since it is dominated by the steering flow associated with the peripheral anticyclone that is analogous to the P pattern when the western cyclone is indeed a TC. If the eastern TC was previously in the S/TE pattern/region and its track turned from westward to northwestward, then this is a result of the ICIE transition mechanism.

Cross-reference:

Beta-Effect Propagation, Peripheral anticyclone p. 57
Standard (S) Pattern p. 19
Poleward (P) Pattern p. 29


TC undergoing ICIE
Track for larger TC
Track for smaller TC
P/EF
A
Usually grows, ending equatorward track in 1–3 days
Track direction also depends upon strength of subtropical ridge to SW
C
A
Equatorward Steering
A
A

Topic: INDIRECT CYCLONE INTERACTION ON EASTERN TC (ICIE) (cont)

MUTUAL ROTATION CHARACTERISTICS

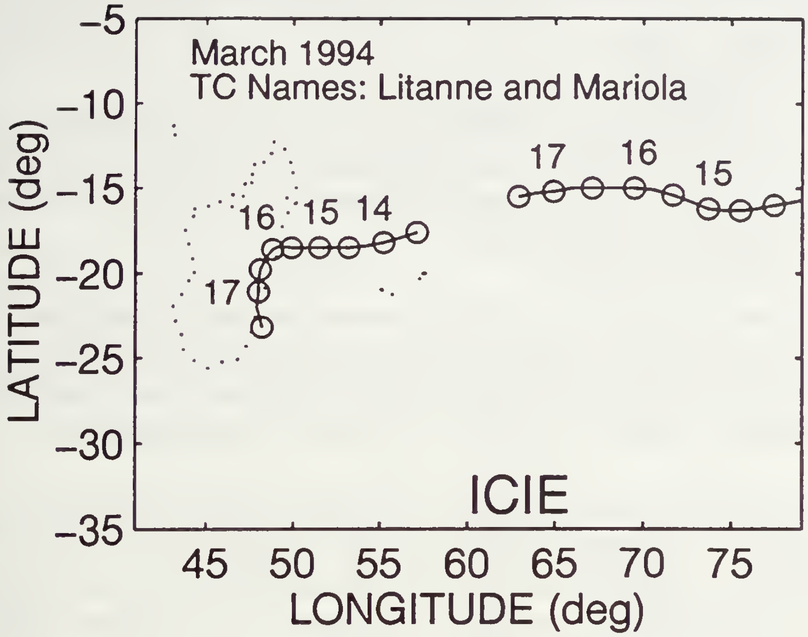
A relative rotation diagram has often been used to describe the Fujiwhara-type cyclonic rotation of a binary TC interaction. Even though the midpoint (centroid) between the two TCs should only be used if the two TCs are the same size, this midpoint is often used for convenience even when different size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

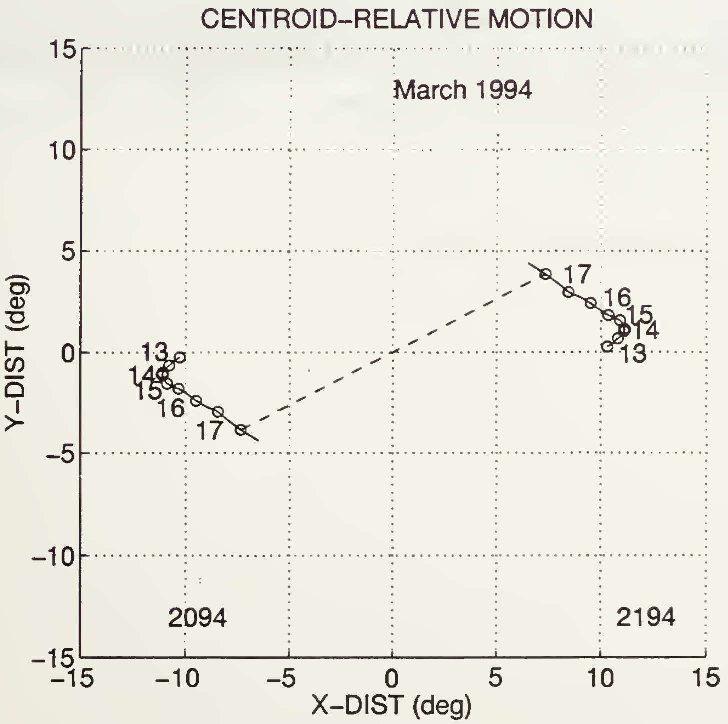
In a centroid-relative motion diagram, the onset of ICIE will normally be manifest as a change from negligible or weak cyclonic rotation to persistent anticyclonic rotation. The angular rotation rate will normally be greater than 1.0 degree per 6 hours. The separation distance may either increase, decrease,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

A comparison of the geographic motion and centroid-relative motion for a pair of TCs are shown at right during the period in which ICIE occurs.

Cross-reference:

Direct Cyclone Interaction (DCI) p. 99


March 1994
TC Names: Litanne and Mariola
ICIE
LATITUDE (deg)
LONGITUDE (deg)
17
16
15
14
17
16
15


CENTROID–RELATIVE MOTION
March 1994
Y–DIST (deg)
X–DIST (deg)
2094
2194
13
14
15
16
17

Topic: INDIRECT CYCLONE INTERACTION ON EASTERN TC (ICIE) (cont)

ICIE SCENARIO ILLUSTRATION

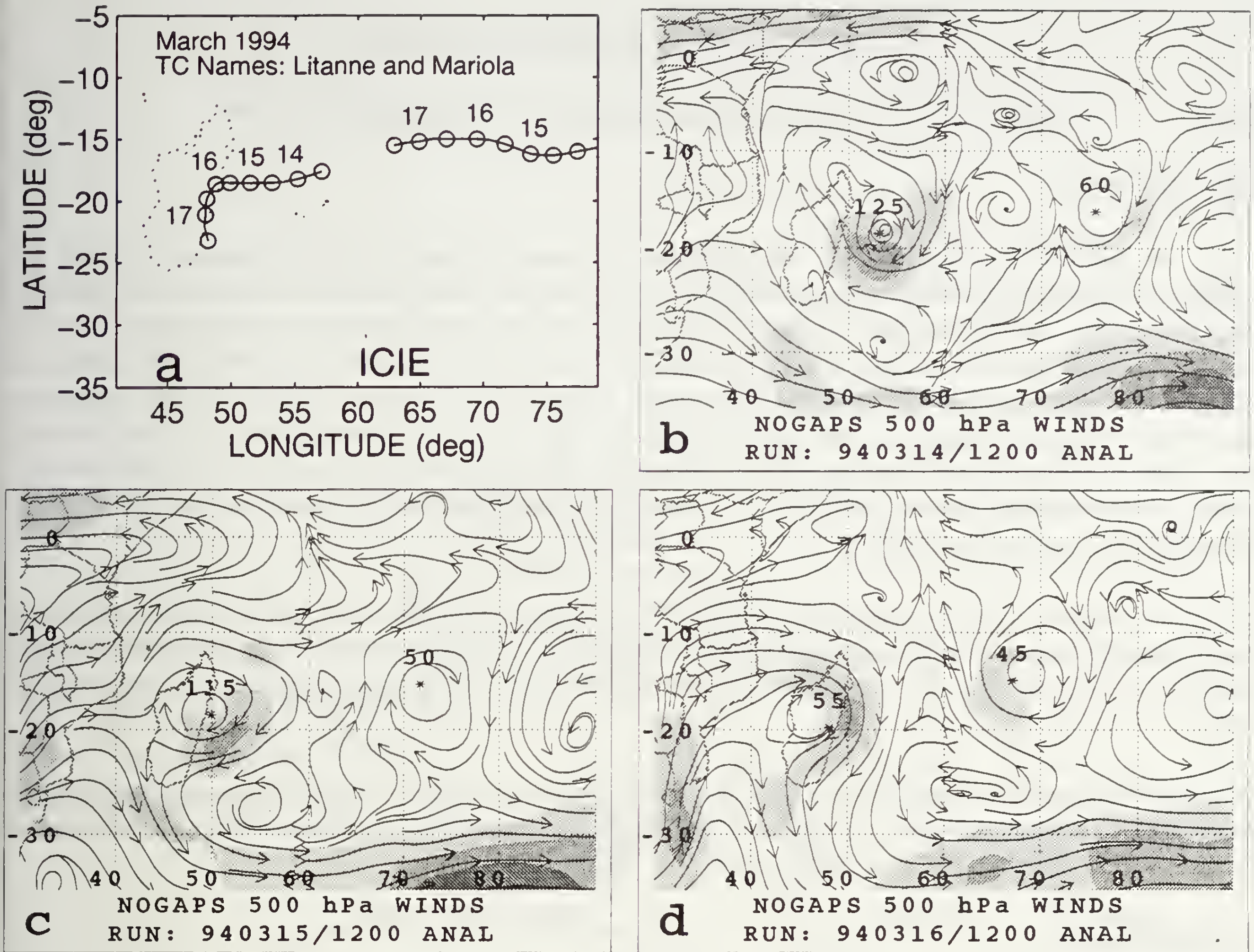
In panel a on the right, the western TC (Litanne) is first moving westward and then has a sharp turn to the south. The ICIE period is associated with a slight equatorward deflection of the eastern TC (Mariola). At 1200 UTC 14 March 1994 (panel b), the two TCs are separated by about 21° long. with a closed anticyclone between them.

At 1200 UTC 15 March (panel c), Litanne is on the east coast of Madagascar. Although the separation distance is still 21° long., a slight equatorward deflection of Mariola has begun. It appears that the peripheral anticyclone of Litanne is responsible for the equatorward deflection. This NOGAPS analysis has no isotach maximum that would indicate such a steering flow.

At 1200 UTC 16 March (panel d), Litanne has turned poleward, which is consistent with the isotach maximum to the east. Notice the meridionally oriented peripheral anticyclone east of Litanne that is connected to the subtropical anticyclone well to the southeast. The isotach maximum is now to the west of Mariola, as would be expected if the steering flow is associated with the peripheral anticyclone of Litanne. However, Mariola also has a fairly large horizontal extent that might contribute to a poleward and westward deflection. The net effect appears to be an offset of meridional deflections, and a westward motion that decreases the separation distance to Lianne to about 19° long. This indicates that an equatorward steering component on the eastern TC during ICI does not necessarily result in an equatorward deflection.

Cross-reference:

Diagnosing Environmental Steering Direction p. 9


March 1994
TC Names: Litanne and Mariola
LATITUDE (deg)
LONGITUDE (deg)
a
ICIE
NOGAPS 500 hPa WINDS
RUN: 940314/1200 ANAL
b
NOGAPS 500 hPa WINDS
RUN: 940315/1200 ANAL
c
NOGAPS 500 hPa WINDS
RUN: 940316/1200 ANAL
d

Topic: INDIRECT CYCLONE INTERACTION ON WESTERN TC (ICIW)

DESCRIPTION

In the ICI-West (or ICIW), the expected poleward deflection of the western TC may be significantly reduced via modification (damping) of the peripheral anticyclone by the cyclone to the east, even though the track of the eastern cyclone 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 ICIW scenario is being eroded and "separated" from the subtropical ridge (STR) by the cyclonic vorticity advection associated with the presence of the eastern cyclone, 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 cyclone further separates the western TC peripheral anticyclone from the STR. Two possible ICIW consequences are:

(1) if the western TC has previously been in a P/PF pattern/region, and thus had a strongly poleward track, then the influence of the eastern cyclone 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/TE.

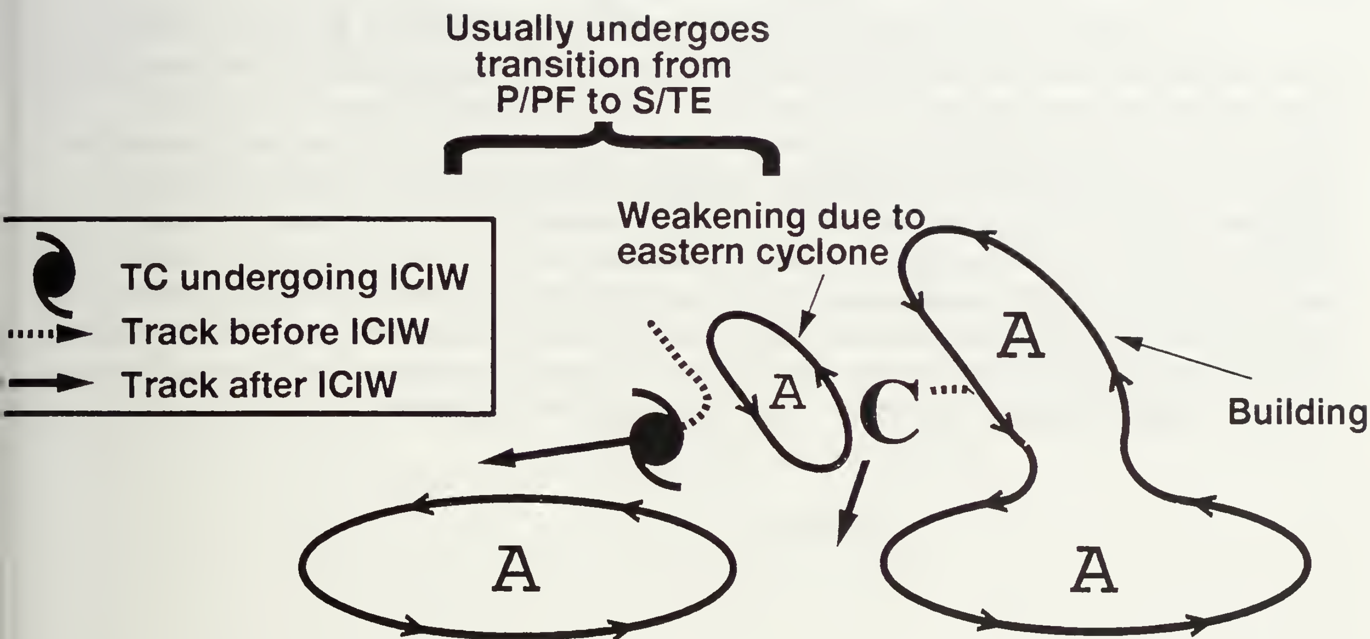
(2) if the western TC has been in a S/TE environment, then any tendency for development of a poleward steering flow associated with the western TC peripheral anticyclone precludes the possibility of a transition to P/PF while ICIW is taking place.

Cross-references:

Beta-Effect Propagation, Peripheral anticyclone p. 57

Poleward (P) Pattern p. 29

Standard (S) Pattern p. 19

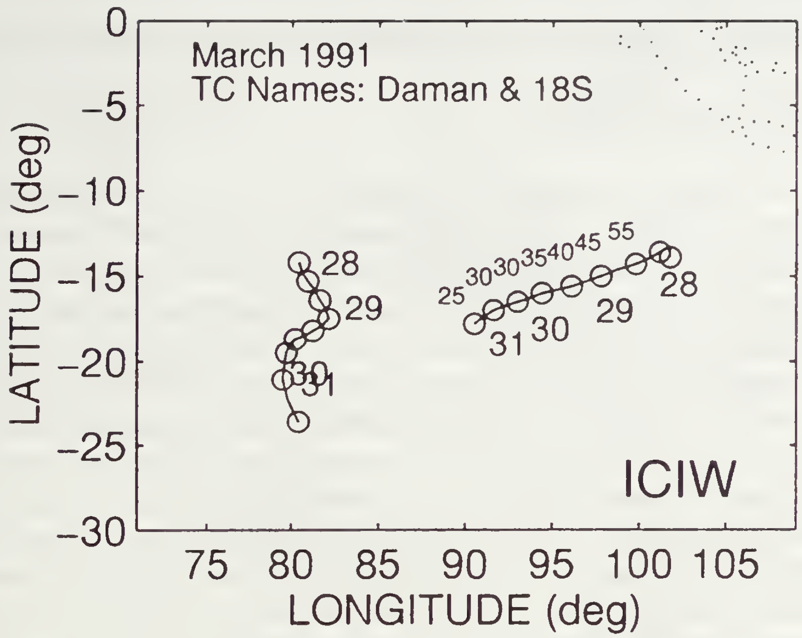

Usually undergoes
transition from
P/PF to S/TE
Weakening due to
eastern cyclone
TC undergoing ICIW
Track before ICIW
Track after ICIW
A
C
A
Building
A
A

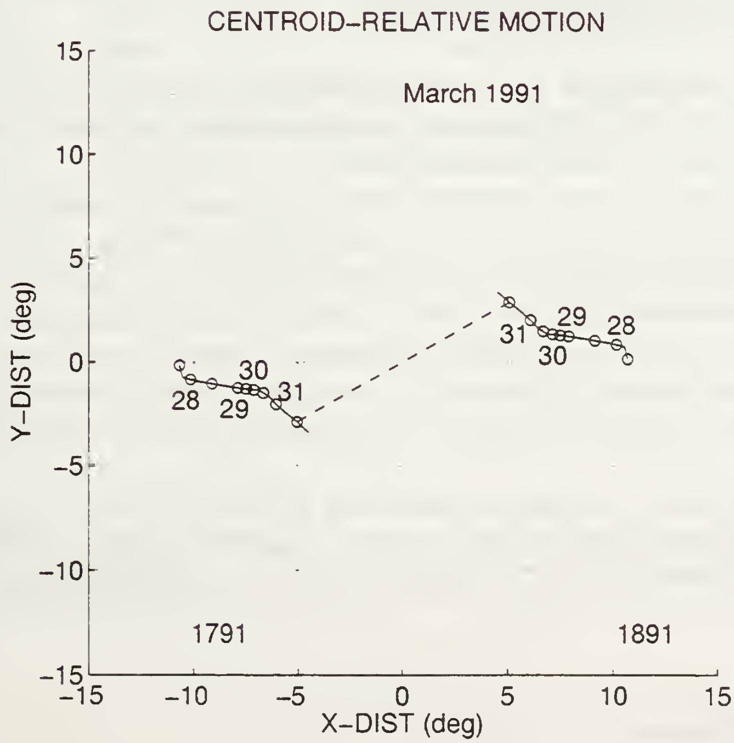
Topic: INDIRECT CYCLONE INTERACTION ON WESTERN TC (ICIW) (cont)

MUTUAL ROTATION CHARACTERISTICS

In a centroid-relative motion diagram, the onset of ICIW 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 TC and the eastern cyclone (which may be a TC).

A comparison of the geographic motion and centroid-relative motion for a pair of TCs is shown at right for a time period during which ICIW occurs. In the geographic plot, the onset of ICIW is indicated by the westward turn of Daman (17S) on 29 March, and the cessation of ICIW is indicated by the resumption of strongly poleward motion on 30 March. In the centroid-relative plot, the period of ICIW is manifest as a period of negligible mutual rotation and negligible change in separation distance that is preceded and followed by weak anticyclonic turning and decreasing separation distance. The reason that cyclonic rotation does not occur during the period of ICIW is that the eastern TC (18S) remains on a primarily westward track both before and after the ICIW, as opposed to following the more poleward path in the ICIW conceptual model on p. 86. Since Daman also turns westward and has about the same direction and speed of motion as 18S, the two TCs have negligible mutual rotation or separation distance change in the centroid-relative plot.


March 1991
TC Names: Daman & 18S
ICIW
LATITUDE (deg)
LONGITUDE (deg)
0
−5
−10
−15
−20
−25
−30
75
80
85
90
95
100
105
28
29
30
31
25
30
30
35
40
45
55
28
29
30
31


CENTROID−RELATIVE MOTION
March 1991
Y−DIST (deg)
X−DIST (deg)
15
10
5
0
−5
−10
−15
−15
−10
−5
0
5
10
15
28
29
30
31
31
30
29
28
1791
1891

Topic: INDIRECT CYCLONE INTERACTION ON WESTERN TC (ICIW) (cont)

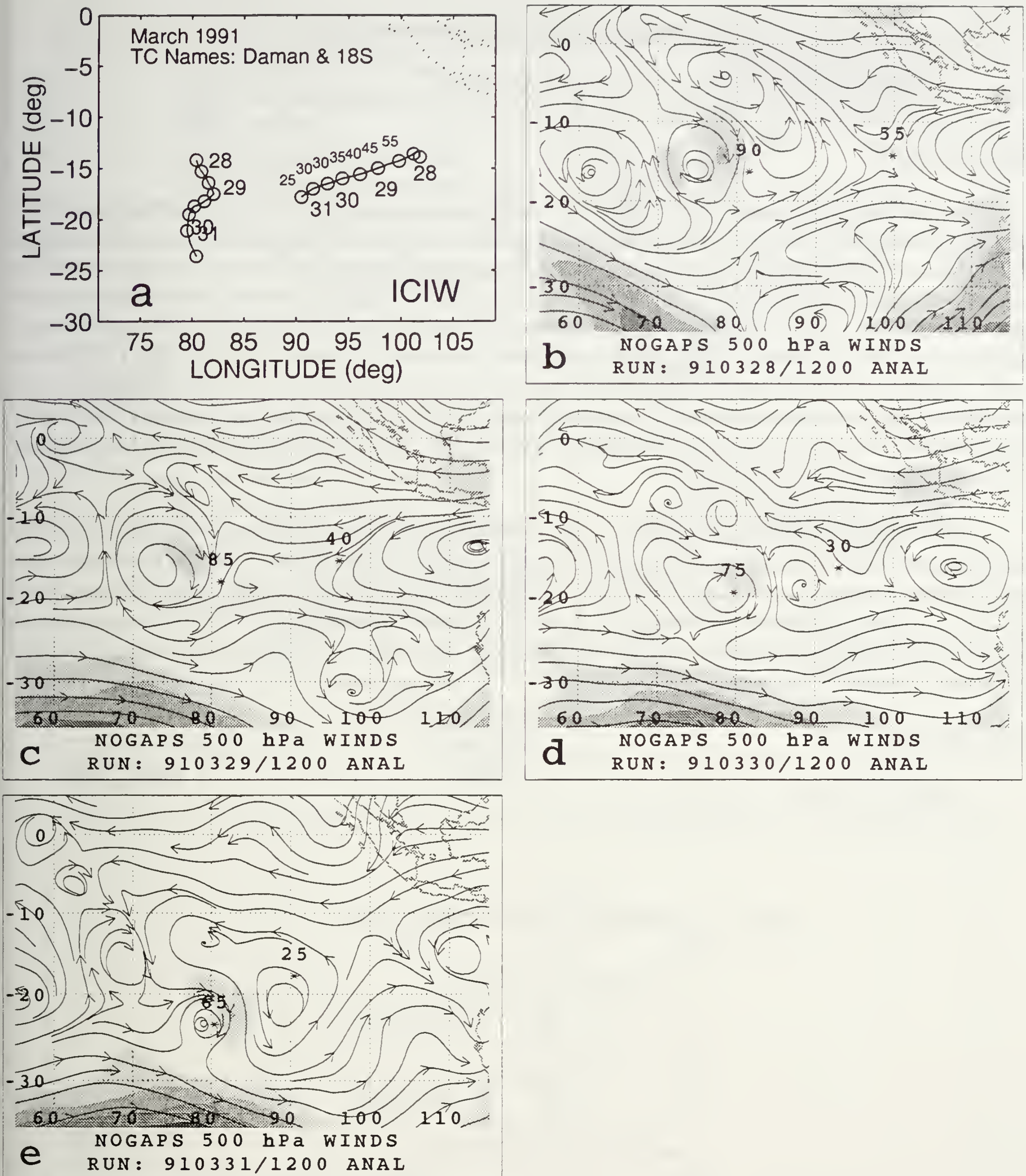
ICIW SCENARIO ILLUSTRATION

In panel a on the right, the track of TC Daman (17S; western TC) is south-southeastward during 28 March 1991. At 1200 UTC 28 March (panel b), the NOGAPS analysis has a prominent anticyclone to the northeast of the analyzed wind center for Daman (near 16° S, 75°E). The isotach maximum to the east of the wind center would support the interpretation that the anticyclone to the northeast is the primary cause of Daman's predominantly poleward motion. At this time, TC-18S (eastern asterisk) is nearly 20° long. to the east of Daman, which is far enough away to not negatively impact the anticyclone. By 1200 UTC 29 March (panel c), the separation distance of the TCs has decreased to about 15° long., and the anticyclone east and north of Daman appears noticeably weaker. Presumably in response to the weakening of the poleward steering flow associated with the anticyclone between Daman and TC-18S, the track of Daman turns onto a west-southwestward heading that is consistent with the steering being from the thin subtropical ridge poleward of Daman. In other words, the environment in the vicinity of Daman has had a transition from P/PF to S/TE and caused the TC to turn westward. This sequence of events is consistent with the ICIW conceptual model on p. 86. Over the next two days (panels d-e), TC-18S dissipates, and the anticyclone to the east of Daman becomes noticeably more prominent, with a resumption of predominantly poleward motion by Daman. In other words, the environment in the vicinity of Daman has had a transition from S/TE to P/PF that caused the TC to turn poleward.

NOTICE: Several inconsistencies are found in panels b and c with regard to the satellite-based positions (asterisks), the NOGAPS-analyzed streamline centers and isotach maxima, and the movement of Daman (cf. p. 10 and associated text):
i) In panel b, when Daman is moving nearly poleward, the satellite-based TC position ought to be between the streamline center and isotach maximum, or about 5° long. to the west of where it actually appears, or the NOGAPS-analyzed location of Daman should be about 5° east (p. 10; middle example). Since the intensity of Daman is 90 kt at this time, such a large fix error is highly unlikely. Rather, it must be assumed that the NOGAPS location of Daman is incorrect, owing to a lack of data, or either a rejection or absence of synthetic TC wind observations. Nevertheless, the location of the isotach maximum to the east of the wind center is consistent with the observed poleward motion of Daman.
ii) In panel c, when Daman is moving predominantly westward, the satellite-based TC position and the NOGAPS analysis of Daman are still inconsistent, and the location of the isotach maximum is inconsistent with the motion of the TC. Such inconsistencies certainly make the interpretation more difficult.

Cross-references:

Poleward (P) pattern p. 29
Standard (S) pattern p. 19


March 1991
TC Names: Daman & 18S
LATITUDE (deg)
LONGITUDE (deg)
a
ICIW
b
NOGAPS 500 hPa WINDS
RUN: 910328/1200 ANAL
c
NOGAPS 500 hPa WINDS
RUN: 910329/1200 ANAL
d
NOGAPS 500 hPa WINDS
RUN: 910330/1200 ANAL
e
NOGAPS 500 hPa WINDS
RUN: 910331/1200 ANAL

Topic: SEMI-DIRECT CYCLONE INTERACTION (SCI)

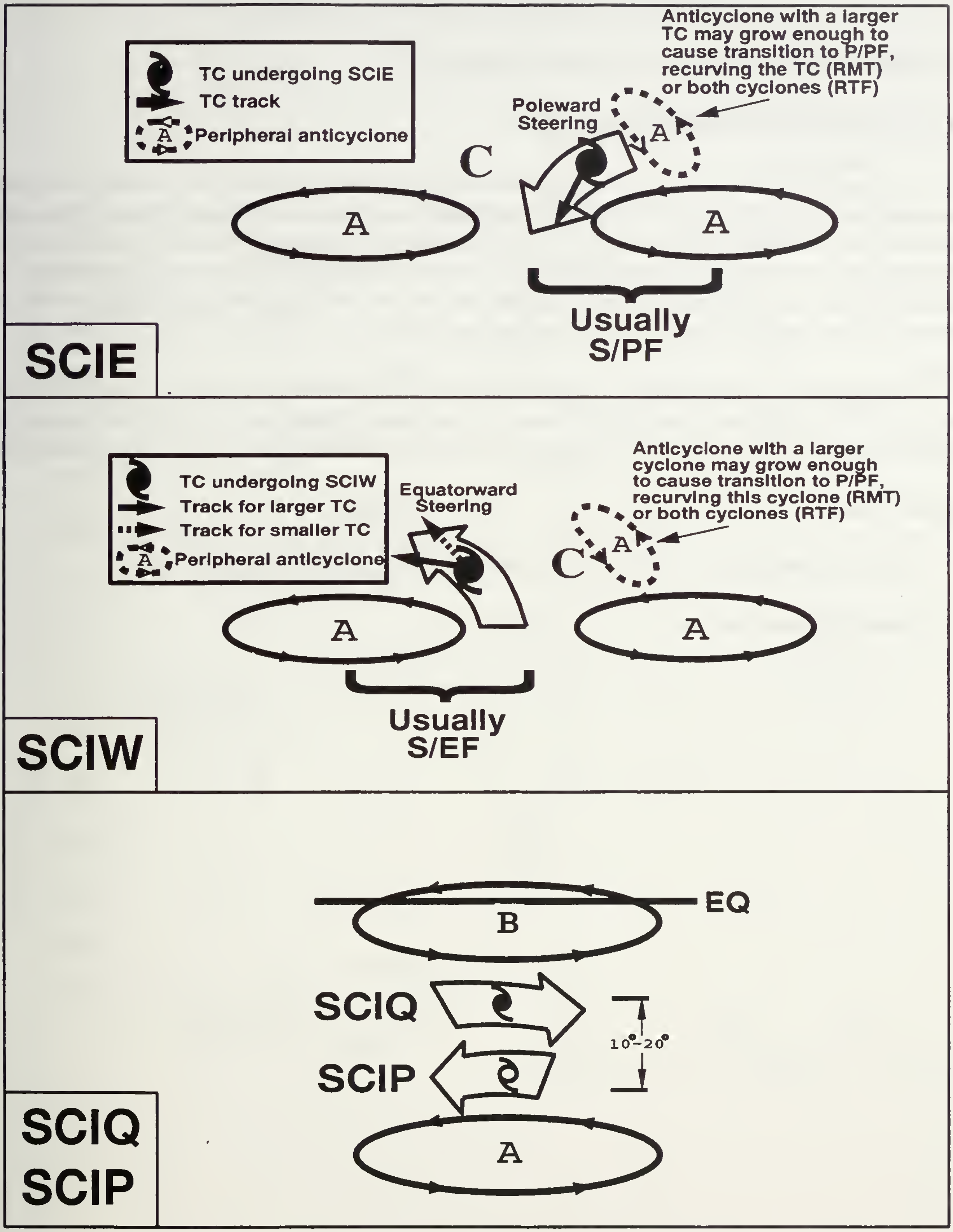
DESCRIPTION

In the Standard (S) synoptic pattern, the simultaneous occurrence of TCs in the Poleward Flow (PF) and Equatorward Flow (EF) regions would be one occurrence of Semi-direct Cyclone Interaction (SCI). A more general condition is that one TC and another cyclone with this same orientation will be said to be experiencing Semi-direct Cyclone Interaction (SCI). When the location of the other cyclone relative to the TC of interest and the adjacent subtropical anticyclone cells satisfy certain requirements, the cyclone and the TC interact in a semi-direct fashion. An eastern TC in the Poleward Flow (PF) region is said to be experiencing Semi-direct Cyclone Interaction-East (SCIE) because it is in poleward steering flow between the western cyclone and the eastern subtropical anticyclone (top panel on right). Similarly, the western TC in the Equatorward Flow (EF) region (middle panel on right) is said to be experiencing SC-West (SCIW).

With a strong equatorward buffer zone, a TC in the Standard/Equatorial Westerlies (S/EW) pattern/region may move eastward to be in an enhanced eastward steering flow between the buffer zone and a cyclone (shown as an open TC symbol in the lower panel on right) -- this is SCI-Equatorward (SCIQ). An alternative is the poleward TC in the lower panel on the right, which is in an enhanced westward steering flow between an equatorward cyclone (here shown as a closed TC symbol) and the subtropical cyclone -- this is SCI-Poleward (SCIP).

Cross-reference:

Standard Pattern p. 19



TC undergoing SCIE
TC track
Peripheral anticyclone
Anticyclone with a larger TC may grow enough to cause transition to P/PF, recurving the TC (RMT) or both cyclones (RTF)
Poleward Steering
C
A
A
A
Usually S/PF
SCIE
TC undergoing SCIW
Track for larger TC
Track for smaller TC
Peripheral anticyclone
Equatorward Steering
Anticyclone with a larger cyclone may grow enough to cause transition to P/PF, recurving this cyclone (RMT) or both cyclones (RTF)
C
A
A
A
Usually S/EF
SCIW
EQ
B
SCIQ
SCIP
10°-20°
A
SCIQ
SCIP

Topic: SEMI-DIRECT CYCLONE INTERACTION (SCI)

MUTUAL ROTATION CHARACTERISTICS

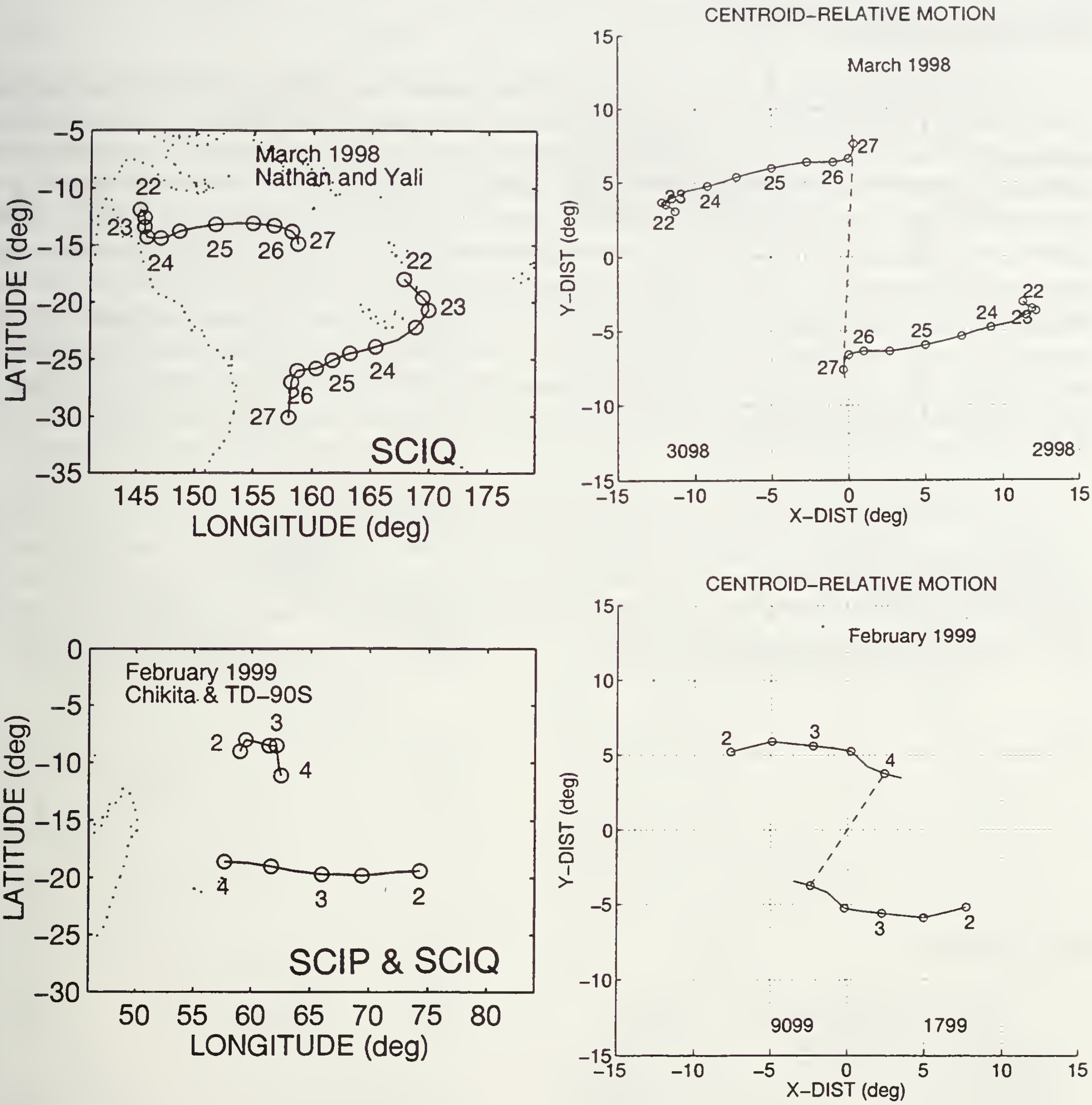
In a centroid-relative motion diagram, the onset of SCI will normally be manifest as a change from negligible or weak anticyclonic rotation to persistent, and moderate cyclonic rotation. The angular rotation rate will normally be from about 1.5 to 5.0 degrees per 6 hours. The rotation rate should be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

Comparisons of the geographic motion and the centroid-relative motion for two pairs of TCs are shown at right for the period in which SCI occurs. In the upper comparison only SCIQ is occurring for the equatorward TC, and in the bottom comparison both SCIP and SCIQ are occurring simultaneously.

Cross-references:

Indirect TC Interaction on Eastern TC, Mutual Rotation Characteristics p. 87

Direct TC Interaction p. 99


March 1998
Nathan and Yali
SCIQ
LATITUDE (deg)
LONGITUDE (deg)
CENTROID-RELATIVE MOTION
March 1998
Y-DIST (deg)
X-DIST (deg)
3098
2998
February 1999
Chikita & TD-90S
SCIP & SCIQ
LATITUDE (deg)
LONGITUDE (deg)
CENTROID-RELATIVE MOTION
February 1999
Y-DIST (deg)
X-DIST (deg)
9099
1799

Topic: SEMI-DIRECT CYCLONE INTERACTION (SCI) (cont)

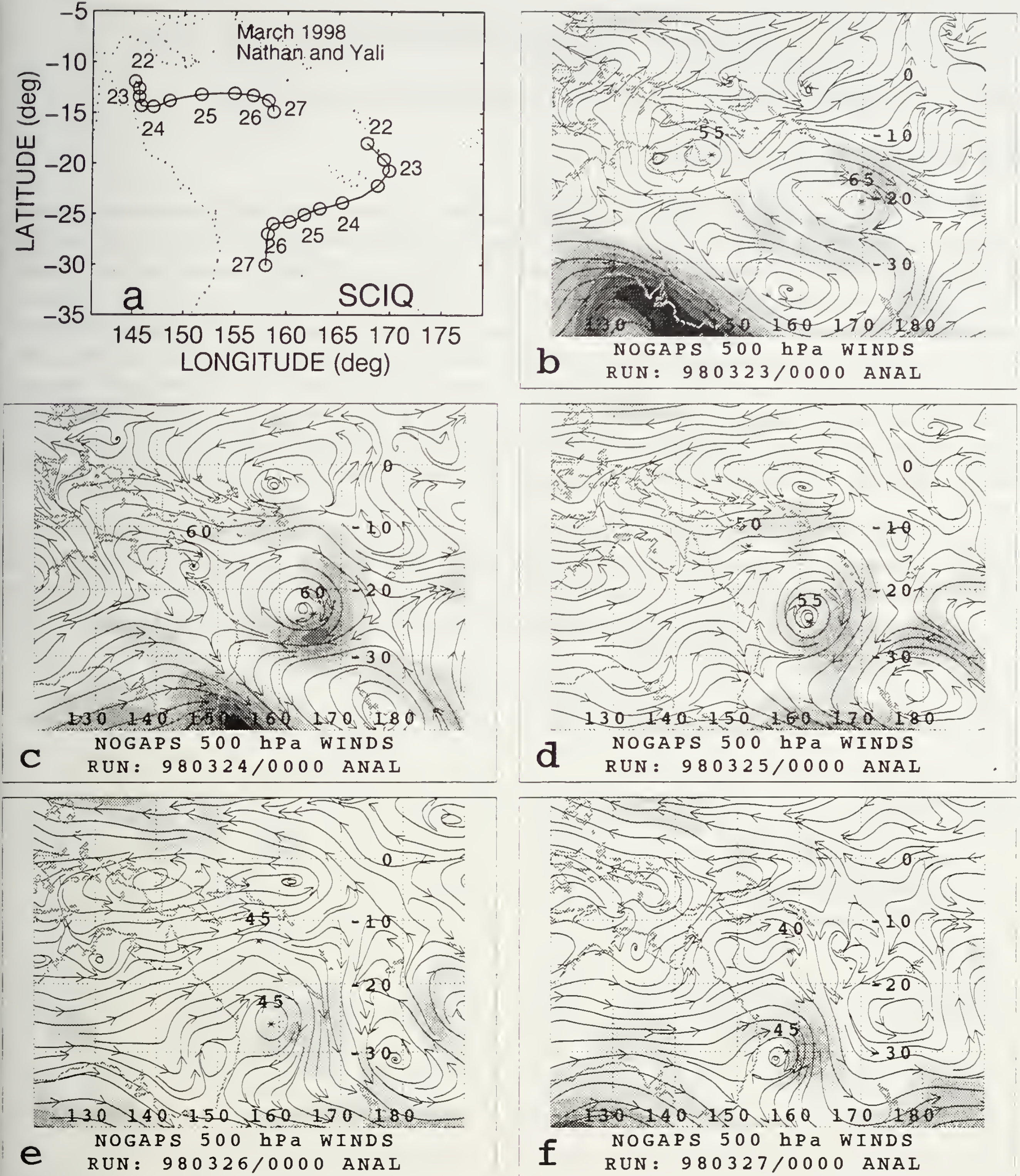
SCIQ SCENARIO ILLUSTRATION

During 23 March 1998, the track of TC Nathan changes (panel a) from slow poleward movement to comparatively rapid and cyclonically curving motion to the east. Simultaneously, TC Yali turns from southeastward movement to west-southwest movement. At 0000 UTC 24 March as the translation speed of Nathan (northwestern TC) increases to the east, the NOGAPS analysis has Nathan entering the strong eastward flow between the very large cyclonic circulation of Yali (southeastern TC) and a counter-clockwise-turning equatorial buffer circulation to the north of Yali (panel c). This time corresponds to when significant cyclonic orbiting begins in the centroid-relative motion plot shown in the upper comparison on p. 94. During 24-26 March (panels c-f), Nathan is clearly advected eastward by the flow between Yali to the south and the buffer circulation to the north, and thus is undergoing SCIQ from Yali. Since the eastward accelerating turn of Nathan occurs when Yali is about 20° lat. away, it is unlikely that Direct Cyclone Interaction (DCI) is occurring. A DCI would imply an unrealistically large size for Yali for an overlap in the two circulations, and this is not evident in the satellite imagery (not shown).

Notice that at 0000 UTC 25 March (panel d), the circulation of Yali is between the circulation of Nathan and the subtropical ridge anticyclone to the southeast. This orientation is consistent with the conceptual model of SCIP shown on p. 92. However, in view of the large difference in the sizes of Nathan (small) and Yali (large), it seems unlikely that significant SCIP was affecting the track of Yali. Thus, this case is an example of one-way SCI.

Cross-references:

SCIQ conceptual model	p. 91
Standard (S) Pattern	p. 19
Direct Cyclone Interaction	p. 99


March 1998
Nathan and Yali
LATITUDE (deg)
LONGITUDE (deg)
a
SCIQ
b
NOGAPS 500 hPa WINDS
RUN: 980323/0000 ANAL
c
NOGAPS 500 hPa WINDS
RUN: 980324/0000 ANAL
d
NOGAPS 500 hPa WINDS
RUN: 980325/0000 ANAL
e
NOGAPS 500 hPa WINDS
RUN: 980326/0000 ANAL
f
NOGAPS 500 hPa WINDS
RUN: 980327/0000 ANAL

Topic: SEMI-DIRECT CYCLONE INTERACTION (SCI) (cont)

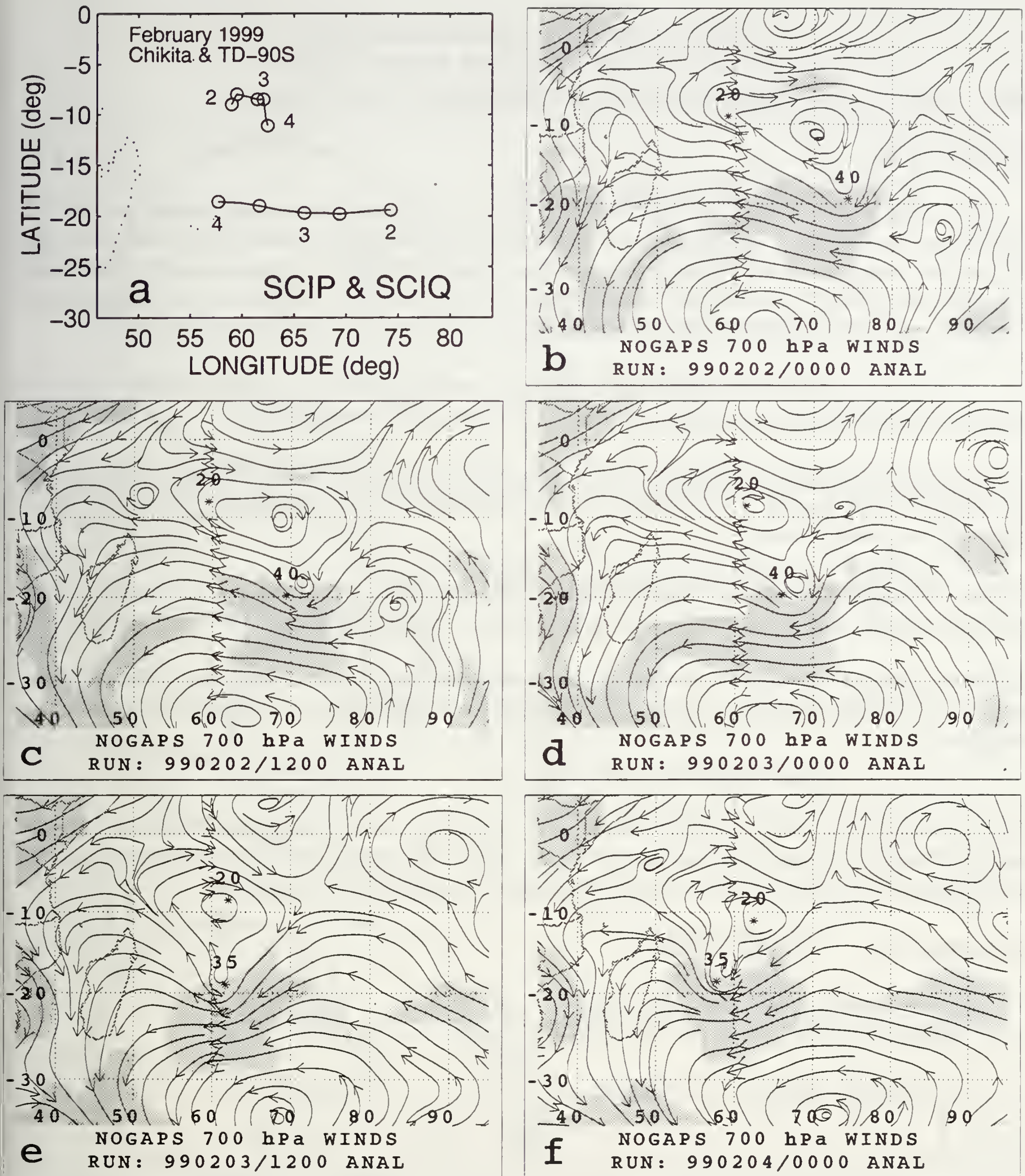
SCIP SCENARIO ILLUSTRATION

During 2-4 February 1999, the track of TC Chikita exhibits a rapid westward motion (panel a; southern track). During the same period, a disturbance (designated 90S solely for the purpose of this discussion), which did not develop into a significant TC, follows a cyclonically looping track to the east and southeast. The NOGAPS analyses during the same period (panels b-f) show that rapid westward movement of Chikita is in response to easterly steering flow produced by the gradient between disturbance 90S to the north and the subtropical ridge anticyclone to the south. This arrangement of the circulations conforms to the SCIP conceptual model. Similarly, the eastward movement of 90S appears to be a response to the westerly steering flow arising from the gradient between TC Chikita to the south and a counter-clockwise-turning buffer circulation to the north (technically a cyclone since the depicted center is just north of the equator). This arrangement of the circulations conforms to the SCIQ conceptual model.

As in the SCI case illustrated on the previous two pages, the apparent interaction of the TC and disturbance commences when they are separated by about 20° lat., which is too far to be attributed to Direct Cyclone Interaction (DCI). Toward the end of the period shown in panel a, the separation of the two TCs becomes less than 10° lat., which means that some DCI may be beginning to occur.

Cross-references:

SCI conceptual models p. 91
Standard (S) Pattern p. 19
Direct Cyclone Interaction p. 99



February 1999
Chikita & TD-90S
LATITUDE (deg)
LONGITUDE (deg)
SCIP & SCIQ
a
NOGAPS 700 hPa WINDS
RUN: 990202/0000 ANAL
b
NOGAPS 700 hPa WINDS
RUN: 990202/1200 ANAL
c
NOGAPS 700 hPa WINDS
RUN: 990203/0000 ANAL
d
NOGAPS 700 hPa WINDS
RUN: 990203/1200 ANAL
e
NOGAPS 700 hPa WINDS
RUN: 990204/0000 ANAL
f

Topic: DIRECT CYCLONE INTERACTION (DCI)

DESCRIPTION

As the name implies, Direct Cyclone Interaction (DCI) requires that the cyclonic circulation of the TC overlaps the circulation of another cyclone. Although both Semi-direct Cyclone Interaction (SCI) and DCI involve two cyclonic circulations, the distinction is that SCI "requires" the presence of a neighboring environmental circulation (subtropical anticyclone). DCI can occur in the absence of an environmental circulation, because the adjacent cyclone has become the dominant feature in advecting the TC.

Both of the circulations may be TCs as on the right, or the other cyclone may be a monsoon depression, cutoff low, etc. It is useful to view DCI as having three modes:

(1) One-way Influence (DCI1) in panel a on the right, in which the circulation of a larger cyclone advects the circulation of a smaller TC circulation, but not vice versa (at least the effect of the smaller TC is negligible in a practical sense).

(2) Two-way Interaction (DCI2) in panel b, in which the circulations of TC and the cyclone advect each other, but usually in an asymmetric fashion (i.e., larger cyclone has more effect on the smaller TC).

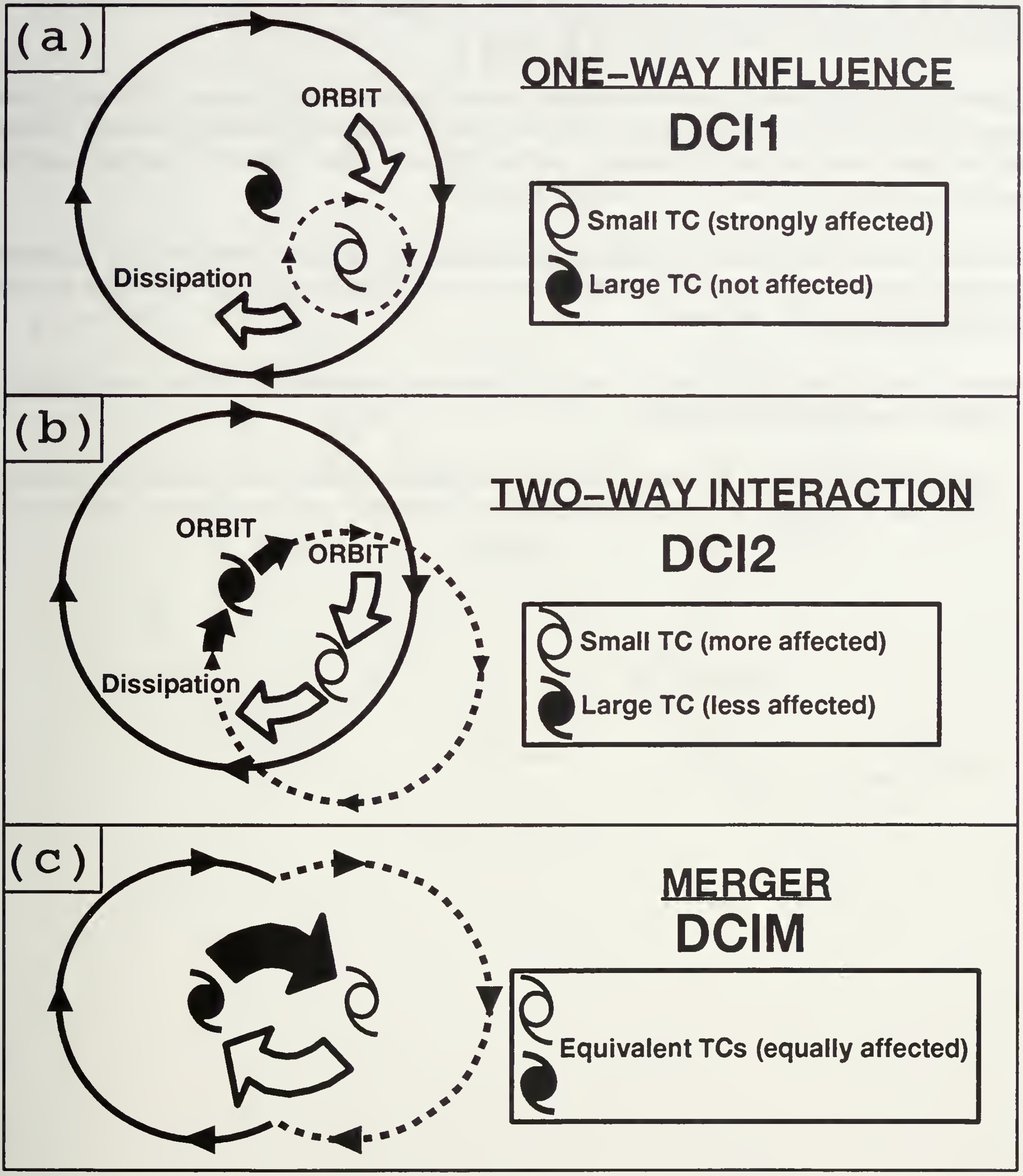
(3) Merger (DCIM) in panel c, in which the circulations not only rotate around each other, but also approach each other with either the TC or the cyclone usually dissipating before the merger process is completed.

NOTE: Except in very unusual circumstances, DCI only occurs when the separation distance between the two circulations 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 SCI or ICIW is taking place.

Cross-references:

Semi-direct Cyclone Interaction (SCI) p. 91
Indirect Cyclone Interaction-West (ICIW) p. 85

Maximum separation for DCI
is 10–12° (600 n.mi. – 720 n.mi.)



Topic: DIRECT CYCLONE INTERACTION (DCI) (cont)

MUTUAL ROTATION CHARACTERISTICS

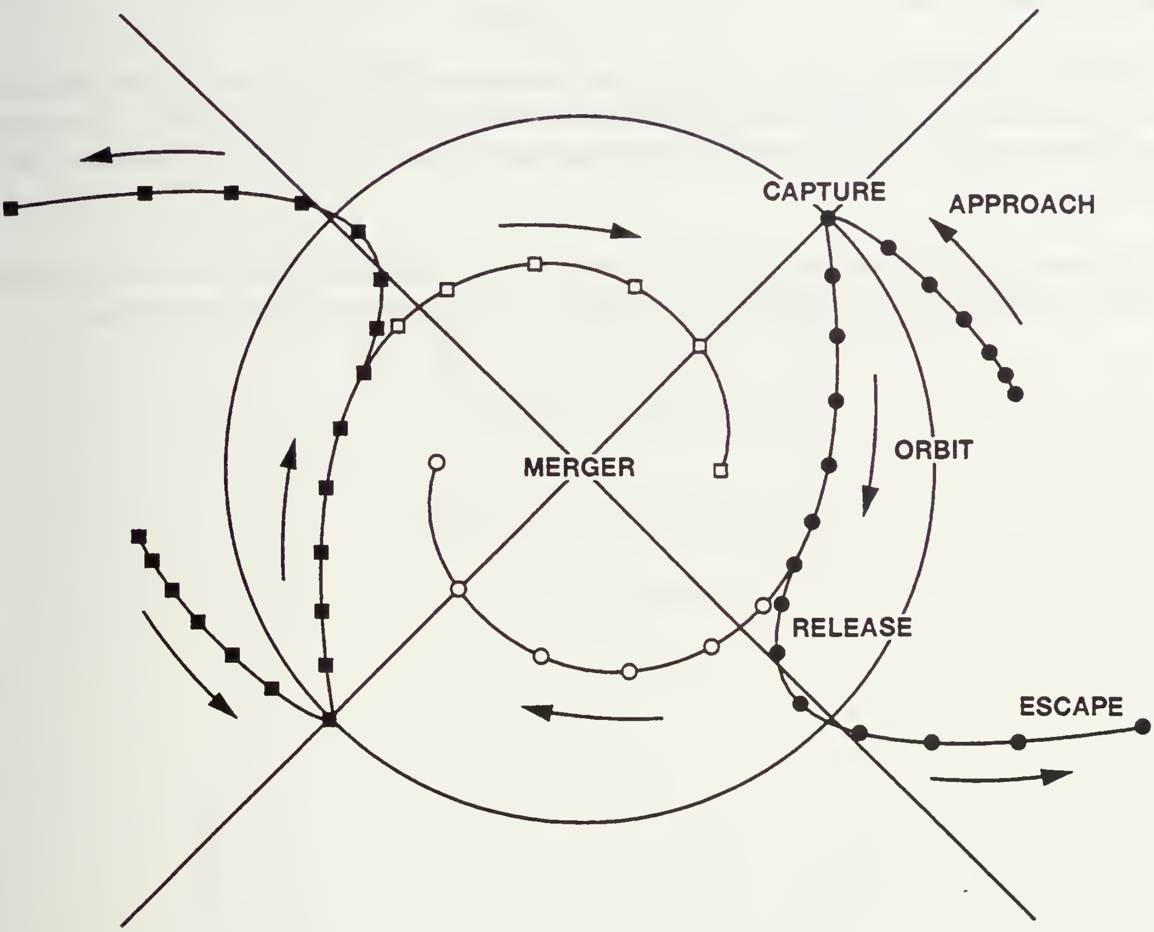
As shown in the hypothetical centroid-relative motion diagram at right the onset of Direct Cyclone Interaction (DCI), which is labeled “capture,” follows a period of approach and begins a period of mutual rotation or “orbit” that has nearly constant separation distance. After rotation through an angle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

(1) one or both of the two circulations "release" the other, and the separation distance begins to increase. By definition, release may occur when either the one-way influence (DCI1) or when a two-way interaction (DCI2) is taking place; or

(2) merger (DCIM) 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 DCI, because the horizontal and vertical shear of the larger cyclone may disperse or disrupt the warm core structure of the smaller TC.

DIRECT CYCLONE INTERACTION (DCI)



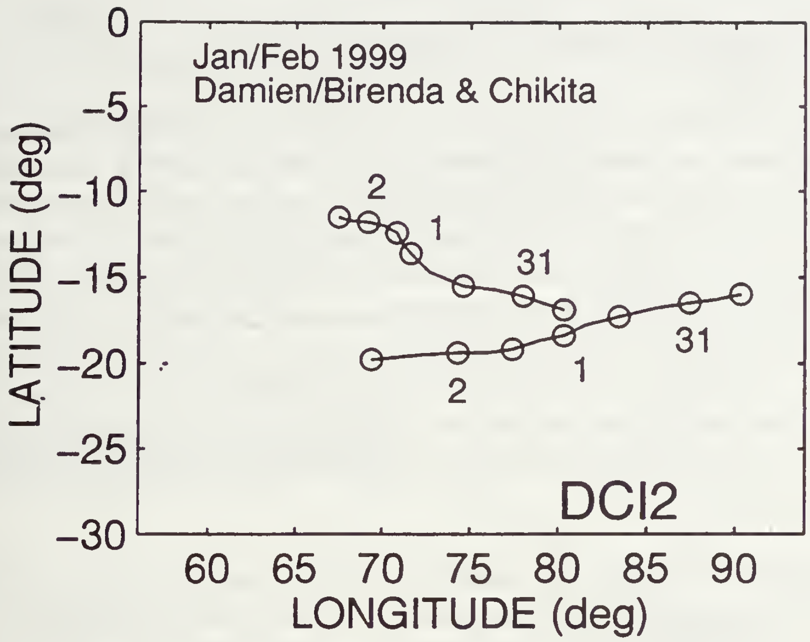
Topic: DIRECT CYCLONE INTERACTION (DCI) (cont)

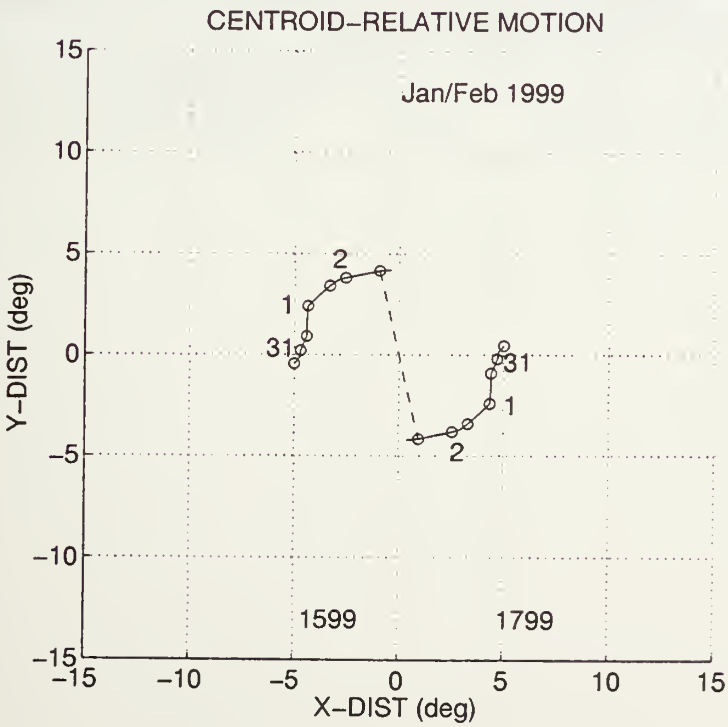
MUTUAL ROTATION CHARACTERISTICS (cont)

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

During one-way influence (DCI1), or two-way interaction (DCI2), the rotation rate will normally be about 5 to 12 degrees per 6 hours, and the separation distance usually changes slowly. A comparison of the geographic motion and the centroid-relative motion for two TCs during the period of DCI2 is shown at right.

The onset of the merger mode (DCIM) 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.


Jan/Feb 1999
Damien/Birenda & Chikita
DCI2
LATITUDE (deg)
LONGITUDE (deg)
0
-5
-10
-15
-20
-25
-30
60
65
70
75
80
85
90
2
1
31
31
1
2

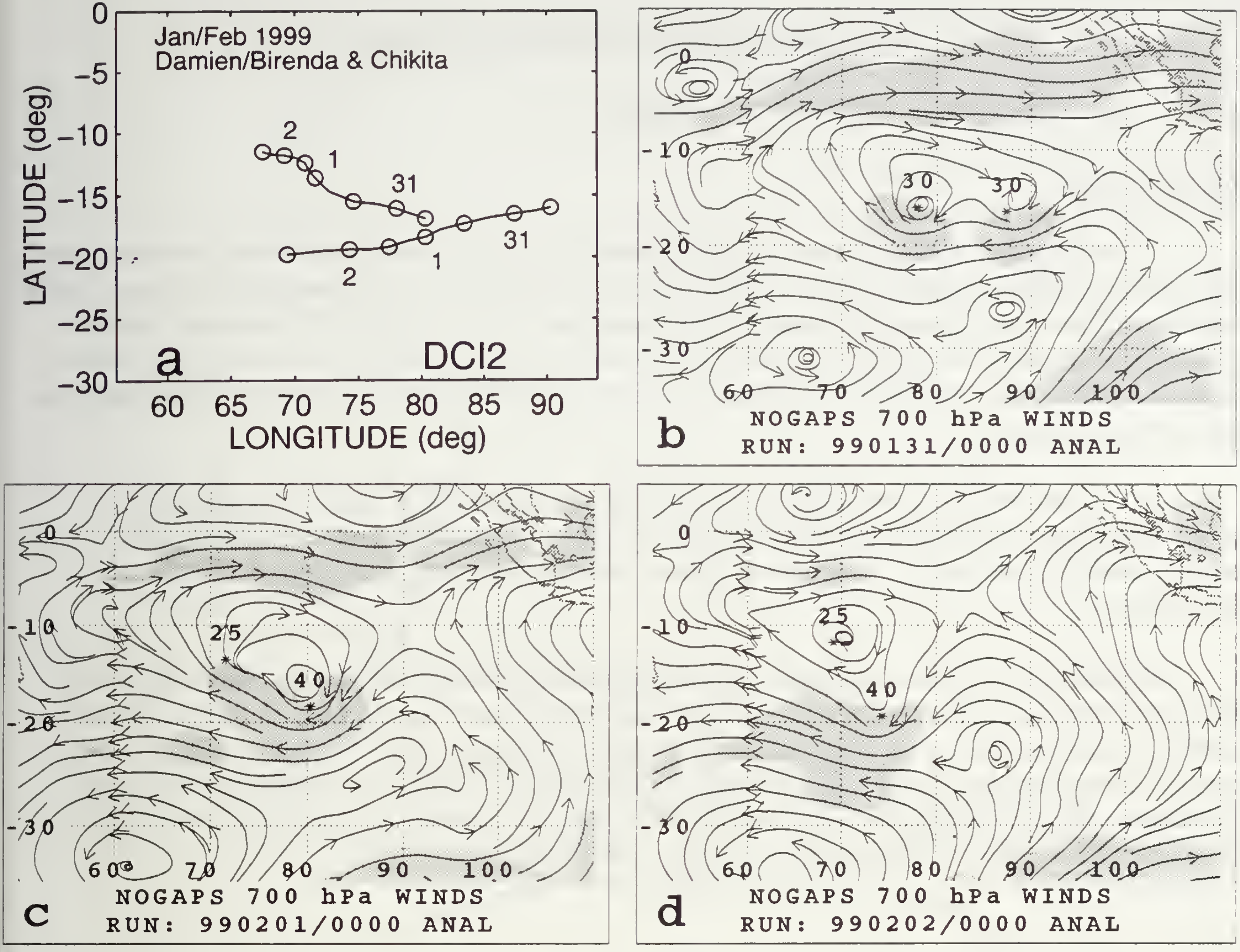

CENTROID-RELATIVE MOTION
Jan/Feb 1999
Y-DIST (deg)
X-DIST (deg)
15
10
5
0
-5
-10
-15
-15
-10
-5
0
5
10
15
2
1
31
31
1
2
1599
1799

Topic: DIRECT CYCLONE INTERACTION (DCI) (cont)

DCI SCENARIO ILLUSTRATION (TWO-WAY INTERACTION)

During the period 31 January to 2 February 1999 (panel a), the track of Damien/Birenda has an unusual west-northwest direction, while TC Chikita is simultaneously moving more rapidly to the west-southwest. The NOGAPS analyses during this period (panel b-d) have difficulty resolving the two TCs into separate circulations, which is typical for the small separation distances that are associated with DCI. Nevertheless, cyclonic relative orbiting is clearly indicated by the changing orientations of the JTWC best-track positions (asterisks). As indicated in the centroid-relative motion diagram for these two TCs (p. 104), a clear increase in cyclonic rotation rate occurred during 31 January as the separation distance became less than 10° lat., which is consistent with the capture phase of the DCI conceptual model. Since the two TCs appear to be of similar size, it is likely that two-way DCI is occurring. However, this cannot be absolutely confirmed. The two TCs did not merge because Damien/Birenda dissipated, perhaps in part due to the proximity of Chikita.

Notice that by 0000 UTC 2 February (panel d), the approximately north-south orientation of the two TCs and the presence of the subtropical anticyclone to the south and a buffer circulation to the north also conforms to the SCIQ/SCIP conceptual model. Thus, the SCI process may be making some contribution to the rate of mutual orbiting of the TCs even though DCI is more likely to be the dominant process in view of the relatively small separation of the TCs.


Jan/Feb 1999
Damien/Birenda & Chikita
LATITUDE (deg)
LONGITUDE (deg)
a
DCI2
b
NOGAPS 700 hPa WINDS
RUN: 990131/0000 ANAL
c
NOGAPS 700 hPa WINDS
RUN: 990201/0000 ANAL
d
NOGAPS 700 hPa WINDS
RUN: 990202/0000 ANAL

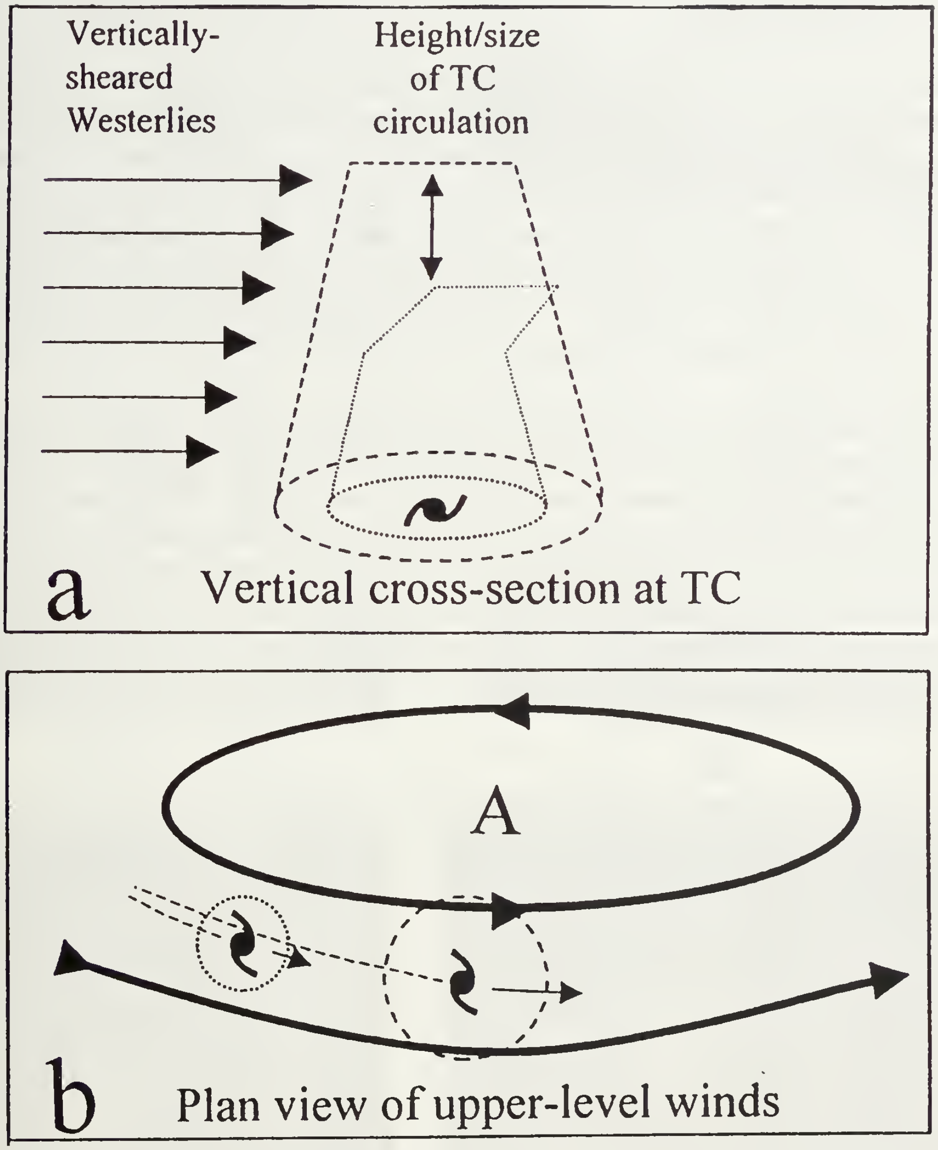
Topic: RESPONSE TO VERTICAL SHEAR

DESCRIPTION

The movement of TCs is primarily a result of advection by the large-scale environmental wind that typically exhibits westerly vertical shear with increasing height due to thermal wind balance in the presence of north-south baroclinity (panel a). Convection in the core of the TC results in vertical momentum transports that tend to maintain the TC as a vertically coherent vortex despite vertical wind shear. Thus, the TC moves in response to the environmental wind averaged over the depth that the convection extends.

A TC that remains comparatively intense (and thus tall) in the presence of a particular vertically-sheared environmental wind (panel a; dashed circulation) will tend to move faster in response to the higher average environmental wind over the depth of the TC (panel b; dashed circulation).

By contrast, a TC that undergoes significant weakening (and thus vertical shrinkage) in the presence of the same vertically-sheared environmental wind (panel a; dotted circulation) will tend to move slower in response to the lower value of average environment wind over the depth of the TC (panel b; dotted circulation). This dependency of the speed of movement of the TC (owing to the advection by the environmental wind) upon the TC intensity in response to the vertical shear of the environmental wind is termed Response to Vertical Shear (RVS).

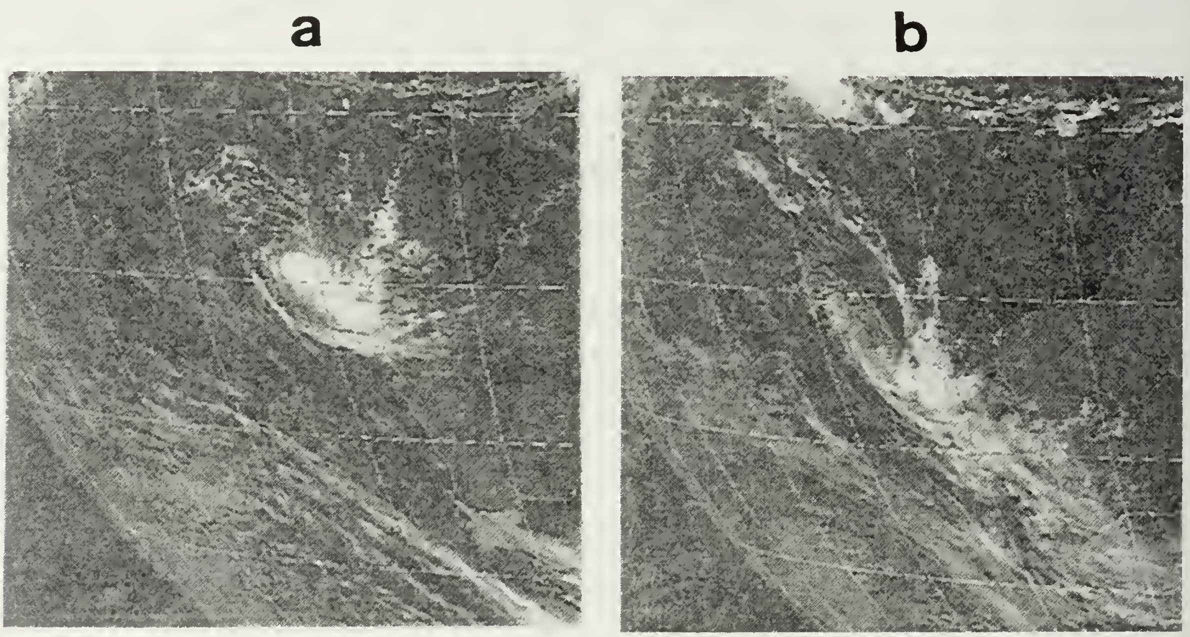

Vertically-
sheared
Westerlies
Height/size
of TC
circulation
a
Vertical cross-section at TC
A
b
Plan view of upper-level winds

Topic: RESPONSE TO VERTICAL SHEAR (cont)

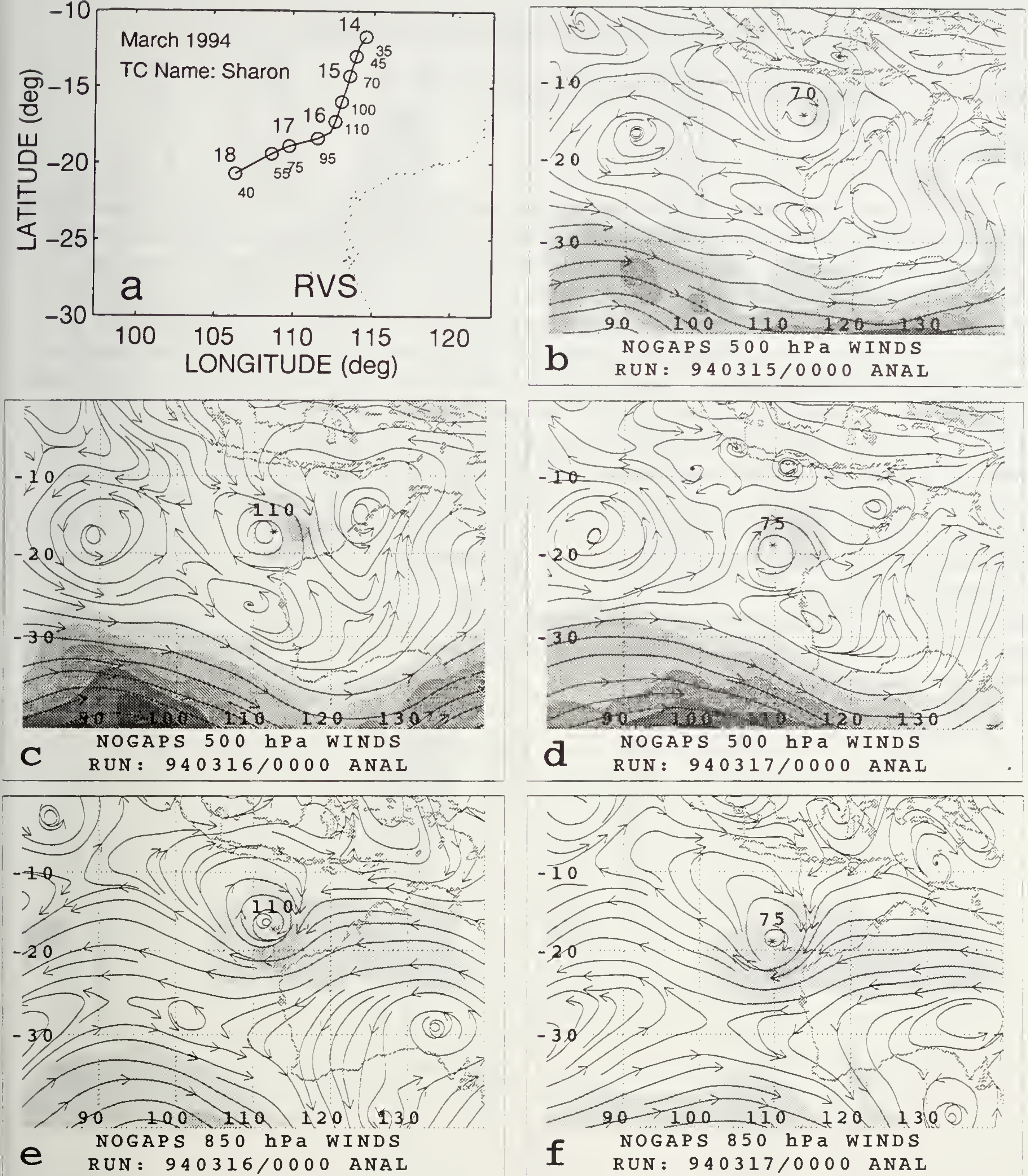
SCENARIO ILLUSTRATION

During 14-15 March 1994, TC Sharon was moving south-southwest while intensifying (panel a). As expected, the 0000 UTC 15 NOGAPS 500 mb streamline/isotach analysis (panel b) has a isotach maximum to the east of the TC (left of the direction of motion), which indicates the 500-mb level of a good proxy for the deep tropospheric layer that is primarily causing the motion of the TC. The shifts of the NOGAPS-analyzed 500 mb isotach maximum to the east and then northeast of the TC at 0000 UTC 16 and 17 March, respectively (panels c and d, respectively) suggest the TC should be about to recurve into the midlatitude westerlies, if 500 mb remains the effective steering level. However, the track of Sharon actually turns to the southwest during the 16-17 March (panel a).

The corresponding NOGAPS 850-mb analyses (panels e and f, respectively) both have isotach maxima to the southeast of the TC, which suggests that 850 mb is roughly the average level of the vertical layer of environmental wind to which the TC is responding. Notice also that the intensity of the TC decreases rapidly after the turn to the southwest during 16 March (panel a). This lowering of the effective steering level as the TC weakens is consistent with the RVS conceptual model. The satellite infrared images below for 0000 UTC 17 and 19 March 1994 show that the decrease in intensity was a result of a shearing away of the central convection of the TC, which left behind a comparatively shallow low-level wind circulation.



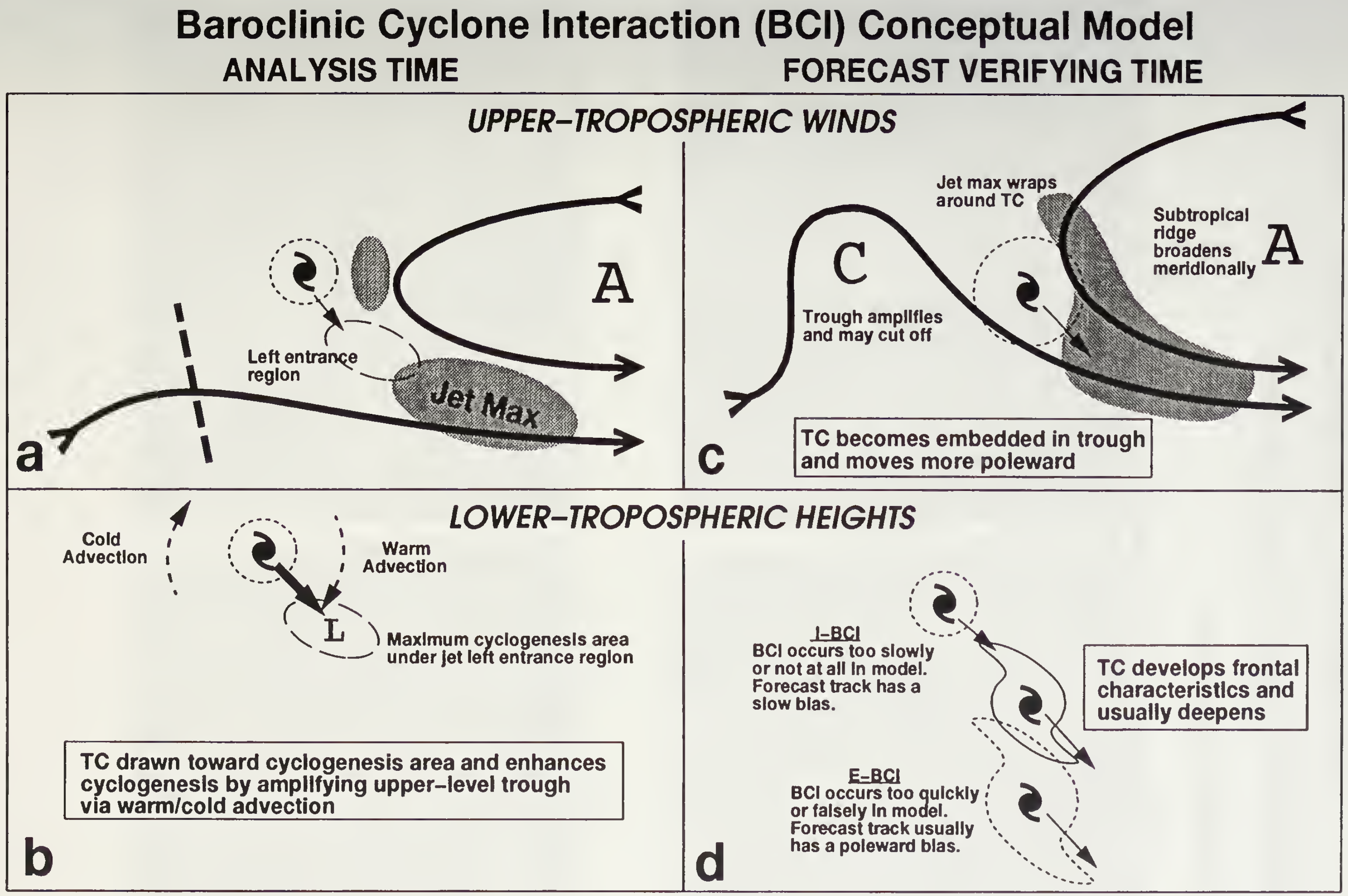
Infrared imagery of TC Sharon at 0300 UTC on (a) 17 and (b) 19 March 1994.


March 1994
TC Name: Sharon
LATITUDE (deg)
LONGITUDE (deg)
a
RVS
b
NOGAPS 500 hPa WINDS
RUN: 940315/0000 ANAL
c
NOGAPS 500 hPa WINDS
RUN: 940316/0000 ANAL
d
NOGAPS 500 hPa WINDS
RUN: 940317/0000 ANAL
e
NOGAPS 850 hPa WINDS
RUN: 940316/0000 ANAL
f
NOGAPS 850 hPa WINDS
RUN: 940317/0000 ANAL

Topic: BAROCLINIC CYCLONE INTERACTION

DESCRIPTION

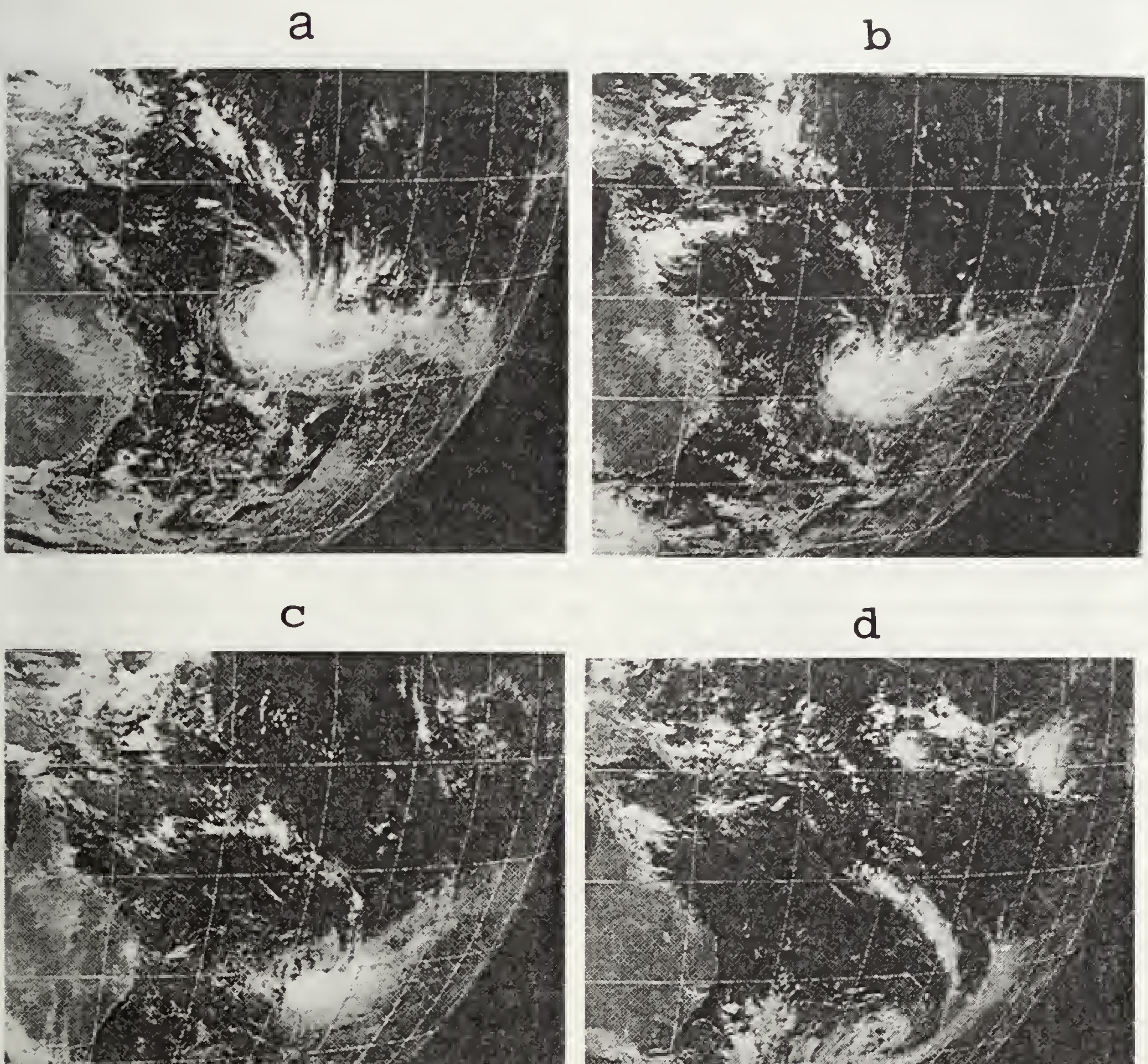
In a potential extratropical transition scenario, the TC is in the vicinity of the mid-tropospheric subtropical ridge axis with a midlatitude trough to the southwest or south. Divergence and vertical wind shear associated with upper-tropospheric jet streaks (panel a on right) to the southwest or southeast may also contribute to the transition from a TC-like structure to a baroclinic, extratropical cyclone. Baroclinic Cyclone Interaction (BCI) refers to the effects on the TC as it becomes constructively aligned with an area of midlatitude baroclinic cyclogenesis. Significant deepening may occur in response to the pre-existing perturbation represented by the TC and baroclinic energy release associated with a midlatitude baroclinic zone. Poleward (equatorward) flow on the east (west) side of the TC in the presence of the meridional temperature gradient will result in warm (cold) advection (panel b) that may also amplify the upper-level ridge/trough pattern via a self-amplification process (panel c). Since the lower-tropospheric warm and cold advection affects the structure of the mid-tropospheric winds that are the steering flow for the TC, a vigorous BCI event may have a significant impact on the TC track. Typically, the greater the deepening of the TC interacting with the baroclinic circulation, the more poleward will be the TC track owing to the BCI-induced amplification of the mid-tropospheric ridge poleward and to the east of the TC. This BCI-process can result in various combinations of direction and speed changes depending on the tilt of the midlatitude trough and its orientation relative to the TC.


Baroclinic Cyclone Interaction (BCI) Conceptual Model
ANALYSIS TIME
FORECAST VERIFYING TIME
UPPER–TROPOSPHERIC WINDS
a
Left entrance region
Jet Max
A
c
C
Trough amplifies and may cut off
Jet max wraps around TC
Subtropical ridge broadens meridionally
A
TC becomes embedded in trough and moves more poleward
LOWER–TROPOSPHERIC HEIGHTS
b
Cold Advection
Warm Advection
L
Maximum cyclogenesis area under jet left entrance region
TC drawn toward cyclogenesis area and enhances cyclogenesis by amplifying upper–level trough via warm/cold advection
d
I–BCI
BCI occurs too slowly or not at all in model. Forecast track has a slow bias.
E–BCI
BCI occurs too quickly or falsely in model. Forecast track usually has a poleward bias.
TC develops frontal characteristics and usually deepens

Topic: BAROCLINIC CYCLONE INTERACTION (cont)

APPEARANCE IN SATELLITE IMAGERY

An example of the Baroclinic Cyclone Interaction (BCI) during the extratropical transition of TC Beti is shown on the satellite visible imagery on the right. At 0300 UTC 27 March 1996 (panel a), Beti has just moved poleward of 20°S and is approaching an east-west oriented baroclinic zone along 25°S. By 0300 UTC 28 March (panel b), Beti is losing its TC-like circulation features as it has become embedded in the baroclinic zone cloudiness. The merged circulation has the characteristic cloud shield on the poleward side at 0300 UTC 29 March (panel c), with much suppressed convection on the western and equatorward sides of the TC, which is near 30°S at this time. Forty-eight hours later (panel d), the system has a classical extratropical cyclone frontal structure with the convective cloud lines around the low and an occluded front to the east. The trailing cold frontal band tends to form a "T-bone" structure as it intersects with the occluded and warm front sections.


a
b
c
d

Topic: BAROCLINIC CYCLONE INTERACTION (cont)

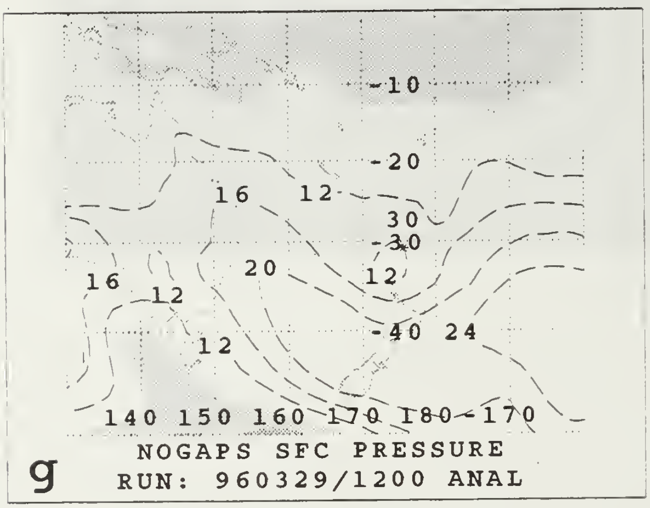
ILLUSTRATION

As shown in panel a on the right and the satellite visible imagery on page 114, TC Beti moved poleward and then eastward during its Baroclinic Cyclone Interaction (BCI). Notice the rapid decrease in intensity (small numbers to right of track in panel a) from 105 kt to 55 kt in 24 hours between 1200 UTC 27 March and 1200 UTC 28 March (satellite image in panel b on page 114 is during this period).

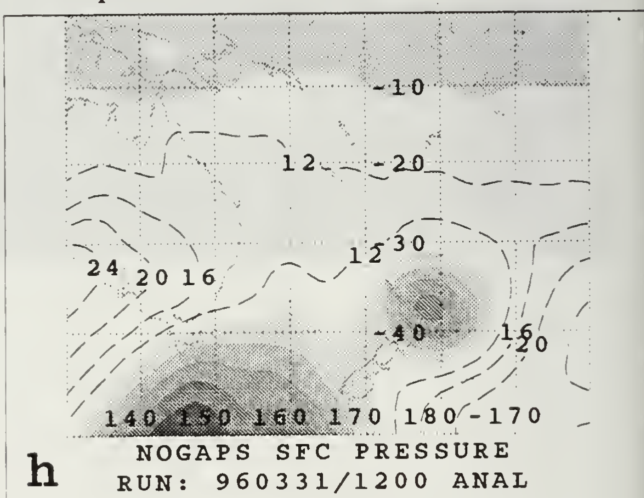
At 1200 UTC 27 March (panel b), the NOGAPS analysis has a well-defined circulation with a 40-kt isotach maximum to the east, which is consistent with the south-southeast track at this time (panel a). By 1200 UTC 28 March (panel c), an amplifying midlatitude trough is approaching. TC Beti appears as an open wave, and the isotach maximum is more to the northeast, which is consistent with the track turn toward the southeast. Amplication of the baroclinic trough has continued at 1200 UTC 29 March (panel d). By this time, TC Beti is estimated to have an intensity of 30 kt, and is located northeast of the center of the 500-mb midlatitude cyclone; that is, where baroclinic cyclogenesis is favored. Evidence that BCI has not yet occurred to any significant degree is suggested by: i) a NOGAPS-analyzed minimum sea-level pressure for Beti that is above 1008 mb (panel g, below), and ii) little indication of Beti's circulation exists at 500 mb (panel d). By 1200 UTC 31 March (panel h, below), significant BCI has occurred, which is indicated by a less than 996 mb minimum sea-level pressure for the extratropical storm Beti (panel h) and the shifting of the sea-level low into vertical alignment with the 500-mb cyclone (compare panel f and h) as expected of a mature occluded extratropical cyclone. Recall that such an occlusion was clearly evident in the satellite imagery (p. 114; lower right image).

Cross-reference:

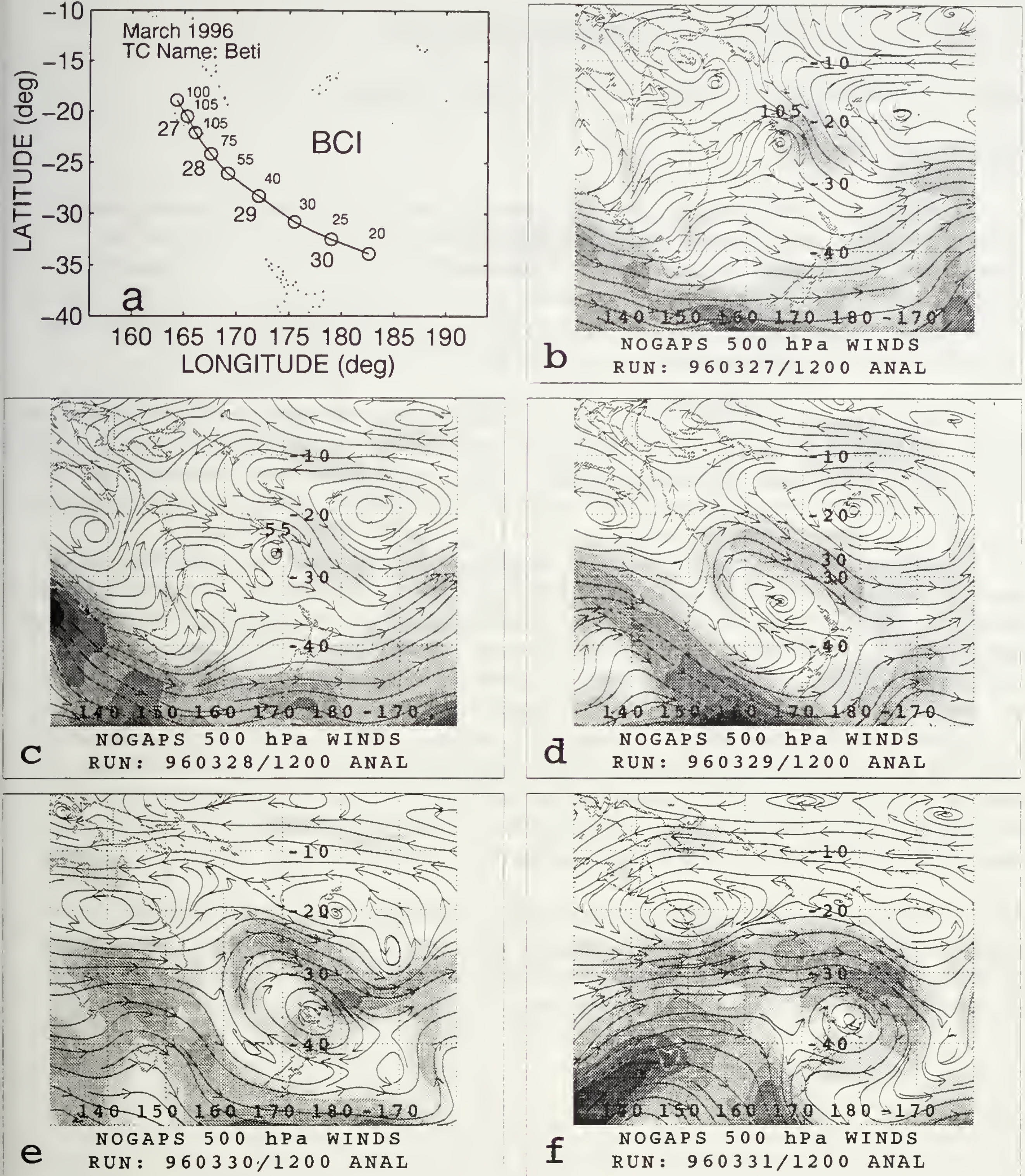
Diagnosing Environmental Steering Direction p. 9



g



h



March 1996
TC Name: Beti
BCI
LATITUDE (deg)
LONGITUDE (deg)
a
NOGAPS 500 hPa WINDS
RUN: 960327/1200 ANAL
b
NOGAPS 500 hPa WINDS
RUN: 960328/1200 ANAL
c
NOGAPS 500 hPa WINDS
RUN: 960329/1200 ANAL
d
NOGAPS 500 hPa WINDS
RUN: 960330/1200 ANAL
e
NOGAPS 500 hPa WINDS
RUN: 960331/1200 ANAL
f

Topic: EQUATORIAL WESTERLY WIND BURST (EWB)

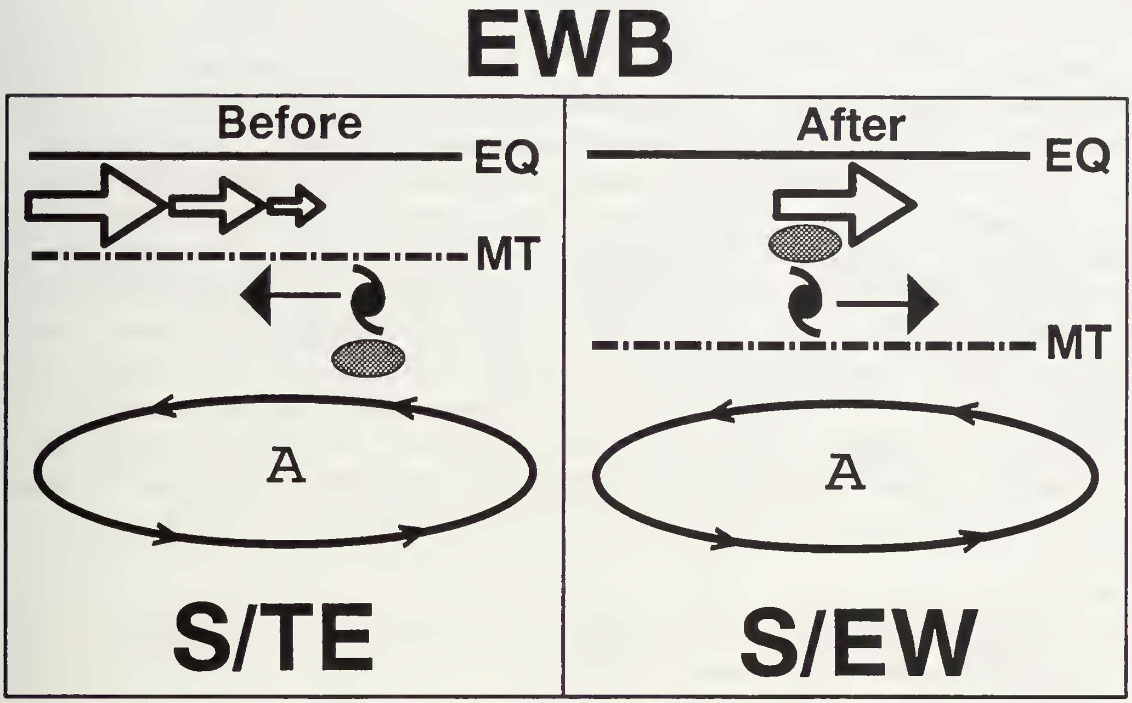
DESCRIPTION

In contrast to a trade wind trough that has easterly winds on both sides of the trough axis, a monsoon trough has westerly winds equatorward of the trough axis and easterly winds on the poleward side. The westerly winds are associated with a buffer circulation that approximately straddles the equator and arise from cross-equatorial flow. The easterly winds are associated with the subtropical ridge. In a streamline analysis, the axis of the monsoon trough connects all points where the zonal component of the environmental wind changes from easterlies to westerlies.

If a TC is located poleward of the monsoon trough axis (the more frequent situation), then the TC will be in the Tropical Easterlies (TE) region and usually will be moving basically westward (panel a). If a TC is located equatorward of the monsoon trough axis (the less frequent situation), then the TC will be in the Equatorial Westerlies (EW) region and will be moving basically eastward (panel b).

The latitudinal location of the monsoon trough basically depends on the relative strength of the subtropical ridge anticyclone and the buffer circulation straddling the equator. Any process that changes the relative strength of these two circulations can change the location of the monsoon trough relative to the TC. Although the physical mechanisms are not well understood, equatorial westerly wind burst (EWB) events have been observed that either propagate from west to east or develop *in situ*, which is equivalent to strengthening of the equatorial buffer circulation. An EWB event results in a poleward movement of the monsoon trough axis, assuming that no compensating increase in the strength of the subtropical ridge circulation occurs. If the poleward shift of the monsoon trough axis occurs at the longitude of a TC and causes the latitude of the monsoon trough axis to cross the latitude of a TC, then the environment structure of the TC will switch from TE to EW and the zonal motion component of the TC will shift from westward to eastward.

NOTE: If a TC is in the EW region and there is either a weakening of the equatorial buffer circulation and/or a strengthening of the subtropical ridge circulation that results in an equatorward shift of the monsoon trough axis that passes the latitude of the TC, then the environment of the TC will transition from EW to TE with a resulting change in motion from eastward to westward.


EWB
Before
EQ
MT
A
S/TE
After
EQ
MT
A
S/EW

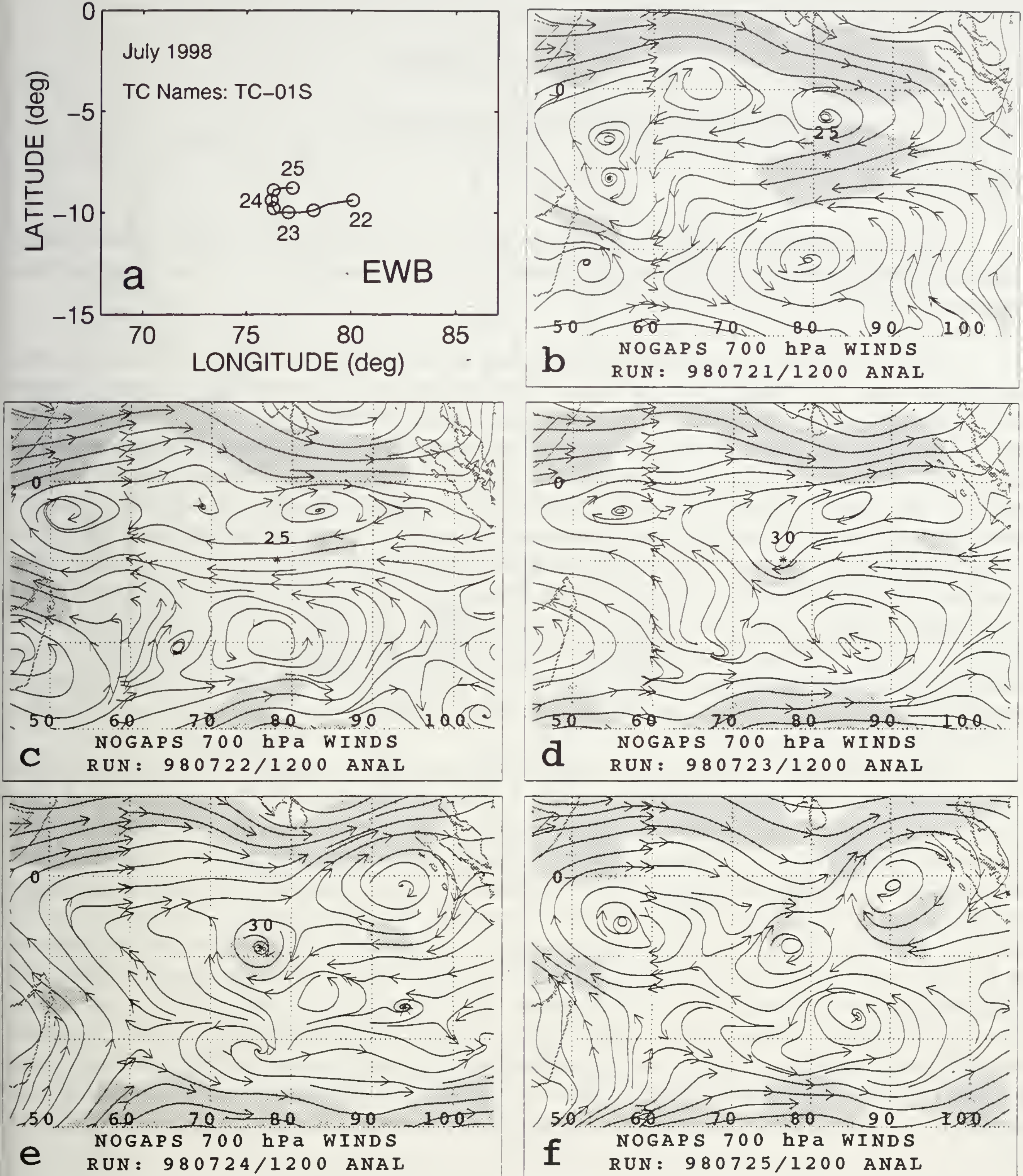
Topic: EQUATORIAL WESTERLY WIND BURST (EWB)

SCENARIO ILLUSTRATION

During 22-25 July 1998, the motion of TC 01S switched from westward to eastward while also being slowly displaced about 1° lat. toward the equator (panel a on the right). At 1200 UTC 21 July (panel b), TC 01S is on the poleward side of an extensive east-west oriented monsoon trough. Notice the extensive 20-kt isotach on the poleward side, which then shrinks considerably by 1200 UTC 22 July (panel c). As TC 01S is no longer in strong easterlies, the westward translation begins to decrease (panel a). Although a small 20-kt isotach maximum reappears on the poleward side at 1200 UTC 23 July (panel d), the westward translation further slows. At 1200 UTC 24 July (panel e), the equatorial westerlies have approached TC 01S, which now is embedded in a nearly circular isotach region and is consequently nearly stationary (panel a). Although no TC position is shown in the NOGAPS analysis at 1200 UTC 25 July (panel f), the associated cyclonic circulation has an isotach maximum on the equatorward side and the cyclone has moved eastward. Although not a classical Equatorial Westerly Wind Burst with a band of strong westerlies spanning the equator, this is a case of EWB for the purpose of a TC track change from westward to eastward.

Cross-reference:

Diagnosing Environmental Steering Direction p. 9



July 1998
TC Names: TC-01S
LATITUDE (deg)
LONGITUDE (deg)
EWB
a
NOGAPS 700 hPa WINDS
RUN: 980721/1200 ANAL
b
NOGAPS 700 hPa WINDS
RUN: 980722/1200 ANAL
c
NOGAPS 700 hPa WINDS
RUN: 980723/1200 ANAL
d
NOGAPS 700 hPa WINDS
RUN: 980724/1200 ANAL
e
NOGAPS 700 hPa WINDS
RUN: 980725/1200 ANAL
f

ENVIRONMENT EFFECTS

Topic: MIDLATITUDE SYSTEM EVOLUTIONS (MSEs)

DESCRIPTION

The fundamental idea of MSE is one of changes to the TC steering flow due to development, dissipation, and/or movement of midlatitude circulations (cyclones, troughs, anticyclones, or ridges) that occur essentially *independent of the TC*.

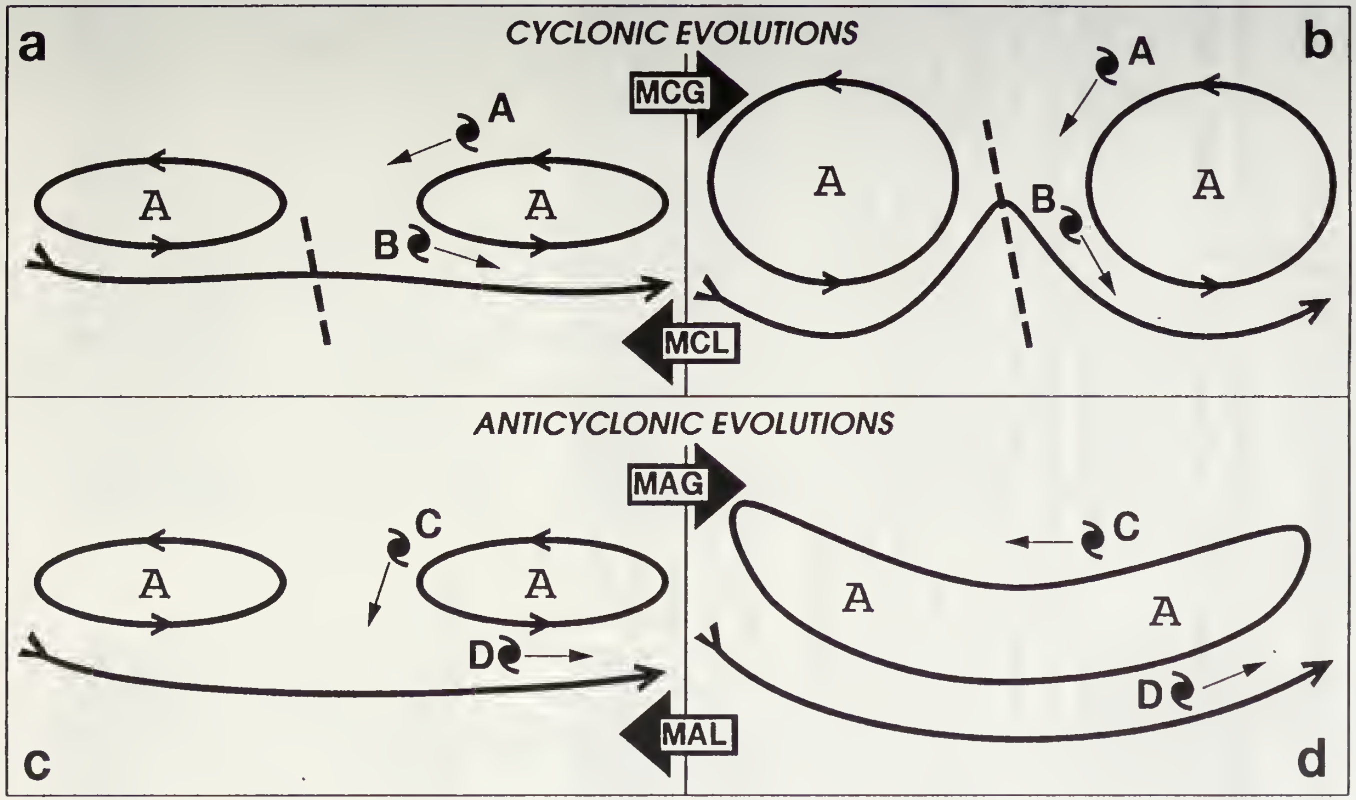
When Midlatitude Cyclogenesis (MCG) occurs, the TC labeled A in panel a, which has been tracking essentially westward in the TE region of a S pattern, may be turned onto a more poleward heading as the developing midlatitude trough or cyclone "breaks" the ridge and creates a more poleward flow in the vicinity of the TC (panel b). Depending on the amplitude of the trough, the environment of the TC will transition to either the PF region of an S pattern, or the RP to TP region of a H pattern. Similarly, TC B that is poleward of the STR axis in panel a which is moving southeastward in the PF region of the M pattern when MCG takes place may then undergo directional and/or speed changes as the developing trough/cyclone alters the direction and strength of the midlatitude flow in which TC B is embedded (panel b). If the MCG changes only the translation speed of the TC, then it will remain in the M/PF pattern/region, or perhaps change to the M/MW region. However, a large amplification of the trough to the west during vigorous MCG may change the direction of the environment steering sufficiently that a region transition may occur within the M pattern (e.g., from MW to PF as suggested in panel b). For simplicity of depiction, Midlatitude Cyclolysis (MCL) is simply depicted as the reverse of MCG (i.e., going from panel b to a).

When Midlatitude AntiycloGenesis (MAG) takes place, the TC labeled C in panel c, which has been tracking southwestward in the PF region of a S pattern or P pattern, may be turned westward (or even north of west) as the developing midlatitude ridge/anticyclone increases the strength of the STR poleward of the TC. If the STR builds sufficiently in association with MAG, then the TC labeled C will be subjected to predominantly easterly or even southeasterly steering (panel d), i.e., may have a change of environment structure from S/PF or P/PF to S/TE or S/EF. When such a MAG event occurs, the TC labeled D in panel c, which has been moving eastward and/or poleward in the midlatitude flow poleward of the STR axis may undergo directional and/or speed changes as the developing midlatitude ridge/anticyclone alters the direction and strength of the midlatitude flow in which the TC is embedded. If the MAG changes only the translation speed of the TC, then it will remain in either a M/PF or M/MW pattern/region combination. If MAG changes the direction of the environmental steering sufficiently, then a region transition can occur within the M pattern (e.g., from MW to EF as suggested in panel d). For simplicity, Midlatitude AnticycloLysis is simply treated as the reverse of MAG (i.e., going from panel d to c).

Cross-references:

Standard (S) pattern	p. 19	Midlatitude (M) pattern	p. 47
High-amplitude (H) pattern	p. 37	Poleward (P) pattern	p. 29

Midlatitude System Evolutions (MSE)



Topic: MIDLATITUDE SYSTEM EVOLUTIONS (MSE) (cont)

ILLUSTRATION: MCG & MAG CAUSING TRANSITIONS WITHIN S PATTERN

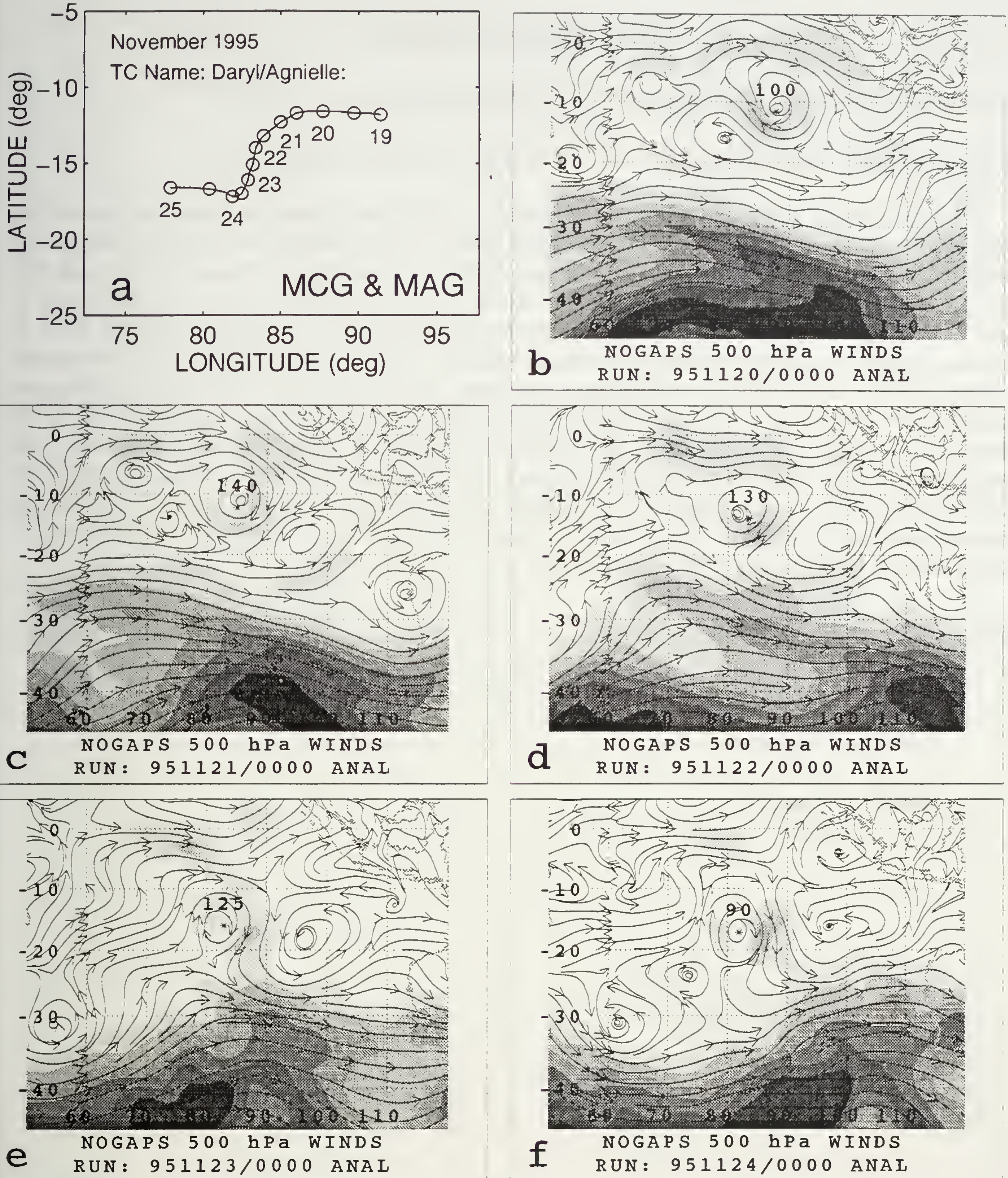
As shown in panel a on the right, the track of TC Daryl/Agnielle first changes from westward to poleward in response to Midlatitude CycloGenesis (MCG) and then returns to a westward motion in response to Midlatitude AnticycloGenesis (MAG).

At 0000 UTC 20 November 1995 (panel b), the NOGAPS analysis has TC Daryl/Agnielle north of the STR with the strongest isotach maximum to the southwest toward a strong anticyclonic cell. By 0000 UTC 21 November (panel c), a midlatitude trough is approaching and the anticyclonic cell to the southwest is displaced equatorward and weakened. By 0000 UTC 22 November (panel d), the midlatitude trough has essentially obliterated the anticyclonic cell, and TC Daryl/Agnielle has begun to move poleward (panel a). As shown for TC A in panel b of the MSE schematic on page 122, TC Daryl/Agnielle is now in the S/Poleward Flow (PF) pattern/region with an isotach maximum on the northwest flank of an anticyclonic cell to the east-southeast.

By 0000 UTC 23 November (panel e), the midlatitude trough is south-southwest of the TC and is moving eastward. Already by 0000 UTC 24 November (panel f), Midlatitude AntiCyclogenesis (MAG) has occurred with the ridging that trails the midlatitude trough re-establishing an anticyclone poleward of TC Daryl/Agnielle. Consequently, an abrupt, stairstep track change to westward motion occurs as the environment structure changes from the S/PF to S/EF pattern/region.

Cross-references:

Diagnosing Environmental Steering Direction	p. 9
Midlatitude System Evolutions (MSE)	p. 121
Standard (S) pattern	p. 19



November 1995
TC Name: Daryl/Agnielle:
LATITUDE (deg)
LONGITUDE (deg)
-5
-10
-15
-20
-25
75
80
85
90
95
19
20
21
22
23
24
25
a
MCG & MAG
100
b
NOGAPS 500 hPa WINDS
RUN: 951120/0000 ANAL
140
c
NOGAPS 500 hPa WINDS
RUN: 951121/0000 ANAL
130
d
NOGAPS 500 hPa WINDS
RUN: 951122/0000 ANAL
125
e
NOGAPS 500 hPa WINDS
RUN: 951123/0000 ANAL
90
f
NOGAPS 500 hPa WINDS
RUN: 951124/0000 ANAL

Topic: MIDLATITUDE SYSTEMS EVOLUTIONS (MSE) (cont)

ILLUSTRATION: MAG CAUSING P TO S PATTERN TRANSITION

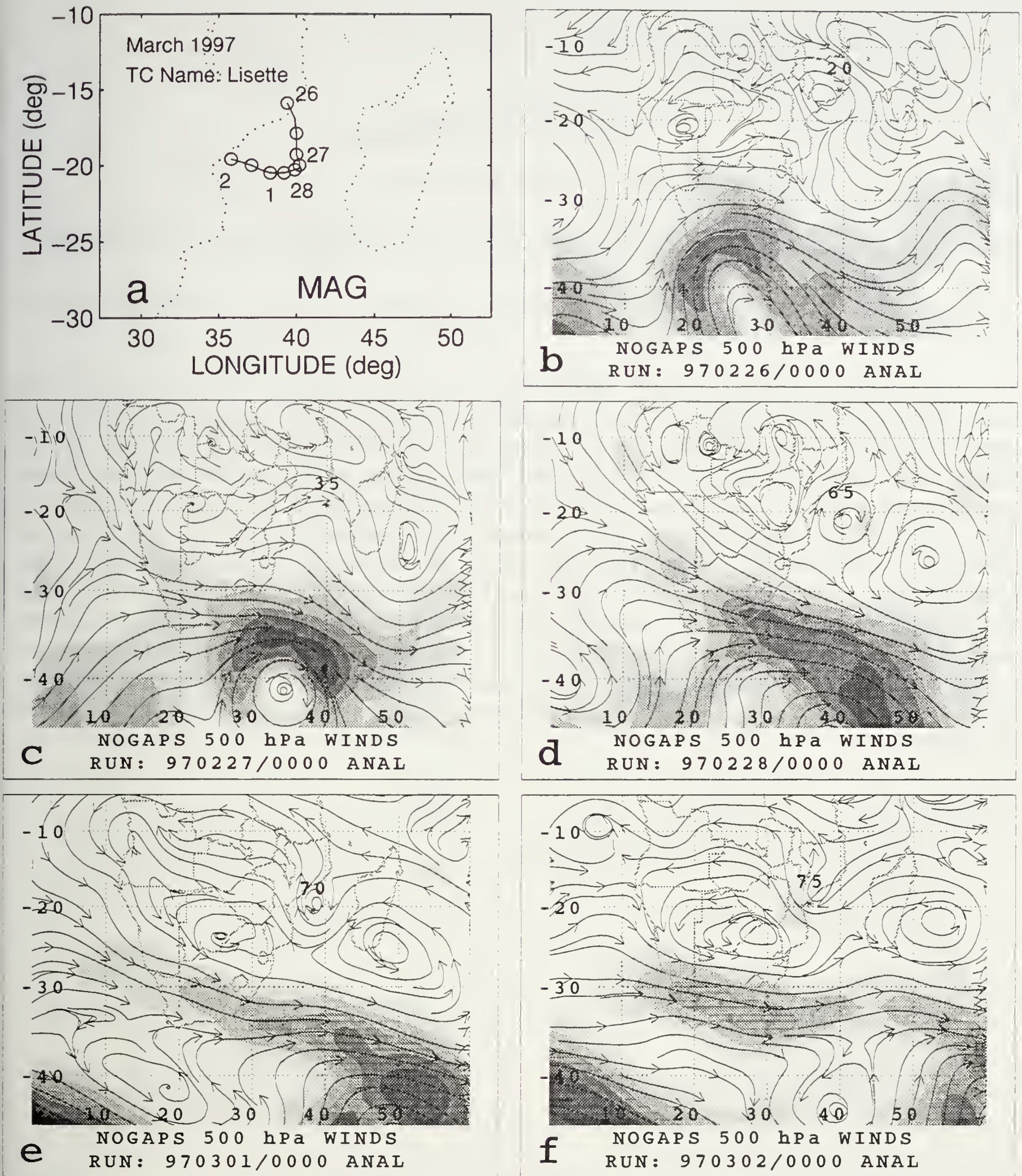
After moving slowly poleward, the translation of TC Lisette slows and then turns toward the west-northwest (panel a on right). At 0000 UTC 26 February 1997 (panel b), the NOGAPS analysis has Lisette in a P pattern with a peripheral anticyclone to the northeast that is connected to a weak STR anticyclonic cell to the southeast. This environmental structure remains the same on 0000 UTC 27 February (panel c) even though a weak midlatitude trough passes to the south. By 0000 UTC 28 February (panel d), ridging downstream from an extensive NW-SE tilted trough to the southwest has replaced the weak midlatitude trough that was present 24 h previously, which is thus Midlatitude AnticycloGenesis (MAG). The re-establishment of a ridge (anticyclone) on the poleward side of TC Lisette is quite evident at 0000 UTC 1 March (panel e). Although no isotach maximum is present at this time, the slow westward drift (panel a) would suggest only a weak environmental steering. By 0000 UTC 2 March (panel f), an isotach maximum is present to the southwest of Lisette, which is consistent with the northwestward translation toward the east coast of Africa. Thus, the MAG has contributed to a transition from the P/PF to a S/EF pattern/region.

Cross-references:

Diagnosing Environmental Steering Direction p. 9

Poleward (P) pattern p. 29

Standard (S) pattern p. 19


March 1997
TC Name: Lisette
26
27
28
1
2
MAG
a
LATITUDE (deg)
LONGITUDE (deg)
-10
-15
-20
-25
-30
30
35
40
45
50
NOGAPS 500 hPa WINDS
RUN: 970226/0000 ANAL
b
NOGAPS 500 hPa WINDS
RUN: 970227/0000 ANAL
c
NOGAPS 500 hPa WINDS
RUN: 970228/0000 ANAL
d
NOGAPS 500 hPa WINDS
RUN: 970301/0000 ANAL
e
NOGAPS 500 hPa WINDS
RUN: 970302/0000 ANAL
f

Topic: MIDLATITUDE SYSTEM EVOLUTIONS (MSE) (cont)

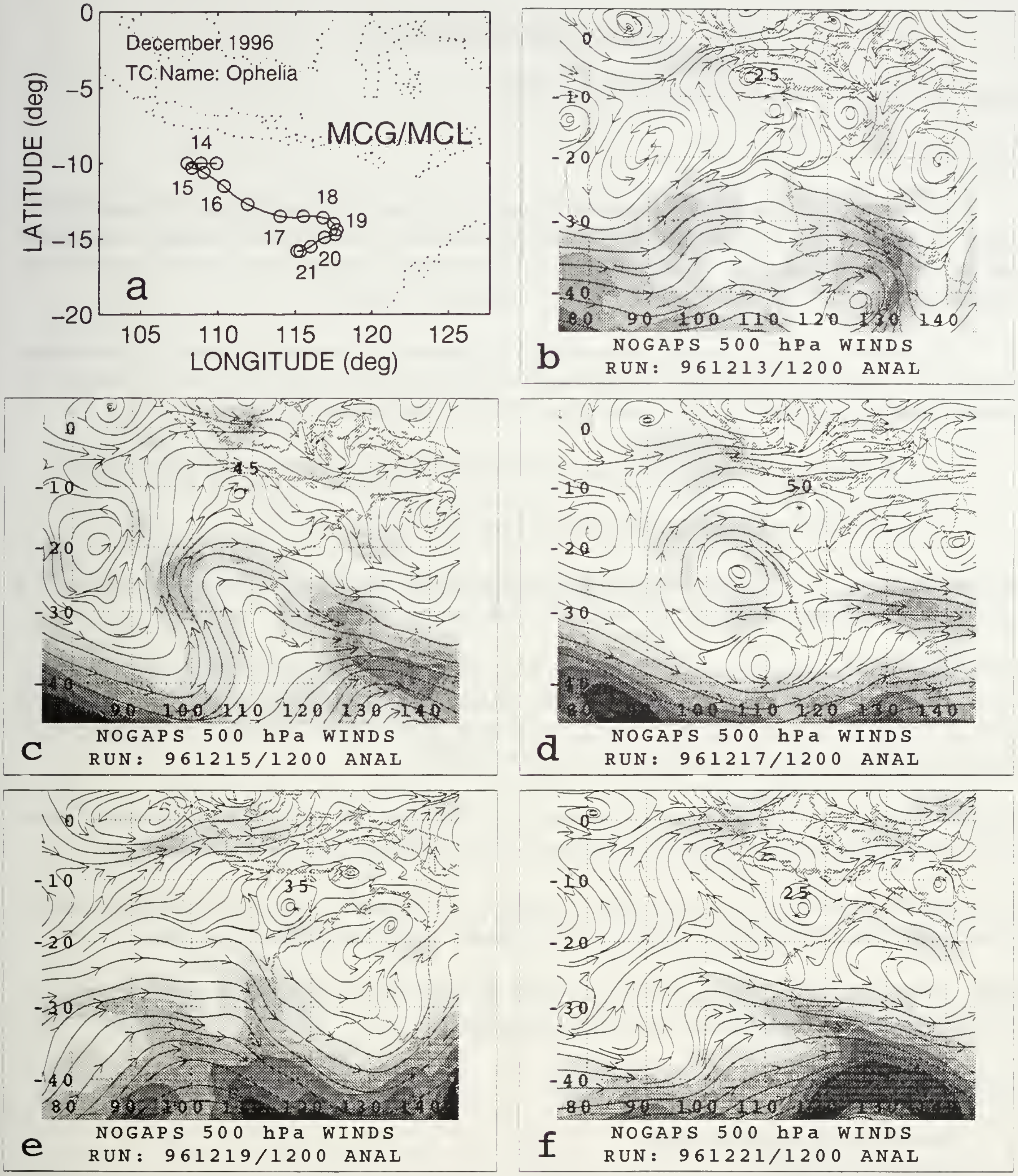
ILLUSTRATION: MCG & MCL CAUSING TRANSITIONS BETWEEN S AND H PATTERNS

As shown in panel a on the right, TC Ophelia experienced a sharp turn from westward to southeastward and then turned eastward before turning toward southwestward.

At 1200 UTC 13 December 1996 (panel b), the NOGAPS analysis has TC Ophelia in weak steering between easterlies to the north and westerlies to the south, which is consistent with its slow westward drift. That is, Ophelia may be classified in a Standard/Tropical Easterlies (S/TE) pattern/region. After 48 h (1200 UTC 15 December; panel c), a deep trough is approaching and Ophelia begins to translate toward the southeast. This Midlatitude CycloGenesis (MCG) event clearly establishes a H pattern. After another 48 h (panel d), the cyclonic circulation associated with Ophelia is near the eastern edge of the Trough Poleward (TP) region of a broad, weakening midlatitude trough. As the trough continues to weaken, which is characterized as Midlatitude CycloLysis (MCL), the anticyclonic cell to the southeast becomes the dominant steering influence. Therefore, Ophelia now turns toward the southwest in the S/PF pattern/region. By 1200 UTC 21 December (panel f), Ophelia has weakened to 25 kt so that the 500-mb analysis is perhaps not the best level for diagnosing the environment structure. No isotach maximum is evident, which is not inconsistent with the essentially stationary motion at this time (panel a).

Cross-references:

Diagnosing Environmental Steering Direction	p. 9
Standard (S) pattern	p. 29
High-amplitude (H) pattern	p. 37


December 1996
TC Name: Ophelia
MCG/MCL
LATITUDE (deg)
LONGITUDE (deg)
a
b
NOGAPS 500 hPa WINDS
RUN: 961213/1200 ANAL
c
NOGAPS 500 hPa WINDS
RUN: 961215/1200 ANAL
d
NOGAPS 500 hPa WINDS
RUN: 961217/1200 ANAL
e
NOGAPS 500 hPa WINDS
RUN: 961219/1200 ANAL
f
NOGAPS 500 hPa WINDS
RUN: 961221/1200 ANAL

ENVIRONMENT EFFECTS

Topic: ADVECTION BY ENVIRONMENT (ADV)

DESCRIPTION

The easterly steering flow in a Standard/Tropical Easterlies (S/TE) 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 TE 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 transitional mechanism responsible for the change in region classification is Advection by the Environment (ADV). Examples of these situations include:

P/PF - M/PF: The poleward flow in the Poleward Flow (PF) region of a persistent Poleward (P) pattern will eventually, and necessarily, advect (ADV) the TC into the Midlatitude pattern/(PF) region without the need for any interaction with the TC in terms of propagation (BEP). See the P and M patterns for illustration; a similar advection may occur from S/PF to M/PF.

P/EW - P/PF: If the TC is in the equatorial westerlies of a P pattern, the flow will naturally tend to advect (ADV) the TC into the PF region to the southeast. See P pattern summary for illustration.

H/EW - H/TP: If the TC is in the equatorial westerlies of a H pattern, the flow will naturally tend to advect (ADV) the TC into the PT region to the southeast. See H pattern for illustration.

M/PF - M/MW - M/EF: Continued advection of the TC can lead to a transition from the PF region to the MW region and even to the EF region of the M pattern.

Cross-references:

Beta-Effect Propagation (BEP)	p. 57
Standard (S) Pattern	p. 19
Poleward (P) Pattern	p. 29
High-amplitude (H) pattern	p. 37
Midlatitude (M) Pattern	p. 47

NO ILLUSTRATION IS PROVIDED (SEE TEXT)

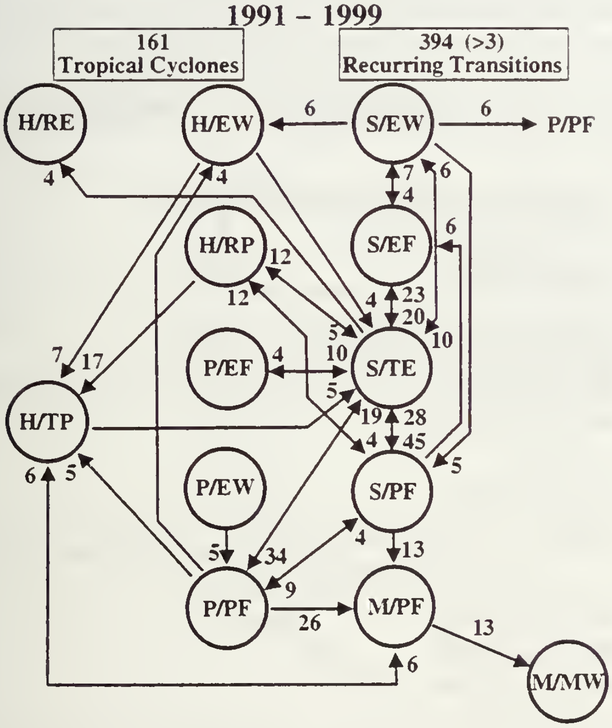
Topic: TRANSITION FREQUENCIES

DESCRIPTION:

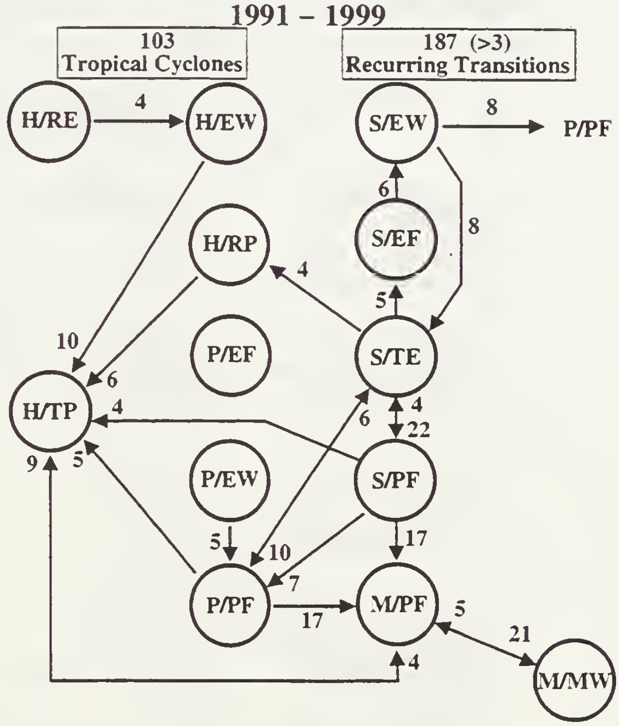
The figures at right show the frequency of recurring (more than three cases) transitions in environment structure from one pattern/region combination to another in the South Indian Ocean (left) and South Pacific Ocean (right) during the 1990-91 through 1998-99 seasons. Among the 161 TCs that spent all or part of their existence in the South Indian Ocean during the period, 394 recurring transitions occurred, which is an average of about five transitions in environment structure for every two TCs. Among the 103 TCs that spent all or part of their existence in the South Pacific Ocean during the period, 187 recurring transitions occurred, which is an average of about two transitions in environment structure per TC.

The complex appearance of the diagrams highlights the fact that many different transition paths are possible. However, notice that comparatively few transition paths occurred frequently. In addition, it is important to remember that only the transition paths that are of concern to the forecaster at any time are those that are leaving the particular pattern/region combination that characterizes the present environment of the TC. Analyses of the relative frequency, and thus the climatological probability, of each path are in the diagrams on the following pages.

Environment Structure Transitions
SOUTH INDIAN OCEAN
1991 – 1999



Environment Structure Transitions
SOUTH PACIFIC OCEAN
1991 – 1999



Topic: TRANSITION PROBABILITIES FROM THE S PATTERN

DESCRIPTION:

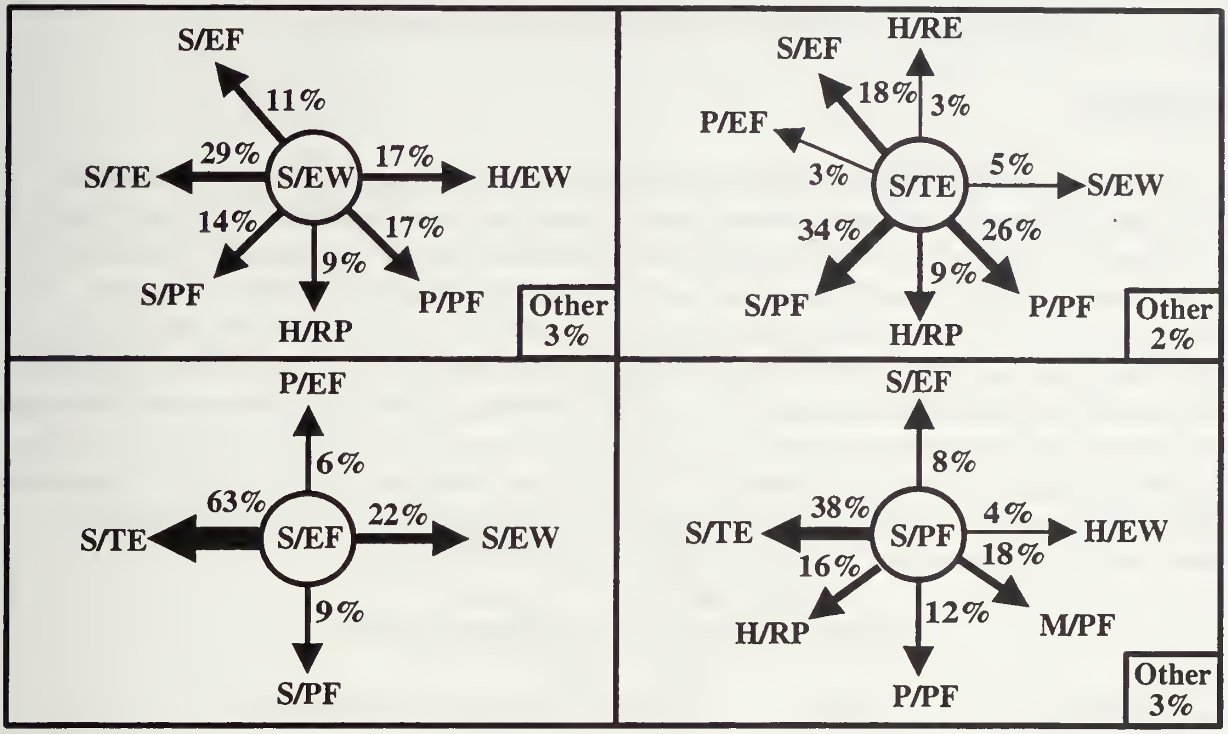
The panels at right show the relative probabilities for transitions from the four synoptic regions of the S Pattern in the South Indian Ocean (upper four) and South Pacific Ocean (lower four). These percentages are based on all transitions from the specific pattern/region within the circle, and thus may differ from the numbers along the arrows on page 132, which omit those transitions that occurred less than three times during the 1990-91 through 1998-99 seasons. To simplify some of the diagrams a few transitions that occurred only once are omitted here, and the percent of cases omitted is indicated in the lower right hand box. Notice that for some of the synoptic regions certain transition paths are much more likely than others, and these are denoted by broader arrows. A listing of these more probable transition paths and the possible transition mechanisms follows:

MORE LIKELY TRANSITION PATHS

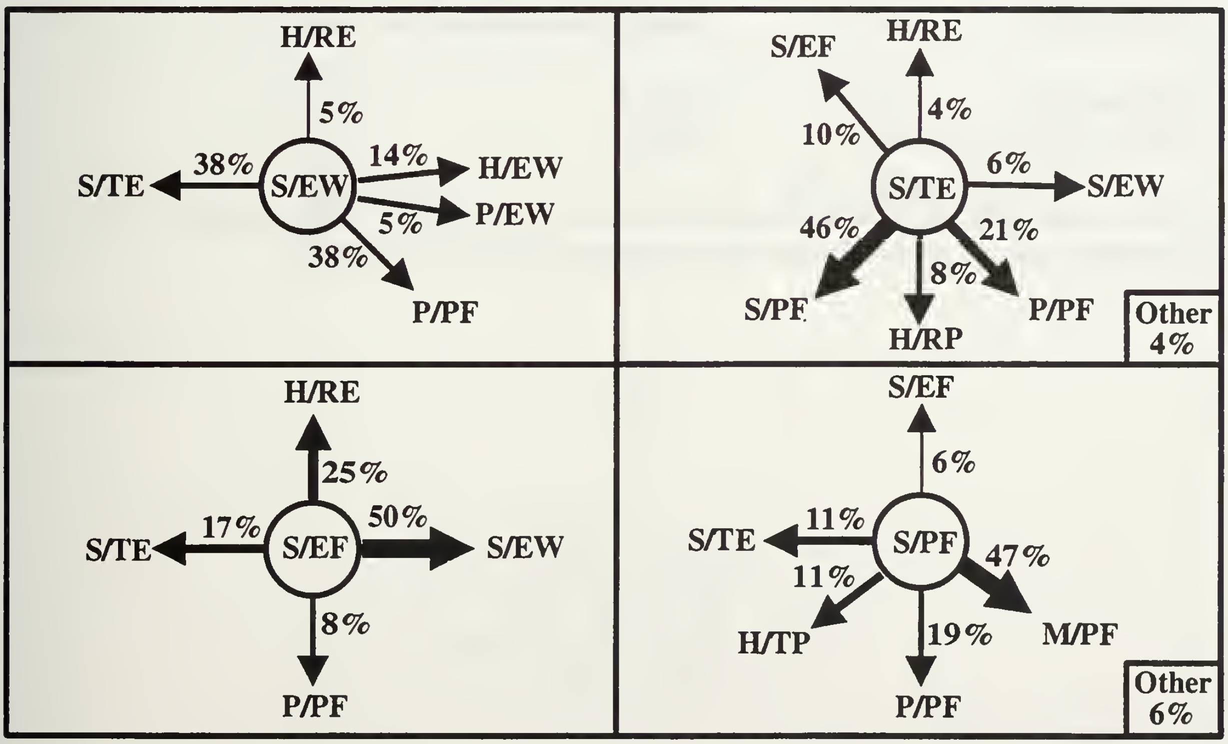
Transitions	Basin(s)	Candidate transitional mechanism(s)
S/EW to S/TE	Both	ADV, MAG, or MCL
S/EW to P/PF	SP	RMT or RTF*
S/TE to S/PF	Both	BEP, MCG, or SCIE*
S/TE to P/PF	Both	RMT, or RTF*
S/TE to S/EF	SIO	MAG, or SCIW*
S/EF to S/TE	SIO	ADV or MAL
S/EF to S/EW	SP	EWB
S/PF to S/TE	SIO	MAG, or MCL
S/PF to M/PF	SP	ADV and BEP
S/PF to P/PF	SWP	RMT, or RTF*

*This transitional mechanism requires the presence of another cyclone (usually a TC or percursor/remnant) at the proper distance and orientation from the subject TC.

SOUTH INDIAN OCEAN



SOUTH PACIFIC OCEAN



Topic: TRANSITION PROBABILITIES FROM THE P PATTERN

DESCRIPTION:

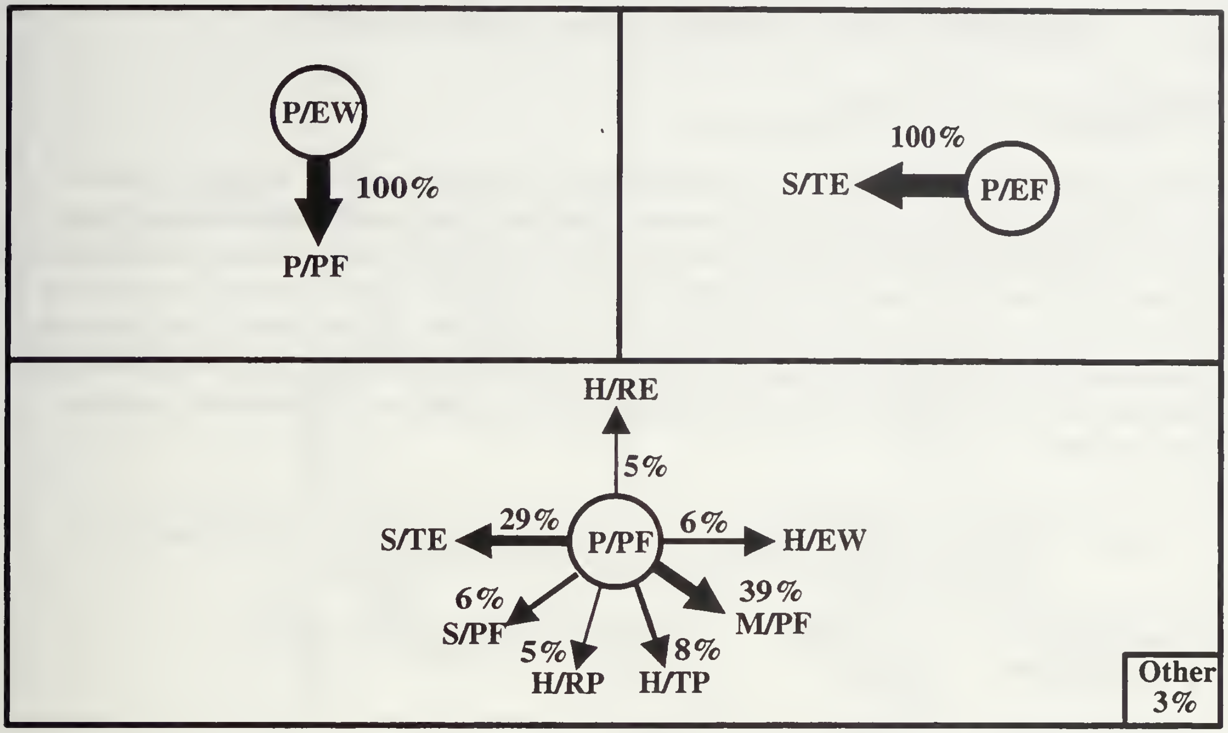
The panels at right show the relative probabilities for transitions from the three synoptic regions of the P Pattern in the South Indian Ocean (upper three) and South Pacific Ocean (lower three). These percentages are based on all transitions from the specific pattern/region within the circle, and thus may differ from the numbers along the arrows on page 132, which omit those transitions that occurred less than three times during the 1990-91 through 1998-99 seasons. To simplify some of the diagrams a few transitions that occurred only once are omitted here, and the percent of cases omitted is indicated in the lower right hand box. Notice that for some of the synoptic regions certain transition paths are much more likely than others, and these are denoted by broader arrows. Even though the transitions from P/EW and P/EF are infrequent (see p. 132), it is significant that 100% of them were to P/PF and S/TE, respectively, for this sample. A listing of these more probable transition paths and the possible transition mechanisms follows:

MORE LIKELY TRANSITION PATHS

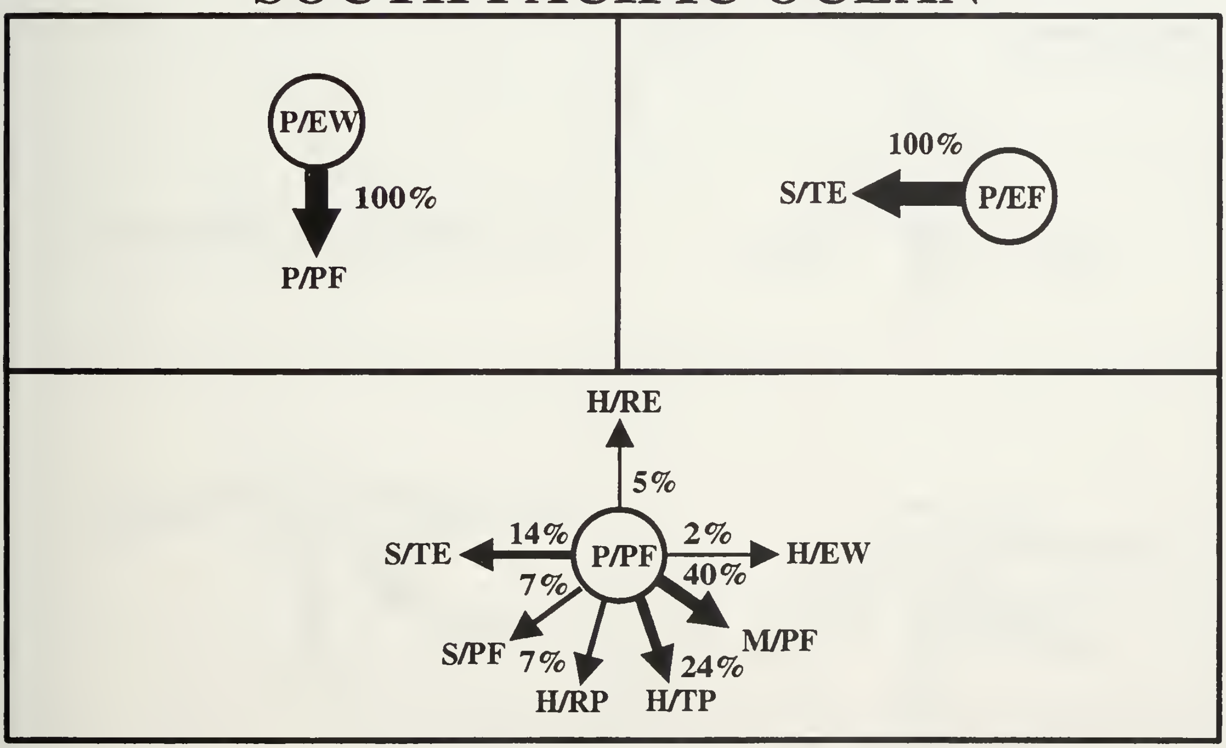
Transitions	Basin(s)	Candidate transitional mechanism(s)
P/EW to P/PF	Both	ADV, RMT, RTF*
P/EF to S/TE	Both	Dissipation/recurvature of western TC
P/PF to M/PF	Both	ADV
P/PF to S/TE	SIO	MAG

*This transitional mechanism requires the presence of another cyclone (usually a TC or percursor/remnant) at the proper distance and orientation from the subject TC.

SOUTH INDIAN OCEAN



SOUTH PACIFIC OCEAN



Topic: TRANSITION PROBABILITIES FROM THE H PATTERN

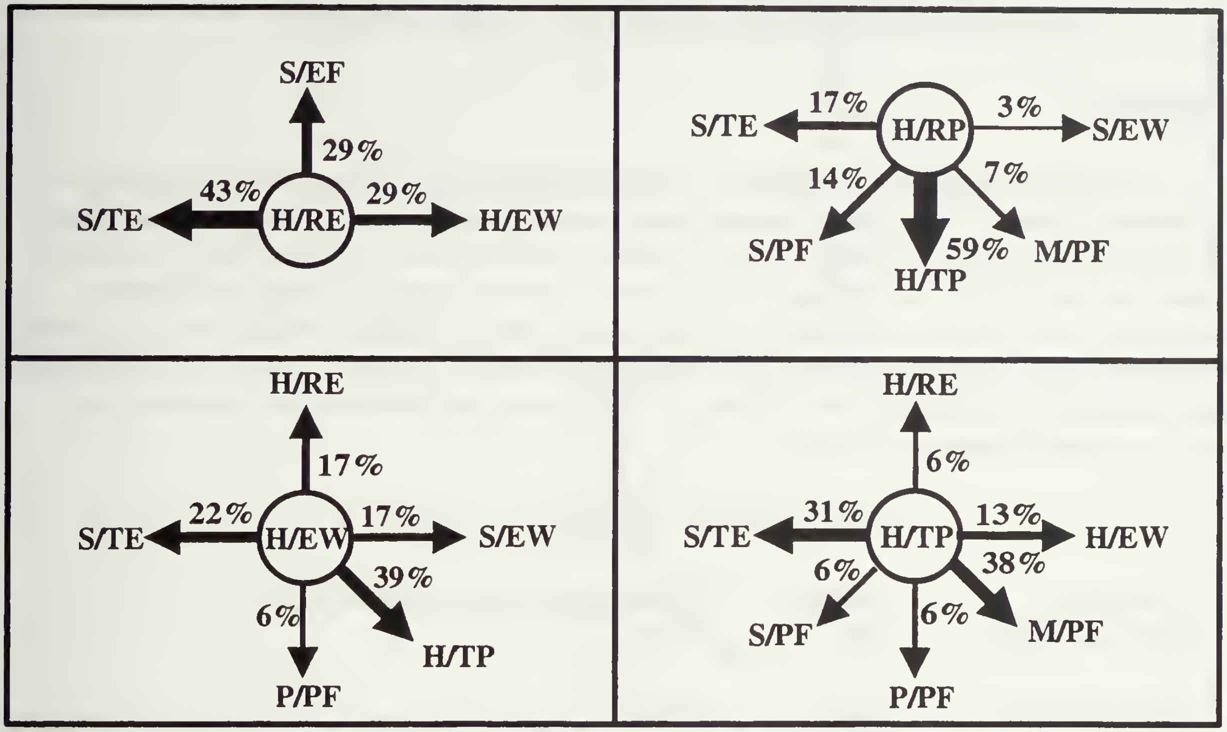
DESCRIPTION:

The panels at right show the relative probabilities for transitions from the four synoptic regions of the H Pattern in the South Indian Ocean (upper four) and South Pacific Ocean (lower four). These percentages are based on all transitions from the specific pattern/region within the circle, and thus may differ from the numbers along the arrows on page 132, which omit those transitions that occurred less than three times during the 1990-91 through 1998-99 seasons. Notice that for some of the synoptic regions certain transition paths are much more likely than others, and these are denoted by broader arrows. A listing of these more probable transition paths and the possible transition mechanisms follows:

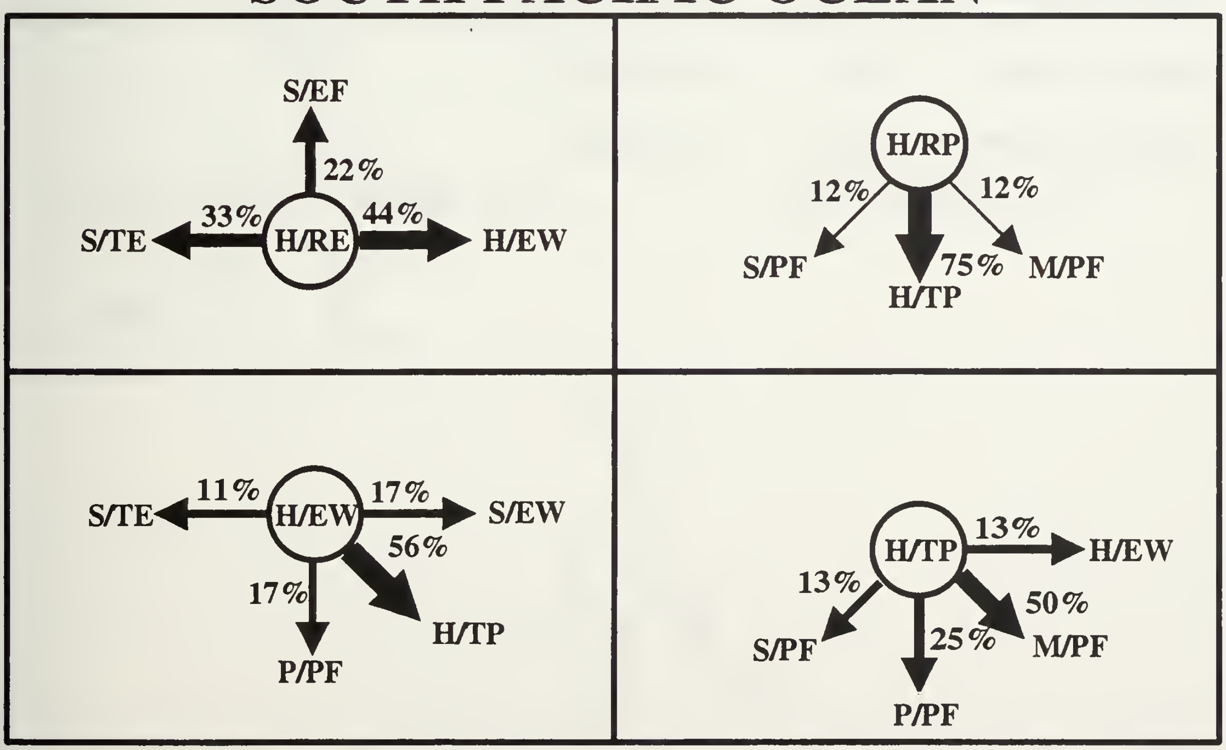
MORE LIKELY TRANSITION PATHS

Transitions	Basin(s)	Candidate transitional mechanism(s)
H/RP to H/TP	Both	MCG
H/EW to H/TP	Both	ADV
H/TP to M/PF	SP	ADV

SOUTH INDIAN OCEAN



SOUTH PACIFIC OCEAN



Topic: TRANSITION PROBABILITIES FROM THE M PATTERN

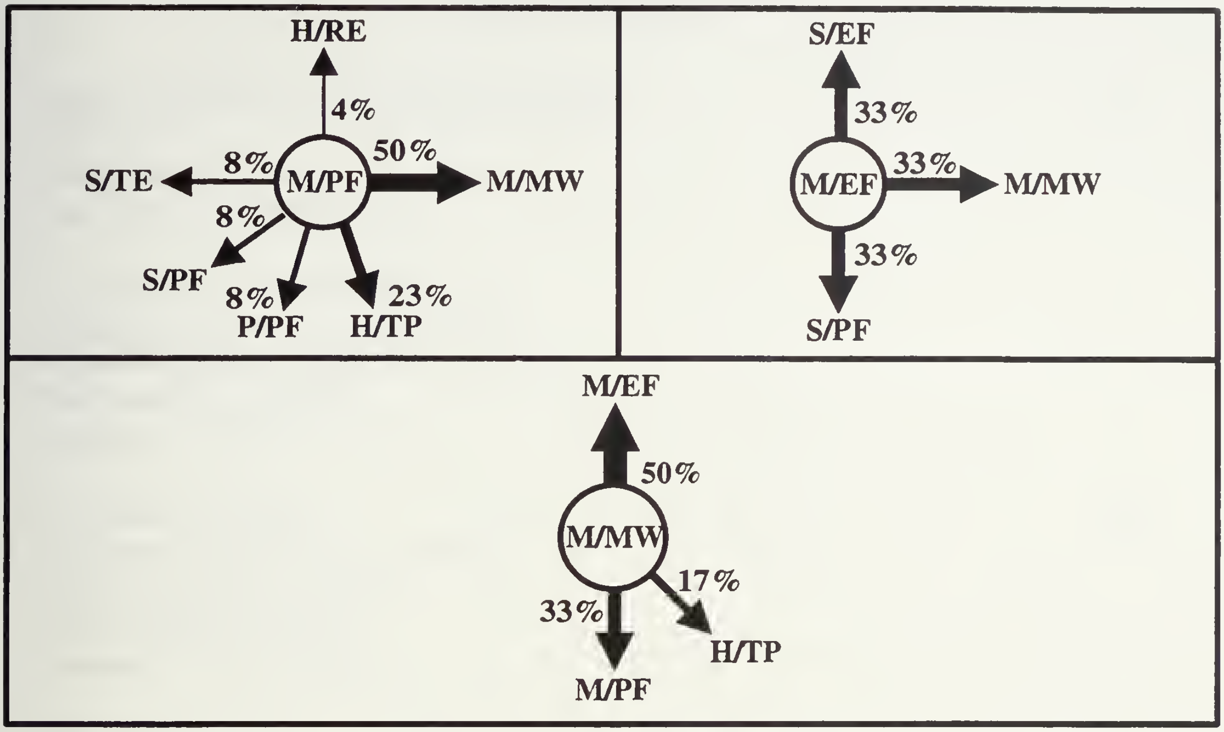
DESCRIPTION:

The panels at right show the relative probabilities for transitions from the three synoptic regions of the M Pattern in the South Indian Ocean (upper three) and South Pacific Ocean (lower three). These percentages are based on all transitions from the specific pattern/region within the circle, and thus may differ from the numbers along the arrows on page 132, which omit those transitions that occurred less than three times during the 1990-91 through 1998-99 seasons. Notice that for some of the synoptic regions certain transition paths are much more likely than others, and these are denoted by broader arrows. A listing of these more probable transition paths and the possible transition mechanisms follows:

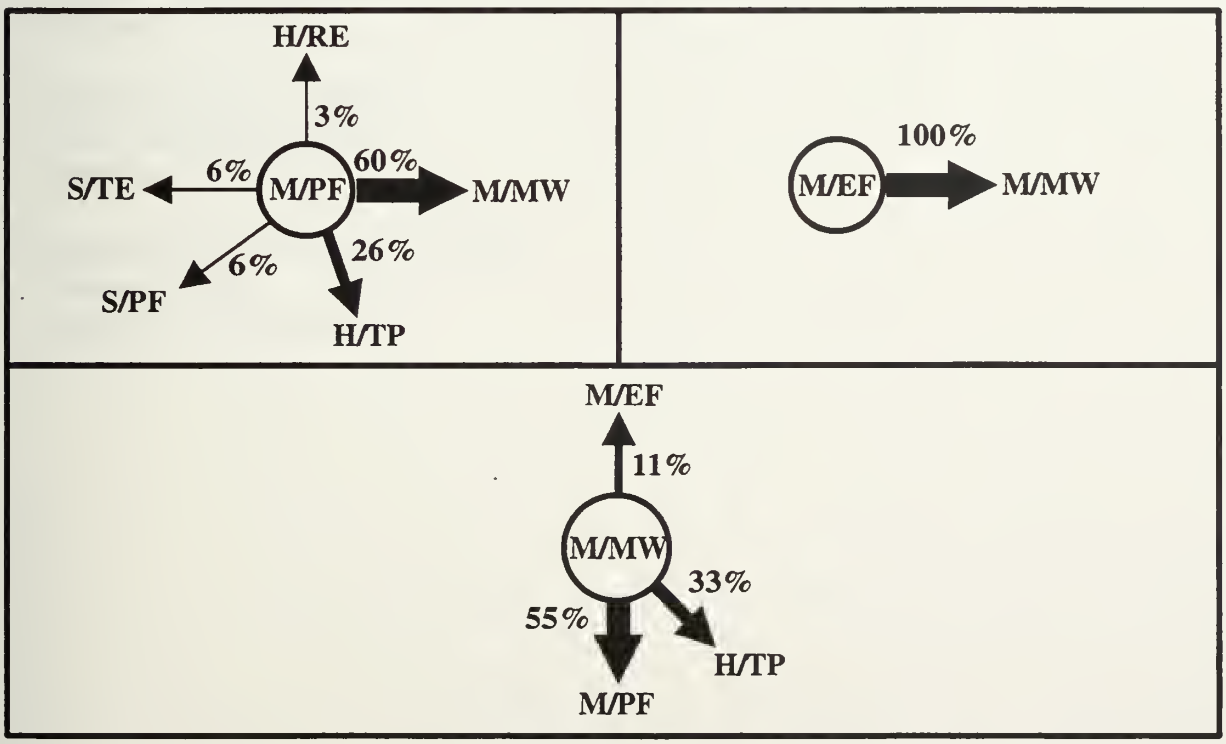
MORE LIKELY TRANSITION PATHS

Transitions	Basin(s)	Candidate transitional mechanism(s)
M/PF to M/MW	Both	ADV
M/PF to H/TP	Both	MCG
M/EF to M/MW	SP	MAL, ADV
M/MW to M/EF	SIO	MAG, ADV
M/MW to M/PF	SP	MCG, ADV

SOUTH INDIAN OCEAN



SOUTH PACIFIC OCEAN



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