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An Observational Analysis of Tropical Cyclone Recurvature

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ABSTRACT

Data for 21 years (1957–77) of North Pacific rawinsondes were examined to investigate the interaction between the synoptic-scale circulation and tropical cyclones prior to, and during, the recurvature process. This study is believed to be the first to quantitatively examine how the environmental wind fields at all levels of the troposphere are related to tropical cyclone motion prior to, and during, recurvature. For tropical cyclones that recurve, significant changes in the upper-tropospheric zonal wind fields were observed 1–2 days prior to beginning recurvature in the environmental sector northwest of the storm. Cyclones actually began to recurve when positive zonal winds (westerlies) penetrated the middle and upper troposphere to within 6° of the cyclone's center. Tropical cyclones that did not recurve consistently showed negative zonal winds at this radius.

From the results of this study, a recurvature forecasting scheme was developed that uses environmental wind field data for the region northwest of the cyclone. This recurvature scheme was tested on 55 tropical cyclones that developed in the northwest Pacific during 1984–86. In general, the movement of these cyclones was found to be fairly well related to the mid- and upper-tropospheric wind fields in areas north, northwest, and west of the cyclone. This recurvature scheme was also applied in real time as part of the Tropical Cyclone Motion Experiment during the summer of 1990 in the northwest Pacific, and was found to show promising results.

1. Introduction

It is well known that, to a large extent, the large-scale environmental wind fields surrounding a tropical cyclone act to govern the motion of the cyclone. Complications in assessing the environmental steering flow arise when westerlies associated with a midlatitude trough appear to the north and west of the cyclone. Previous research by George and Gray (1976) showed that when the upper-tropospheric (200 mb) zonal component of the environmental wind field in areas 8°–20° poleward of the cyclone was positive and strong, the cyclone was likely to begin turning to the right of its previous westward track and, thereby, recurve. Guard (1977) employed the results of George and Gray to improve forecasts of recurvature and motion changes for northwest Pacific cyclones. Guard found that in the presence of 200-mb patterns with characteristics similar to those of George and Gray's study, 75% of westward-moving cyclones underwent recurvature, with the remaining 25% tending to continue moving westward.

Gentry (1983) also showed that the current location of westerlies in relation to the cyclone governed subsequent track changes. Gentry found that when the mean upper-tropospheric ($\sim$200 mb) zonal wind 1500–2000 km northwest and west of the cyclone exceeded 20 m s^{-1}, 80% of the cyclones recurved before traveling more than 12° longitude farther west. This result is similar to Guard's results in that about the same percentage of the cyclones in Gentry's study actually recurve when strong westerlies were located at a specified radius poleward of the cyclone.

It has been inferred from these studies that although positive 200-mb zonal winds to the north and west of the cyclone are a prerequisite for recurvature, they are not a sufficient condition for recurvature to actually occur. It is likely that westerly winds must penetrate both closer to the center of the cyclone and downward through the midtroposphere to cause recurvature to commence. This paper examines more closely how the zonal component of the environmental wind field interacts with the outer (6°–8°) circulation of the cyclone prior to, and immediately after, the cyclone begins the recurvature process.

We begin (section 2) with a brief description of the rawinsonde datasets and compositing procedures used in the study, and then make an extended discussion of the results in section 3. In section 4, we apply these results to describe a simple objective recurvature forecasting scheme based on observed values for a recurvature potential that is derived from environmental flow data for areas adjacent to the west Pacific tropical cyclones.

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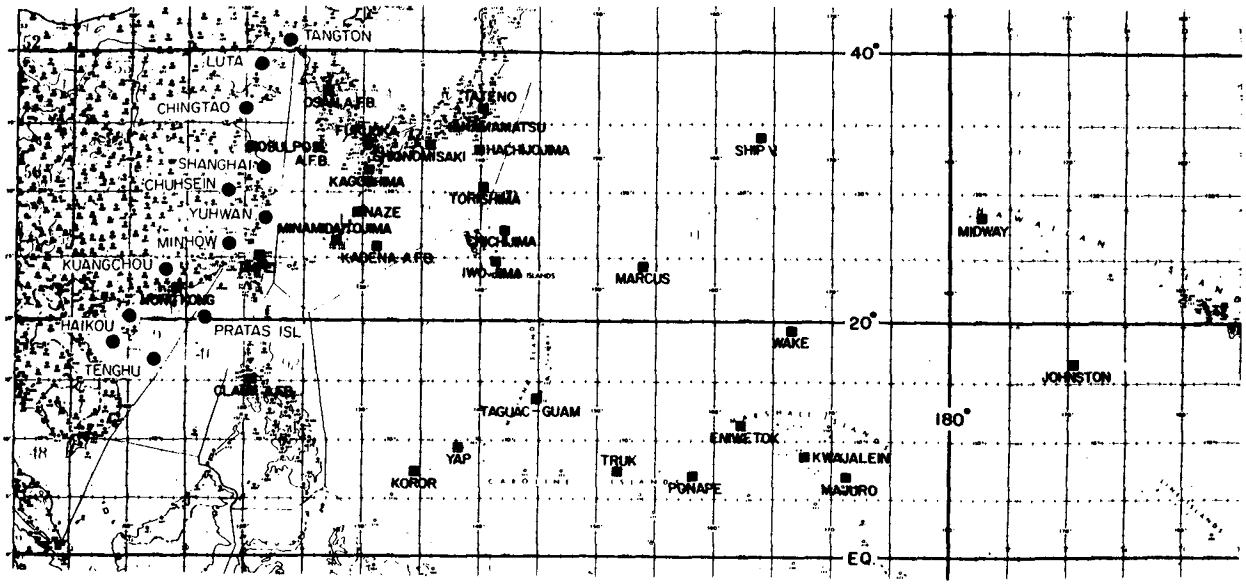

FIG. 1. Locations of the 42 northwest Pacific rawinsonde stations used in this study.

2. Methodology

a. Composite analysis

The environmental wind fields associated with the recurvature of tropical cyclones[1] have been analyzed for 21 years (1957–77) of northwest Pacific rawinsonde data (Fig. 1). Rawinsonde data were used to study recurvature for the following reasons. 1) Rawinsondes provide data for all levels of the troposphere and lower stratosphere. By analyzing data gathered by rawinsondes, detailed analyses of wind fields at all levels of the troposphere can be accomplished. 2) Rawinsonde data are the actual data that were measured relative to the cyclone. Hence, unlike many cyclone steering studies that are based on smoothed or interpolated wind analysis fields generated by computer models, rawinsonde data represent the actual winds occurring at that time. In addition, using rawinsonde data avoids the "bogus vortex" problem inherent in computer simulations. 3) Rawinsonde data have advantages over other types of data-gathering platforms such as aircraft and satellites; research and reconnaissance aircraft typically record data at only one level of the atmosphere and only near (0°–4°) the cyclone's center (Weatherford and Gray 1988). Although satellites have virtually unlimited areal coverage, they can only indirectly infer tropical and subtropical wind fields at two approximate levels (approximately 200 and 950 mb), and only with confidence when clouds are present.

Tropical cyclones, especially recurving tropical cyclones, often spend the majority of their lifetimes over data-sparse ocean areas. Consequently, to obtain statistically valid samples, rawinsonde data for multiple cases must be composited for most purposes. Thorough descriptions of the rawinsonde compositing techniques used in this study are given by Gray (1981) and Ruprecht and Gray (1974), and in numerous related Colorado State University papers on tropical cyclone motion (e.g., Hodanish 1991). For our purposes, we will simply state that there are typically too few rawinsonde stations sufficiently in proximity of most tropical cyclones to allow for detailed analyses of environmental flow fields surrounding individual events. However, by compositing data for many tropical cyclones with similar characteristics, most of these data limitations can be avoided.

The distribution of typical data used for the rawinsonde compositing technique are displayed in Fig. 2 on a 15° circular radius grid that is divided into octants, each spanning a 45° tangential arc. The center of the grid corresponds to the storm center. The grid is oriented so that octant 1 points to true north.

b. Cyclone track stratifications

Before discussing the parameters of cyclone tracks in detail, a formal definition of tropical cyclone recurvature is needed. According to the Joint Typhoon Warning Center (JTWC 1988), tropical cyclone recurvature is "the turning of a tropical cyclone from an initial path west and poleward to (a subsequent heading) east and poleward." As shown in Fig. 3, JTWC emphasizes the location at which the cyclone's track first takes on an eastward component of motion. The point of initial recurvature will be defined as the "be-

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[1] "Tropical cyclone" in this paper refers to any warm-core cyclonically rotating storm system with sustained wind speeds of 17 m s^{-1} or greater.

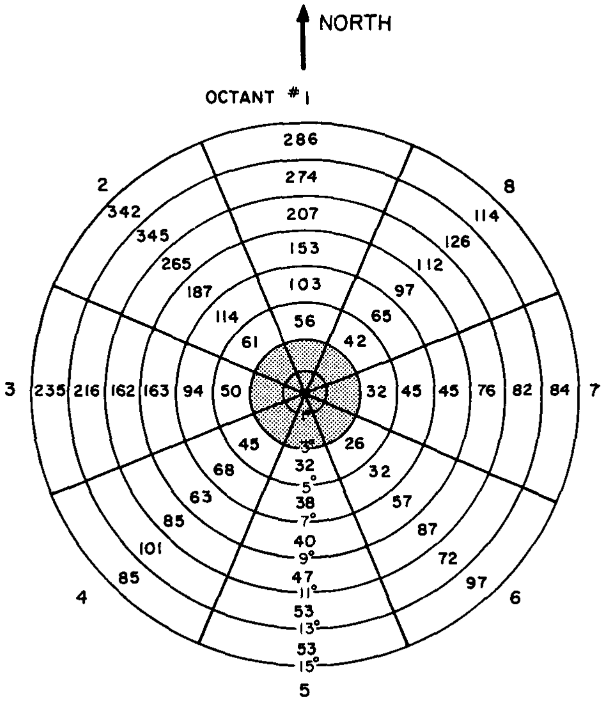

FIG. 2. Grid used for compositing rawinsonde data. The numbers inside each radial octant sector represent the number of rawinsonde observations for the class of cyclones characterized as sharply recurving. (The cyclone dataset stratifications are defined in section 2b.)

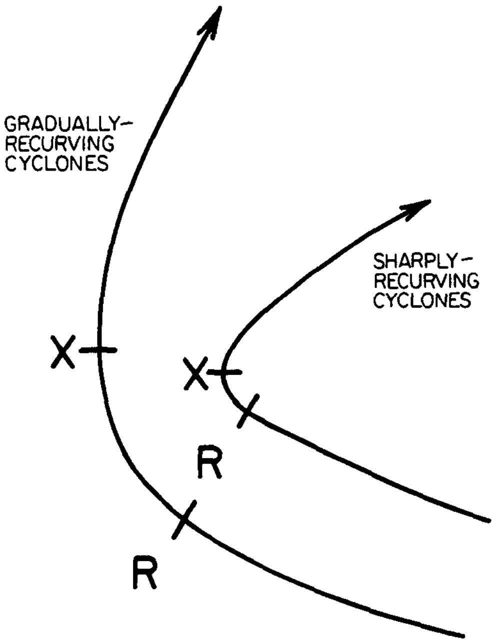

FIG. 3. Typical tracks for sharply recurving and gradually recurving cyclones. The large *R* represents the beginning of recurvature or *R* points; the location where both sharply recurving and gradually recurving cyclones first begin to turn to the right from their west-northwest track. The large "X" marks the location where the cyclone actually undergoes recurvature as defined by JTWC.

ginning of recurvature", or *R* point. Figure 3 shows an example of comparative gradually and sharply recurving cyclones and the associated *R* points. In this study, the location where the sharply recurving and gradually recurving cyclones first begin to deviate to the right of their previous west-northwest track is the point of primary importance. The location in the cyclone track where this deviation begins marks the point where the surrounding environmental wind fields first begin to change the direction of the recurving cyclones. This study of tropical cyclone motion analyzes the following four types of recurvature tracks: sharply recurving (SR) cyclones, gradually recurving (GR) cyclones, left-turning (LT) cyclones, and nonrecurving (NR) cyclones. The distinguishing properties for each of these four track types are shown in Fig. 4.

For the purposes of this study, a sharply recurving cyclone is formally defined as a cyclone that changes direction a minimum of 45° to the right of its previous west-northwest course within 36 h after passing the *R* point. The cyclone must also have undergone recurvature (by JTWC definition) within 48 h after passing the *R* point. In addition, sharply recurving cyclones must have previously moved on a course between 260° and 330° for a minimum of 24 h prior to reaching the *R* point. This last restriction is also necessary (for the purposes of this study) so that any changes that occur in the wind fields prior to the beginning of recurvature can be delineated. A majority of the cyclones that recurved sharply had west-northwest tracks that lasted for more than 48 h. Figure 5 shows a composite analysis for a portion of the 63 sharply recurving cyclone tracks that were analyzed in this study.

Gradually recurving cyclones were those cyclones that changed direction a minimum of 30° (but less than 45°) to the right of their previous west-northwest

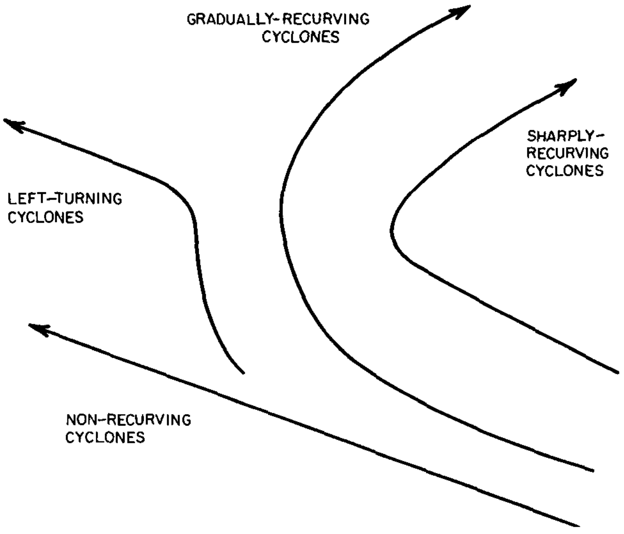

FIG. 4. Typical tracks for the four basic types of cyclones defined and analyzed in this study.

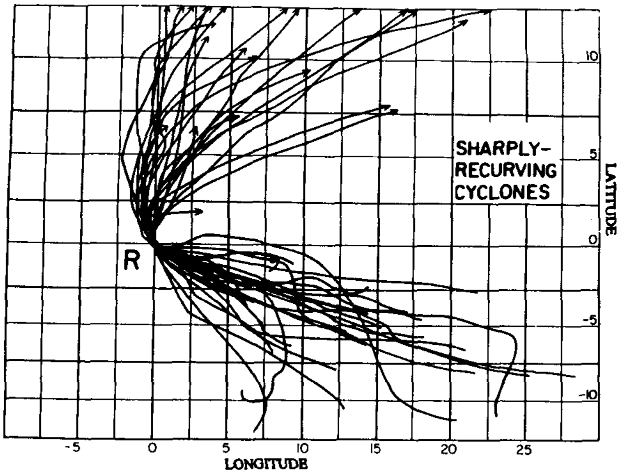

FIG. 5. Tracks of 24 of the 63 sharply recurving cyclones that were analyzed in this study. The sample size in this figure was restricted to 24 of the 63 total storms to allow qualitative comparison with the entire sample of 24 gradually recurving cyclones that is shown in Fig. 6. Each sharply recurving cyclone track is plotted relative to the *R* point.

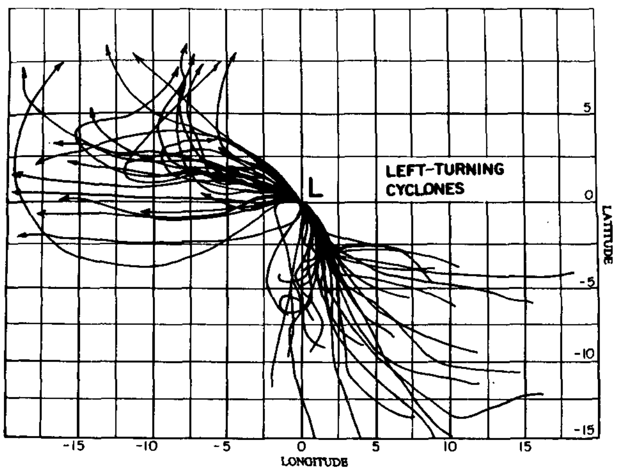

FIG. 7. As in Figs. 5 and 6 but for the tracks of the 29 left-turning cyclones that were analyzed in this study. Each left-turning cyclone track is shown plotted relative to the *L* point.

course within 36 h after passing the *R* point. These gradually recurving cyclones must also have undergone recurvature within 72 h after passing the *R* point. In addition, these cyclones must also have been moving on a course between 260° and 330° for a minimum of 12 h prior to reaching the *R* point. Figure 6 shows tracks for 24 gradually recurving cyclones.

A left-turning cyclone in this study is a cyclone that is on a northerly course but instead of recurving to the northeast turns back toward the left and resumes a west-northwest course. The location where a left-turning cyclone begins to resume a west-northwest track is termed the "*L* point". The *L* point is thus similar to the *R* point of sharply and gradually recurving cyclones, but where the cyclone turns to the left instead of the right. More precisely, a left-turning cyclone is a cyclone that was moving on a course between 320° and 045° for a minimum of 36 h prior to reaching the *L* point. After passing the *L* point, a left-turning cyclone must take a heading between 320° and 250° for a minimum of 36 h. Figure 7 shows a composite of the tracks for the 29 left-turning cyclones that were identified and analyzed as part of the study.

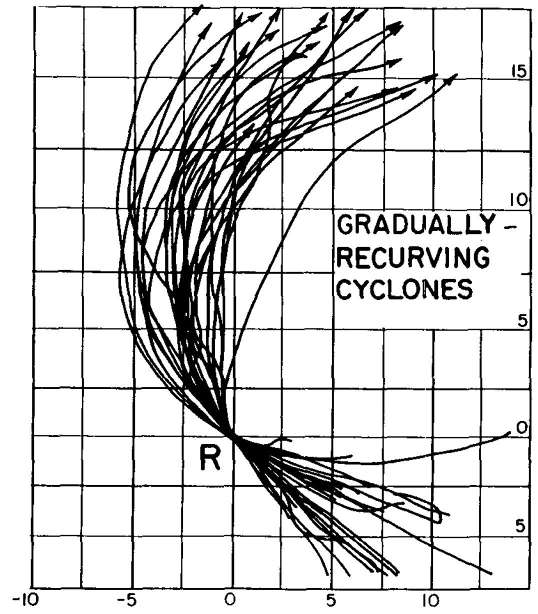

FIG. 6. As in Fig. 5 but for the tracks of the 24 gradually recurving cyclones that were analyzed in this study. Each gradually recurving cyclone track has been plotted relative to the *R* point.

To further differentiate sharply recurving and gradually recurving cyclones from those cyclones that continue moving west throughout their lifetimes, a nonrecurving cyclone dataset was also assembled and analyzed. The nonrecurving cyclones were defined as cyclones that tracked fairly continuously on a heading between 260° and 320° throughout their lifetimes.[2] Figure 8 shows a portion of the 85 nonrecurving cyclone tracks that were analyzed in this study.

c. Characteristic time periods for cyclone recurvature

The temporal changes in the environmental wind fields surrounding sharply recurving, gradually recurving, and left-turning cyclones were characterized for 24-h time segments. This segmentation concept is illustrated in Fig. 9. Time has been measured relative

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[2] If the cyclone should deviate from its west-northwest course (i.e., 260°–320°) (but this deviation does not last longer than 24 h), then the cyclone is still considered a nonrecurving cyclone.

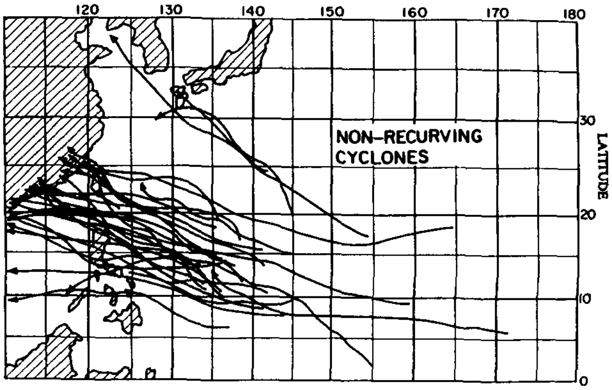

FIG. 8. Tracks for a sample of 30 of the total 85 nonrecurving cyclones that were analyzed. As in Fig. 6; the sample size in this figure has been restricted to allow qualitative comparisons with the other three classes of recurvature.

to the *R* point for the sharply recurving and gradually recurving cyclones, and relative to the *L* point for left-turning cyclones. By orienting and analyzing the cyclone data in this fashion, it was possible to examine the interaction between the synoptic-scale wind fields and the cyclone's circulation both prior to and after the cyclones began recurving (or resumed a west-northwest course in the case of the left-turning cyclones).

Tracks for sharply recurving cyclones were divided into five consecutive 24-h periods. The first three periods—SR0, SR1, and SR2 (Fig. 9)—occurred as the cyclones were moving west-northwest prior to attaining the *R* point. The fourth and fifth time periods (i.e., SR3 and SR4) occurred after the cyclone had passed the *R* point. Similarly, gradually recurving cyclone tracks were divided into six consecutive 24-h periods (Fig. 9); in this case, the first two periods, GR1 and GR2, occurred as the cyclones moved west-northwest prior to the *R* point. The remaining four periods—GR3, GR4, GR5, and GR6—occurred after the cyclone had passed the *R* point. As shown in Fig. 9, sharply recurving and gradually recurving cyclone periods 1 (SR1, GR1), 2 (SR2, GR2), and 3 (SR3, GR3) are functionally concurrent relative to the *R* point. By stratifying the cyclones in this fashion, temporal comparisons can be made between gradually and sharply recurving cyclones as they approach and pass the *R* point.

Left-turning cyclone tracks in Fig. 9 were divided into four consecutive 24-h time periods. The first two periods, LT3 and LT4, occur before the cyclone reached the *L* point, whereas the remaining two periods, LT5 and LT6, occurred after the cyclone had passed the *L* point.

Tracks for nonrecurving cyclones were partitioned differently from the previous three cyclone datasets. Since no track reference point equivalent to the *L* or *R* points was designated for the nonrecurving cyclones, the entire length of each nonrecurving cyclone track was divided into three equal periods. The first period, NR1 in Fig. 9, represented the first third of the cyclone track, and similarly thereafter, the remaining two periods, NR2 and NR3, represented the last two-thirds. Although nonrecurving cyclone tracks varied both temporally and spatially, the average length of each NR period was 50 h. Figure 10 and Table 1 summarize information on the mean speed and direction for sharply recurving, gradually recurving, left-turning, and nonrecurving cyclone time periods.

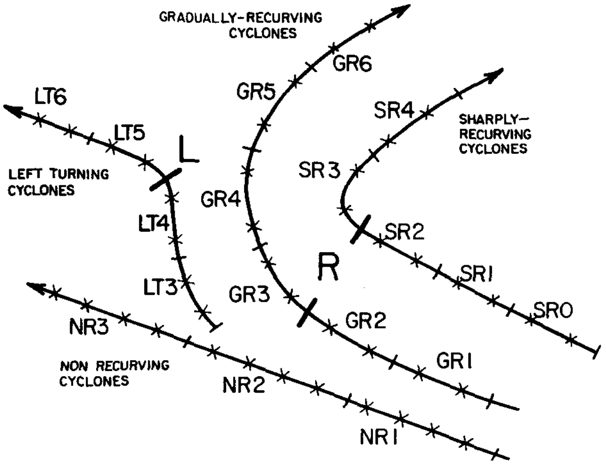

FIG. 9. Conceptual illustrations of sharply recurving (SR0–SR4), gradually recurving (GR1–GR6), left-turning (LT3–LT6), and nonrecurving (NR1–NR3) cyclone tracks divided into individual 24-h time segments. Table 1 and Fig. 10 summarize individual characteristics of each time period for each track type. The small "X" symbols plotted on the cyclone tracks denote the times (0000 and 1200 UTC) when rawinsonde data was collected from the surrounding northwest Pacific rawinsonde network.

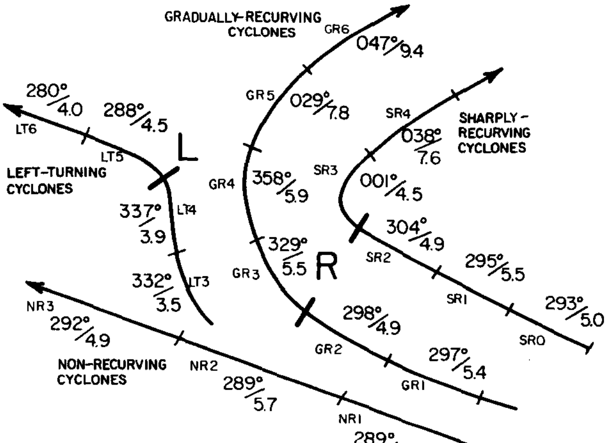

FIG. 10. Composite average speed and direction for each sharply recurving, gradually recurving, left-turning, and nonrecurving cyclone time periods. Units are expressed as meters per second.

TABLE 1. Summary of mean observed characteristics for each of the sharply recurving, gradually recurving, left-turning, and nonrecurving time periods. Standard deviations of about 15° and about 2.5 m s^{-1} were observed for all direction and speed (respectively) classes. (See section 4 for a discussion of sample variability.)

Name	Time period	Description	Average composite		No. of time periods
			Direction (°)	Speed (m s^{-1})	
Sharply recurving cyclones	SR0	48–72 h before *R* point	293 (WNW)	5.0	55
	SR1	24–48 h before *R* point	295 (WNW)	5.5	62
	SR2	0–24 h before *R* point	304 (WNW)	4.9	63
	SR3	0–24 h after *R* point	001 (N)	4.5	59
	SR4	48–72 h after *R* point	038 (NE)	7.6	52
Gradually recurving cyclones	GR1	24–48 h before *R* point	297 (WNW)	5.4	24
	GR2	0–24 h before *R* point	298 (WNW)	4.9	24
	GR3	0–24 h after *R* point	329 (NNW)	5.5	24
	GR4	24–48 h after *R* point	358 (N)	5.9	22
	GR5	48–72 h after *R* point	029 (NNE)	7.8	19
	GR6	72–96 h after *R* point	047 (NE)	9.4	16
Left-turning cyclones	LT3	24–48 h before *L* point	332 (NNW)	3.5	29
	LT4	0–24 h before *L* point	337 (NNW)	3.9	29
	LT5	0–24 h after *L* point	288 (WNW)	4.5	29
	LT6	24–48 h after *L* point	280 (WNW)	4.0	25
Nonrecurving cyclones	NR1	First third of track	289 (WNW)	5.4	78
	NR2	Second third of track	289 (WNW)	5.7	85
	NR3	Third third of track	292 (WNW)	4.9	75

3. Environmental wind fields associated with recurving, nonrecurving, and left-turning cyclones

a. Basic features

As was discussed in the previous section, the main objective of this study was to identify those features of the wind fields surrounding tropical cyclones that govern recurvature. This objective was attained by first determining which locations, measured relative to the center of each cyclone, best differentiated the recurving from the nonrecurving cyclones. This was accomplished by first examining how the outer radius (i.e., 8° from the center) environmental wind fields of nonrecurving cyclones differ from those of sharply recurv-

TABLE 2. Zonal (top) and meridional (bottom) wind differences between sharply recurving cyclones prior to recurvature (period SR2) versus the entire track of the nonrecurving cyclones. Units are expressed as meters per second.

	Sharply recurving cyclones (period SR2) minus nonrecurving cyclones							
p (mb)	Octant 1	Octant 2	Octant 3	Octant 4	Octant 5	Octant 6	Octant 7	Octant 8
Zonal wind differences at 8° from cyclone's center								
100	14.5	16.6	7.8	1.8	4.3	3.5	2.9	9.3
200	15.4	16.3	8.7	3.7	3.0	0.4	1.9	4.8
300	9.7	17.6	10.0	2.4	1.4	1.3	0.6	3.7
400	8.5	13.8	8.6	−0.4	−0.1	4.2	−0.7	3.7
500	6.6	11.6	5.9	−0.1	−1.2	−0.5	−0.2	3.7
600	3.8	6.8	2.4	−1.3	−2.5	−0.5	1.4	4.0
700	3.0	4.3	−0.7	−1.8	−2.1	1.7	0.7	2.8
800	3.1	2.2	−0.7	−2.1	−3.3	2.5	−0.5	2.7
Layer average	8.1	11.2	5.3	0.3	−0.1	1.6	0.8	4.3
Meridonal wind differences at 8° from cyclone's center								
100	6.4	4.9	2.0	1.4	1.7	0.2	0.8	4.2
200	10.9	1.3	−1.9	−0.8	1.9	−0.3	−0.6	4.3
300	5.1	1.4	−3.8	−1.1	0.7	−0.5	1.1	4.2
400	3.8	0.9	−0.3	0.9	−0.1	−1.9	2.9	2.3
500	2.6	0.4	1.3	0.2	−1.2	−0.6	1.7	0.5
600	3.1	0.9	−0.6	−1.0	−2.6	−2.3	1.2	0.3
700	1.3	1.9	−0.3	−2.0	−1.7	−0.1	0.7	−0.3
800	1.6	0.7	−0.1	−1.1	0.2	0.2	1.3	0.1
Layer average	4.4	1.6	−0.5	−0.4	−0.1	−0.7	1.1	2.0

TABLE 3. Zonal (top) and meridional (bottom) wind differences between gradually recurving cyclones prior to recurvature (period GR2) versus mean conditions for the nonrecurving cyclones. Units are expressed as meters per second.

	Gradually recurving cyclones (period GR2) minus nonrecurving cyclones							
p (mb)	Octant 1	Octant 2	Octant 3	Octant 4	Octant 5	Octant 6	Octant 7	Octant 8
Zonal wind differences at 8° from cyclone's center								
100	−3.0	8.5	−2.0	−2.7	4.0	4.4	0.8	2.2
200	−1.2	3.4	2.6	−0.7	1.9	0.2	1.6	3.8
300	−2.6	2.7	1.0	−1.9	1.3	1.2	−1.1	1.0
400	−1.0	3.7	−0.5	−0.2	−3.1	−1.3	−1.9	−3.6
500	0.5	4.5	1.2	2.1	−1.3	−1.8	1.8	−2.2
600	0.7	5.8	0.0	−0.3	0.9	−1.9	−0.1	−2.3
700	2.2	4.1	0.7	−1.1	−0.4	−1.3	−0.3	0.1
800	3.2	2.8	−2.1	1.7	0.1	0.0	0.5	−2.1
Layer average	−0.2	4.5	0.1	0.4	0.4	−0.1	0.2	−0.4
Meridional wind differences at 8° from cyclone's center								
100	4.3	−0.5	−1.6	−0.9	1.9	−0.6	1.9	−1.8
200	−0.4	−0.1	−1.1	1.1	−4.8	2.6	3.0	−1.8
300	2.3	4.5	−1.0	−0.1	−2.0	2.6	3.1	−1.1
400	3.4	4.4	0.8	3.0	1.5	2.2	0.4	0.2
500	1.2	3.8	1.5	−0.2	2.3	0.3	1.3	−1.2
600	2.0	3.4	−0.6	−2.7	−0.4	1.0	0.8	−1.7
700	2.5	2.4	−0.4	−3.0	0.3	0.5	0.3	−1.6
800	2.9	1.5	−1.0	−3.6	0.4	0.8	0.4	1.0
Layer average	2.3	2.4	−0.4	−0.8	−0.1	1.2	1.4	−0.6

ing and gradually recurving cyclones prior (period 2) to the beginning of recurvature.

Table 2 summarizes the differences between composited zonal and meridional wind data for sharply recurving cyclones prior to beginning recurvature versus the mean track of the nonrecurving cyclones. As shown in Table 1, at 8° from the center of the cyclone, the largest wind field difference occurred in the zonal components of the middle and upper troposphere in areas to the north, northwest, and west (i.e., octants 1, 2 and 3, respectively). This result was not surprising considering that the northwest region is where westerly winds associated with an eastward-moving trough in the midlatitude westerly wind regime will first begin to interact with the outer circulation of a cyclone.

Differences between zonal and meridional winds for gradually recurving cyclones minus nonrecurving cyclones (again at 8° from the center) just prior (period 2) to beginning recurvature are summarized in Table 3. By comparing with the data in Table 2, it can be seen that these differences are significantly smaller than those observed for the sharply recurving cyclones. The largest differences once again occur in the zonal component in the northwest region (octant 2). As expected, the large-scale synoptic pattern most favorable for gradual recurvature was a weakening subtropical ridge axis. A west-northwest-moving cyclone positioned southwest of the ridge axis will first encounter this weakness on its northwest side.

There are two especially outstanding characteristics of the outer wind field difference values shown in Tables 2 and 3. The first is that both the zonal and meridional wind field differences equatorward of the cyclone are comparatively small, even though both the sharply and gradually recurving cyclones were to begin recurving within approximately 12 h. The second characteristic is that the 8° zonal wind field differences in the north-

TABLE 4. Mean zonal winds (top) and zonal wind differences (bottom) for six radial bands of sharply recurving (SR) cyclones minus nonrecurving (NR) cyclones during periods SR1, SR2, and SR3 in octant 2. Units are expressed as meters per second.

p (mb)	4°	6°	8°	10°	12°	14°	
Zonal winds for octant 2 sharply recurving cyclones radius from center cyclone							
200	−1.5	4.5	0.9	8.3	22.4	22.8	
350	−4.9	−2.7	−3.3	8.8	16.5	19.4	period SR1
500	−10.2	−2.8	−2.7	6.4	9.2	12.7	
200	−3.8	0.4	13.7	22.8	27.1	30.6	
350	−7.6	−0.2	11.9	18.4	23.9	25.1	period SR2
500	−12.4	−3.2	6.5	12.9	14.5	16.7	
200	1.7	16.0	20.5	29.5	33.5	35.5	
350	2.5	16.9	23.4	26.8	27.4	30.0	period SR3
500	−0.6	6.6	11.5	16.8	17.9	19.0	
Zonal wind differences for octant 2 (SR versus NR) radius from center of cyclone							
200	−2.3	−3.1	12.8	14.5	4.7	7.8	period SR2 minus period SR1
350	−2.7	2.5	15.2	9.6	7.4	5.7	
500	−2.2	−0.4	9.2	6.5	5.3	4.0	
200	5.5	15.6	6.8	6.7	6.4	4.9	period SR3 minus period SR2
350	10.1	17.1	11.5	8.4	3.5	4.9	
500	11.8	9.8	5.0	3.9	3.4	2.3	

west region (octant 2) are significantly larger than the meridional wind differences, especially for the sharply recurving cyclone stratifications.

The preceding discussion has shown that the environmental wind fields in the region northwest of the cyclones are important in discerning between nonrecurving cyclones versus recurving cyclones prior to recurvature. To determine which radial locations (i.e., how far from the center) in this region show the most significant changes prior to and during the beginning of recurvature, zonal wind fields at various radii for the sharply recurving and gradually recurving cyclones were compared for periods 1, 2, and 3. Table 4 shows these zonal wind and zonal wind differences for sharply recurving versus nonrecurving cyclones at selected pressure levels in octant 2 (northwest) for radial belts extending from 4° through 14°. In SR1, the nearest significant positive zonal winds (i.e., winds greater than 5 m s^{-1} throughout the layer) are located beyond 10° radius. In SR2, significant positive zonal winds reach to within 8° of the center of the cyclones. Although the zonal wind (difference) changes that occur between these two time periods (lower portion of Table 4) are rather large, especially at 8° and 10°, the cyclones at SR2 remain on a west-northwest course. Between periods SR2 and SR3, the zonal winds at 6° change significantly, shifting from a weak easterly component to a westerly component; it is between these two time periods that the cyclones begin sharp recurvature (e.g., Fig. 9).

Table 5 shows zonal wind differences (GR − NR) and the time changes of these differences for gradually recurving versus nonrecurving cyclones at selected pressure levels in octant 2 (northwest), extending from 4° to 14°. The nearest positive zonal winds at GR1 are located beyond 12°. However, during GR2, the positive zonal winds appear to have penetrated close to 8°. Note that the largest changes between these two time periods occur at 8° and 10°, but again, the cyclones at GR2 remain on a west-northwest course. Between periods GR2 and GR3, the zonal winds at 6° and 8° shift from an easterly component to a westerly component. It is also between these two periods that the gradually recurving cyclones begin to recurve.

TABLE 5. Zonal winds (top) difference (GR − NR) and time change of these zonal wind differences (bottom) for gradually recurving versus nonrecurving clones during periods GR1, GR2, and GR3 in octant 2. Units are expressed as meters per second.

p (mb)	4°	6°	8°	10°	12°	14°	
Zonal winds for octant 2 gradually recurving cyclones radius from center cyclone							
200	−3.2	−9.4	−4.9	−2.5	1.6	7.2	
350	−6.7	−7.4	−7.3	−2.6	3.1	5.1	period GR1
500	−7.5	−7.1	−3.8	−0.6	5.0	5.7	
200	2.6	−3.6	−0.8	10.6	8.9	13.5	
350	−7.7	−5.4	−0.8	4.9	5.3	5.7	period GR2
500	−11.4	−4.9	−0.6	4.3	3.6	2.9	
200	−0.9	1.8	6.3	12.2	11.0	16.1	
350	−4.8	0.6	4.0	4.3	7.4	9.9	period GR3
500	−10.5	−1.5	3.7	3.2	5.1	7.2	
Zonal wind differences for octant 2 radius from center of cyclone							
200	5.8	5.8	4.1	13.1	7.3	6.3	period GR2 minus period GR1
350	−1.0	2.0	6.5	7.5	2.2	0.6	
500	−3.9	2.2	3.2	4.9	−1.4	−2.8	
200	−3.5	5.4	7.1	1.6	2.1	2.6	period GR3 minus period GR2
350	2.9	6.0	4.8	−0.6	2.1	4.2	
500	0.9	3.4	4.3	−1.1	1.5	4.3	

Tables 4 and 5 show that both the sharply recurving and gradually recurving cyclones had one feature in common: The cyclones did not begin to recurve until positive zonal winds penetrated to within 6° of the cyclone's center in octant 2. Zonal winds beyond 6° could change significantly and have no effect on the direction of the cyclone. Thus, it was shown that prior to beginning recurvature, the largest differences between the wind fields surrounding recurving versus nonrecurving west-northwest-moving cyclones occurred in the zonal component of the wind field 6° to 8° northwest of the cyclone's center. Consequently, the rest of this study will examine details of the zonal component of the wind field throughout the tropospheric wind field in the area 6°–8° north, northwest, and west of the four cyclone stratifications. Specifically, we examine how these winds interact with the cyclone's immediate environment as they moved on their respective tracks.

b. Nonrecurving cyclones

Figures 11 and 12 show the zonal wind profiles at 6° and 8°, respectively, for the three nonrecurving time periods NR1, NR2, and NR3 in octants 1, 2, and 3. As can be seen in Fig. 11, the 6° wind profiles show that zonal winds in all three octants are from an easterly component for all three nonrecurving time periods throughout the troposphere except in octant 1. Here (i.e., octant 1), the zonal winds in the upper troposphere have only a weak westerly component. The 8° wind profiles in Fig. 12 show that the zonal winds in octant 1 for periods NR1 and NR2 are easterly but that westerly zonal winds penetrate into the middle and upper troposphere during period NR3. The wind profiles in octant 2 also show that weak westerly zonal winds have penetrated the 200–400-mb layer at period NR3. The profiles in octant 3 show that the zonal winds for all three nonrecurving periods are from an easterly component throughout the troposphere.

c. Sharply recurving cyclones

Figure 13 shows the zonal wind profiles for sharply recurving cyclones at 6° radius during five time periods in octants 1, 2, and 3. Prior to the beginning of sharp recurvature (i.e., periods SR0, SR1, and SR2), the 6°

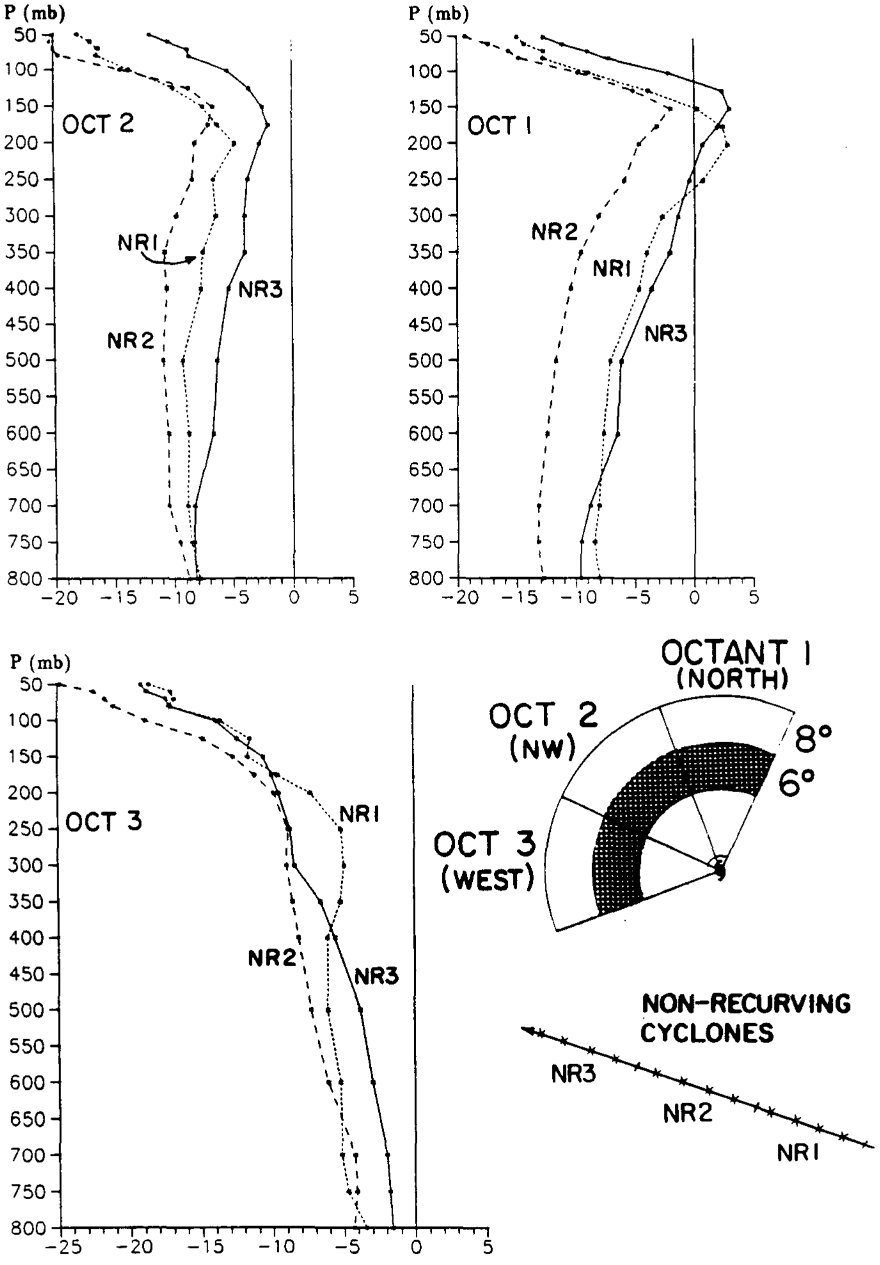

FIG. 11. Zonal wind profiles at 6° (radial distance from the center) for the three nonrecurving periods NR1, NR2, and NR3 in octant 1 (upper right), octant 2 (upper left), and octant 3 (lower left). Units are expressed as meters per second.

zonal wind profiles in octants 1 and 2 show that the zonal winds are from an easterly component in the middle and lower troposphere and from a weak westerly component in the upper troposphere. The SR0, SR1, and SR2 zonal winds in octant 3 are from an easterly component at all levels of the troposphere. The zonal profiles of the sharply recurving cyclones during these three periods prior to the beginning of recurvature are similar to nonrecurving cyclone profiles (cf. Fig. 11) except for the positive zonal winds in the upper troposphere in octants 1 and 2. Since these relatively weak positive zonal winds occur during all three periods prior to beginning sharp recurvature, they are likely the result of seasonal climatology and are not believed to be directly related to the sharp recurvature process.

Significant changes in the zonal wind fields take place in all three octants during period SR3. During the previous three periods, when the cyclones were moving west-northwest, zonal winds in the middle and upper troposphere in all three octants were from an easterly

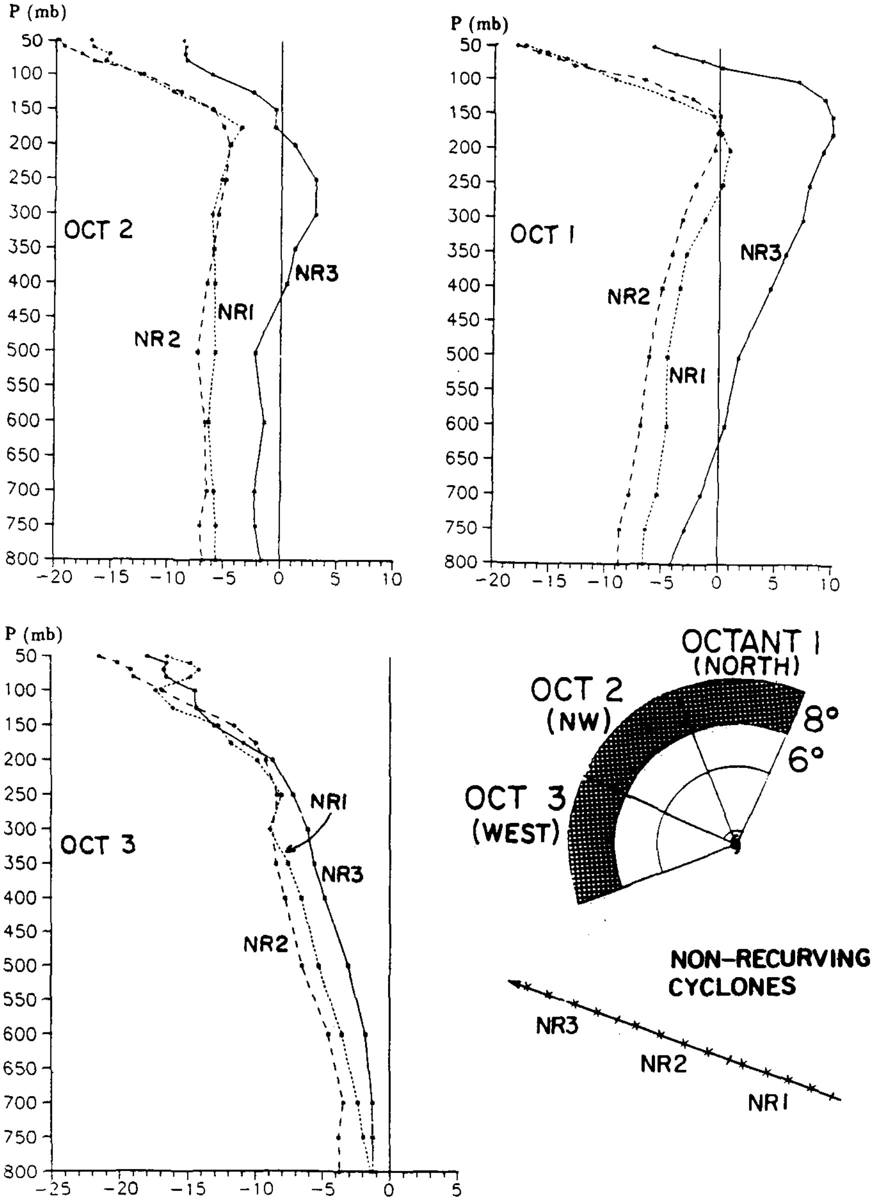

FIG. 12. Zonal wind profiles at 8° for the three nonrecurving periods NR1, NR2, and NR3 in octant 1 (upper right), octant 2 (upper left), and octant 3 (lower left). Units are expressed as meters per second.

or weak westerly component. As the cyclones begin to recurve sharply during period SR3, zonal winds in the middle and upper troposphere in all three octants shift to strong westerly components. As shown in Table 6, changes in the zonal wind between SR2 and SR0 are minimal. However, once the cyclones begin to recurve (i.e., SR3) the differences (SR3 − SR2) become quite large. As the cyclones continued to recurve sharply to the northeast (period SR4), zonal profiles in all three octants become increasingly sheared from the west. The cyclone direction changes between these time periods could also be interpreted as motion acceleration to the northeast.

Zonal wind profiles at 8° for sharply recurving cyclones during five periods are shown in Fig. 14. The profiles in octants 1 and 2 for the first two sharply recurving time periods (SR0 and SR1) show zonal winds from an easterly component in the middle and lower troposphere but from a weak westerly component in the upper troposphere. Note that the profiles at this radius for these two time periods show characteristics similar to those of the nonrecurving cyclones during periods NR1 and NR2 (i.e., Fig. 12). The changes that occur during period SR2 at 8° are similar to those that occur between periods SR2 and SR3 at 6°. The mid- and upper-tropospheric zonal winds in octants 1 and

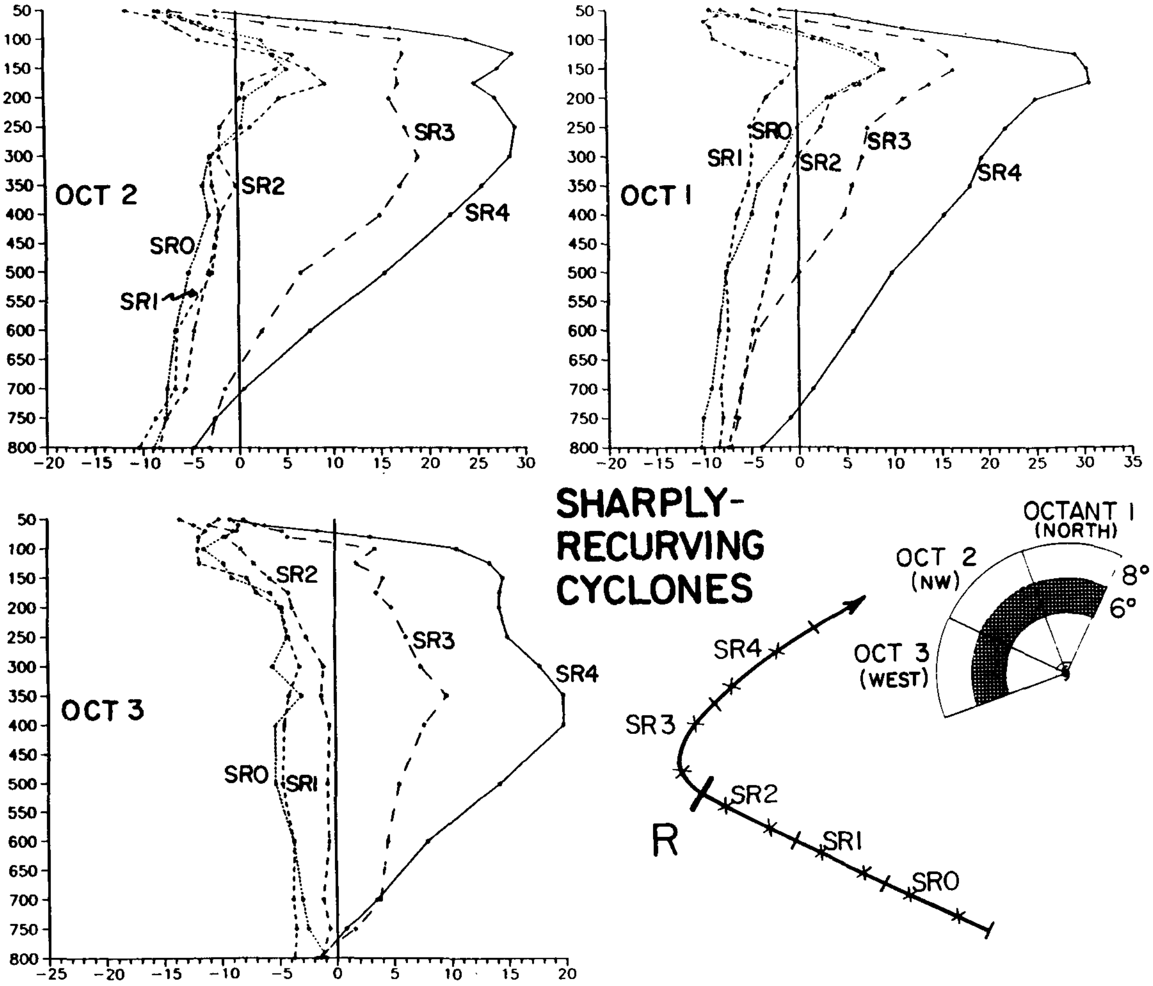

FIG. 13. Zonal wind profiles at 6° during the five sharply recurving time periods in octant 1 (upper right), octant 2 (upper left), and octant 3 (lower left). Units are expressed as meters per second.

2 at 8° shift from an easterly component to a westerly component between periods SR1 and SR2 (Table 7). Whereas the zonal component of this wind is in excess of +10 m s^{-1} in the middle and upper troposphere during period SR2, the cyclones remained on a westerly course. As the cyclones begin to recurve during periods

TABLE 6. Temporal changes of the zonal wind during sharply recurving periods SR3 versus SR2 (24-h change), and SR2 and SR0 (48-h change). The changes were observed at 6° from the center of the cyclone in octants 1, 2, and 3. Units are in meters per second.

	Sharply recurving cyclones zonal wind differences at 6° radius					
	Octant 3 (west)		Octant 2 (northwest)		Octant 1 (north)	
p (mb)	SR3 − SR2	SR2 − SR0	SR3 − SR2	SR2 − SR0	SR3 − SR2	SR2 − SR0
100	11.8	3.2	17.1	2.6	10.5	0.9
150	9.9	3.3	12.6	−1.1	7.4	−0.2
200	8.7	1.1	15.6	−0.5	7.4	0.2
250	8.7	1.7	19.4	−2.3	4.9	2.5
300	8.4	4.5	20.8	1.0	6.8	1.6
350	11.0	1.7	17.1	3.5	6.9	2.9
400	8.3	4.7	16.8	1.1	7.0	2.7
500	6.2	4.5	9.8	2.0	3.3	4.4
600	5.1	3.1	7.1	1.9	0.6	3.5
700	5.0	1.8	4.1	1.9	0.0	3.1
800	−0.4	−0.5	5.2	0.6	0.3	2.8

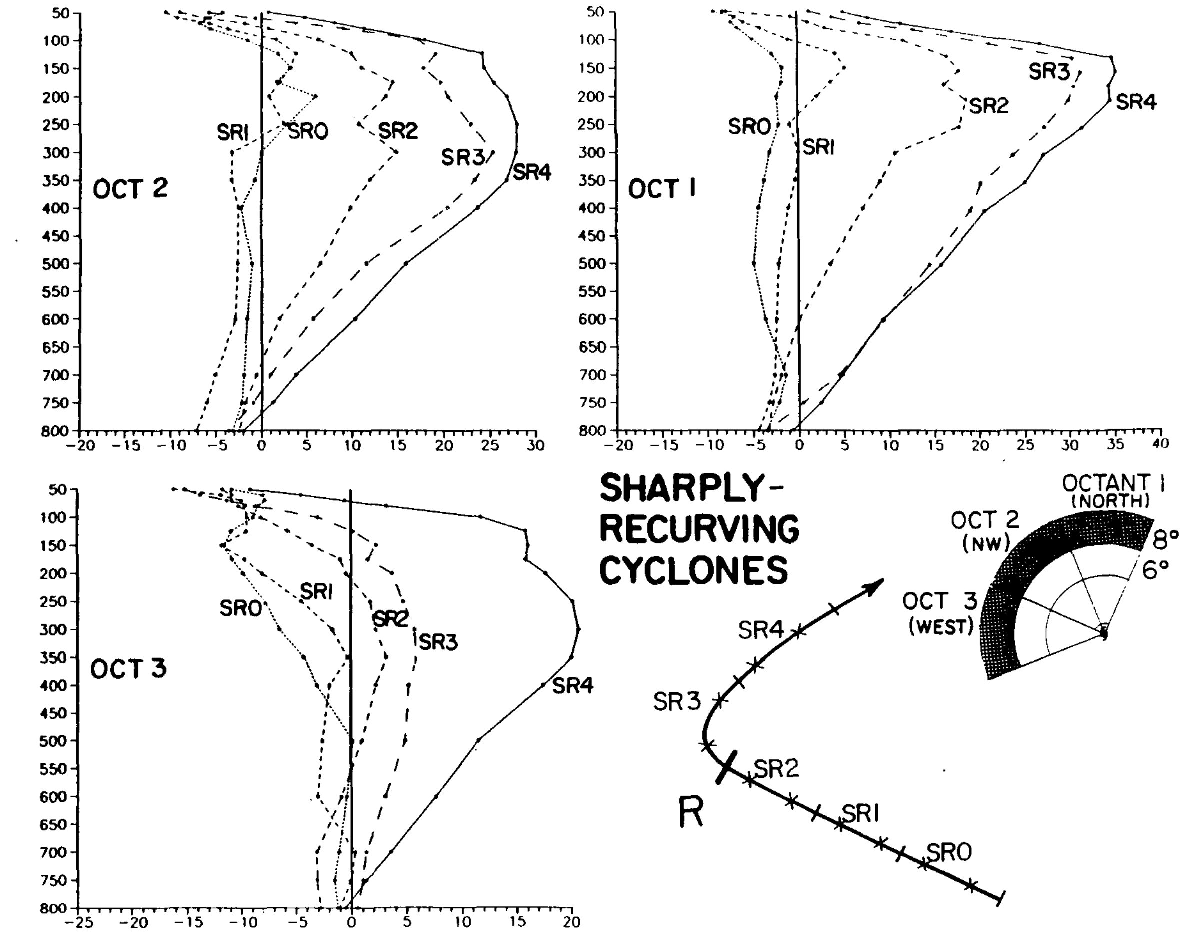

FIG. 14. Zonal wind profiles at 8° during the five sharply recurving periods in octant 1 (upper right), octant 2 (upper left), and octant 3 (lower left). Units are expressed as meters per second.

SR3 and SR4, the zonal profiles at 8° become even more strongly sheared from the west.

d. Gradually recurving cyclones

Figure 15 and Fig. 16 show the 6° and 8° zonal wind profiles for the six gradually recurving time periods in octants 1, 2, and 3. Prior to the beginning of gradual recurvature (periods GR1 and GR2), zonal profiles in octants 1, 2, and 3[3] at 6° show winds from an easterly component throughout the troposphere. As the cyclones gradually begin to recurve during period GR3, zonal winds in the middle and upper troposphere in octant 2 and in the midtroposphere in octant 3, shift from an easterly to a westerly component. However, zonal winds in octant 1 remain negative in nearly all levels of the troposphere. The changes in the zonal wind fields at specific heights between periods GR2 and GR3 are summarized in Table 8. As the cyclones continued to recurve during periods GR4, GR5, and GR6, zonal

TABLE 7. Changes in the zonal wind between sharply recurving time periods SR2 and SR1 (24-h change), and SR1 and SR0 (24-h change). The differences are taken at 8° from the center of the cyclone in octants 1 and 2. Units are in meter per second.

Sharply recurving cyclones zonal wind differences at 8° radius

p	Octant 2 (northwest)		Octant 1 (north)	
(mb)	SR2 − SR1	SR1 − SR0	SR2 − SR1	SR1 − SR0
100	4.6	3.2	12.7	3.9
150	7.9	−0.2	12.6	6.9
200	12.8	−5.1	16.5	4.4
250	8.2	−0.4	18.8	1.2
300	18.0	−3.1	10.7	3.2
350	15.2	−2.6	9.3	3.5
400	12.3	−0.3	8.2	3.3
500	9.2	−1.6	5.7	2.8
600	4.9	−1.3	2.5	1.3
700	4.5	−3.1	−0.7	1.2
800	4.7	−4.0	−1.0	0.8

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[3] The data at period GR1 at 6° and 8° in octants 1 and 2 were limited to two to five observations. No data were available at these radii in octant 3.

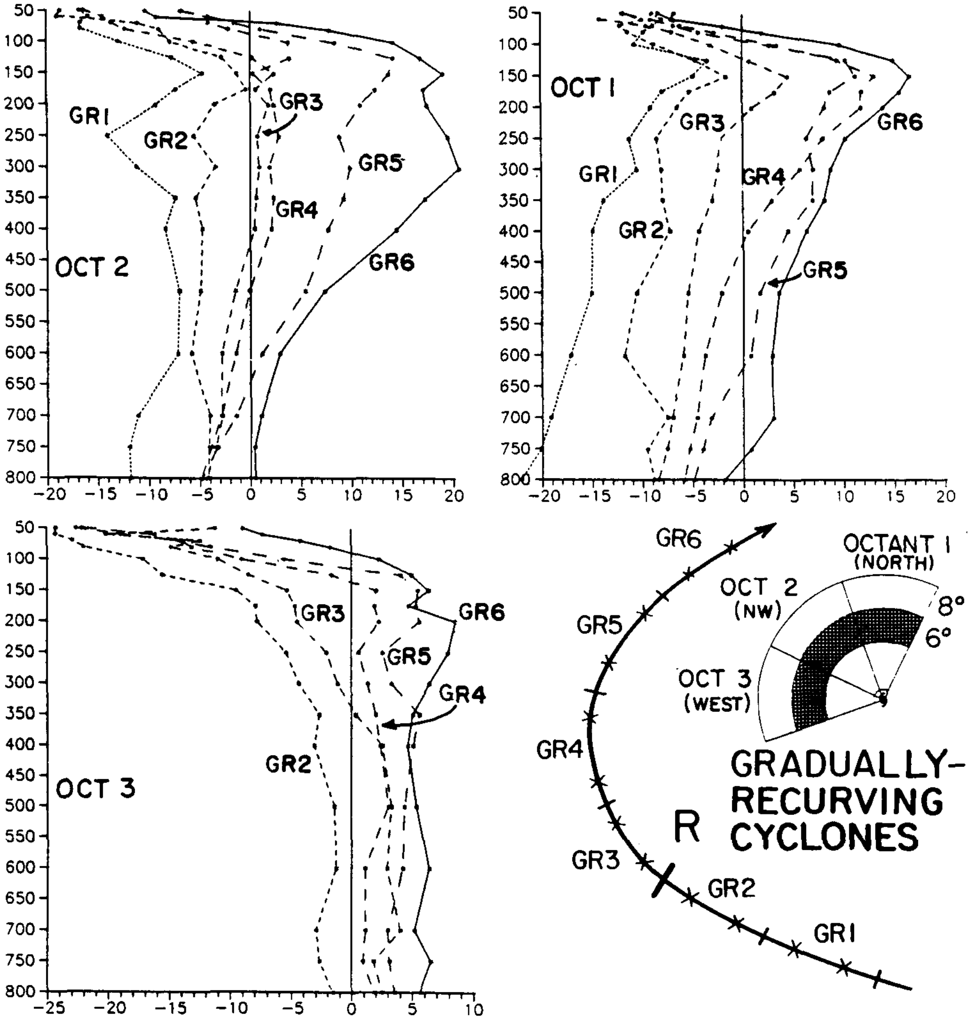


FIG. 15. Zonal wind profiles at 6° during the six gradually recurving periods in octant 1 (upper right), octant 2 (upper left), and octant 3 (lower left). Units are expressed as meters per second.

winds in the middle and upper troposphere became positive and increased gradually in speed in all three octants.

TABLE 8. Gradually recurving zonal wind fields at 6° during periods GR2 and GR3 in octants 2 and 3. Note that the zonal winds shift from an easterly to a westerly component between periods GR2 and GR3. Units are meters per second.

p (mb)	Octant 3 (west) GR3	Octant 3 (west) GR2	Octant 2 (northwest) GR3	Octant 2 (northwest) GR2
100	−11.0	−17.2	−5.6	−7.9
150	−5.3	−9.5	2.3	−1.3
200	−4.5	−7.8	1.8	−3.6
250	−2.1	−5.4	0.7	−5.6
300	−1.1	−4.3	0.9	−3.5
350	0.3	−2.7	0.6	−5.4
400	2.6	−3.1	0.5	−4.7
500	3.3	−1.4	−1.5	−4.9
600	2.9	−1.3	−2.8	−5.9
7800	4.0	−2.9	−2.8	−4.1
800	2.5	−1.6	−4.4	−4.2

Zonal wind profiles at 8° radius for the six gradually recurving time periods are shown in Fig. 16. The zonal profiles for period GR1 are from an easterly component throughout the troposphere in octants 1 and 2. During period GR2, zonal winds in octants 1 and 3 are still from an easterly component throughout most of the troposphere, whereas zonal winds in octant 2 have become neutral. As the cyclones begin gradual recurvature during GR3, zonal winds in the middle and upper troposphere in octants 1 and 2 shift to westerly components, while only midtropospheric zonal winds shift to a westerly component in octant 3. As the cyclones continue to recurve to the north and northeast during the remaining three periods (GR4–GR6), zonal winds in all three octants become positive and gradually increase in speed throughout the troposphere.

e. Left-turning cyclones

Until now, most of the discussion of tropical cyclones has dealt with cyclones that turn to the right of their

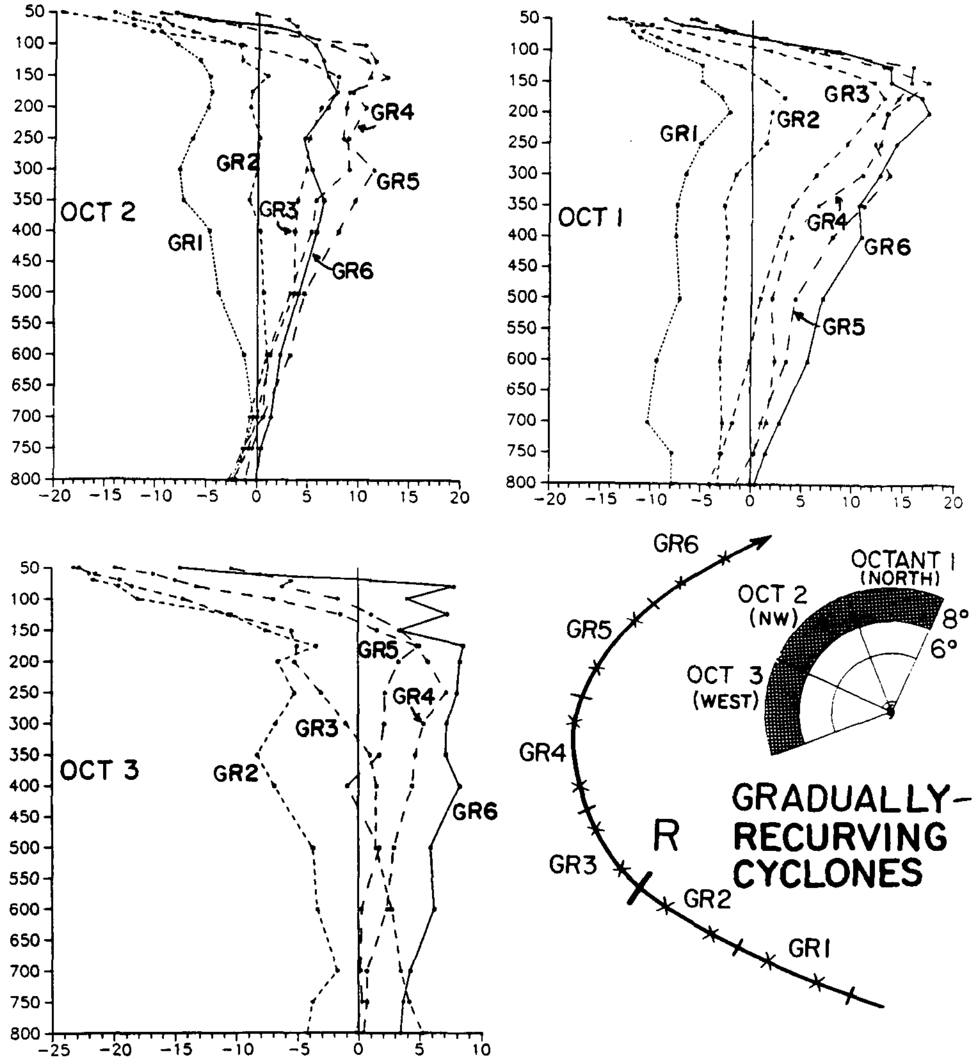


FIG. 16. Zonal wind profiles at 8° during the six gradually recurving periods in octant 1 (upper right), octant 2 (upper left), and octant 3 (lower left). Units are expressed as meters per second.

previous west-northwest track. In this section, zonal and vector (i.e., $u + v$) wind profiles are employed to show how environmental wind fields associated with a north-northwest-moving cyclone can change with time to cause a cyclone to resume a west-northwest course.

Figure 17 shows zonal wind profiles at 6° for the four left-turning time periods (LT3–LT6) in octants 1, 2, and 3. The 6° zonal wind profiles in octant 1 during these four periods are fairly similar to each other. However, important differences exist in the upper troposphere as to the pressure level at which the zonal wind shifts from an easterly to a westerly component. During periods LT3 and LT4, as the cyclones were moving slowly north-northwest, the changeover from easterlies to westerlies in octant 1 occurred at approximately 375 mb and at approximately 350 mb, respectively; as the cyclone turned to the left and resumed a west-northwest track (i.e., periods LT5 and LT6), the changeover to westerlies in octant 1 occurred higher up, at the approximately 300- and 250-mb levels, respectively.

The zonal wind profiles in octant 2 show that positive zonal winds existed in the upper troposphere during three of the four periods. However, these positive zonal winds are weak (<5 m s^{-1}) and are believed to play no significant role in the north to west direction change. Zonal profiles in octant 3 show that zonal winds at 6° change considerably during each of the four left-turning time periods. The zonal winds during period LT3 are negative throughout the middle and lower troposphere but are strongly sheared above the 350-mb level, changing from -11 m s^{-1} at 350 mb to $+4$ m s^{-1} at the 200-mb level. The LT4 zonal profile shows that the winds in the middle and upper troposphere shifted from an easterly component to a westerly component

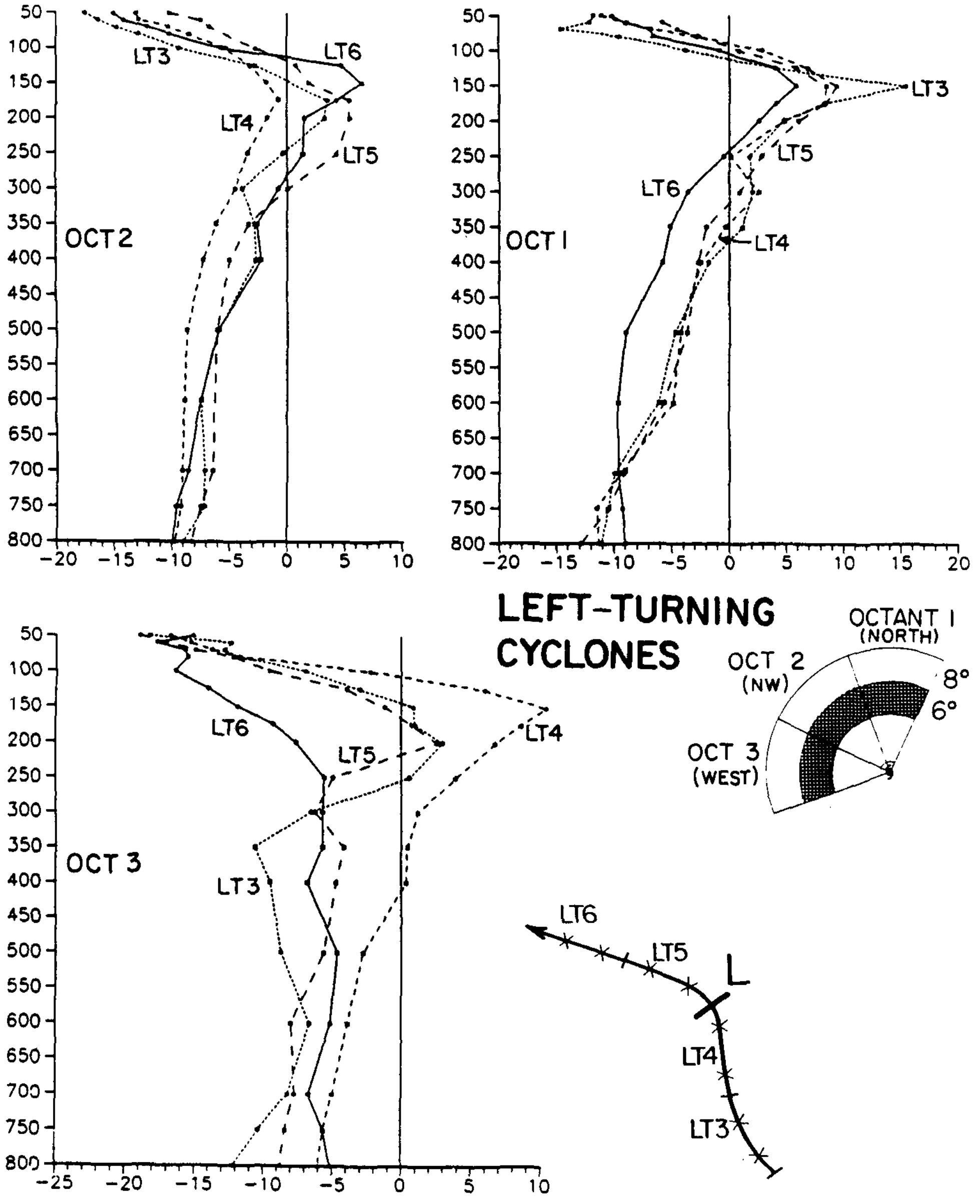


FIG. 17. Zonal wind profiles at 6° during the four left-turning cyclone periods in octant 1 (upper right), octant 2 (upper left), and octant 3 (lower left). Units are expressed as meters per second.

between periods LT3 and LT4. As summarized in Table 9, the zonal wind differences between periods LT4 and LT3 show an 11 m s^{-1} increase at 350 mb, a 7 m s^{-1} increase at 500 mb, and a 10 m s^{-1} increase at 175 mb. As the cyclones turned back toward the west-northwest during period LT5, the zonal winds shifted back to an easterly component once again with only weak westerlies at the 200-mb level. The LT6 zonal profile shows that the zonal winds at all levels, including the upper troposphere, are from an easterly component during this period.

Figure 18 shows zonal wind profiles at 8° radius during the four left-turning time periods for octants 1, 2, and 3. The 8° zonal wind profiles in octant 1 are nearly identical to each other, each profile showing weak easterlies below the 500-mb level. Above this level, zonal winds become positive and are sheared from the west. Zonal winds in octant 2 show relatively little shear in the vertical. The four left-turning zonal profiles in octant 3 are also similar to each other except in the upper troposphere. When the cyclones are moving north during periods LT3 and LT4, the zonal profiles are sheared from the west above the 250-mb level. However, once the cyclones return to a west-northwest course (LT5 and LT6), shear in the upper troposphere dissipates.

TABLE 9. Zonal winds (top) and temporal changes in the zonal wind (bottom) at 6° radius in octant 3 between the four left-turning changes in the cyclone time periods.

	Zonal winds octant 3 (west) at 6°			
p (mb)	LT3	LT4	LT5	LT6
100	−6.9	−2.2	−9.6	−16.4
150	0.9	10.4	−1.2	−11.9
200	3.0	6.8	2.6	−7.6
250	0.6	3.9	−5.0	−5.6
300	−6.6	1.2	−6.3	−5.7
350	−10.6	0.4	−4.2	−5.7
400	−9.5	0.4	−4.7	−6.8
500	−8.7	−2.8	−5.6	−4.6
600	−6.6	−3.9	−8.0	−5.1
700	−8.3	−5.0	−7.7	−6.7
800	−12.2	−6.0	−8.8	−5.2

	Zonal wind differences between time periods		
p (mb)	LT4 − LT3	LT5 − LT4	LT6 − LT5
100	4.7	−7.4	−6.8
150	9.5	−11.6	−10.7
200	3.8	−4.2	−10.2
250	3.3	−8.9	−0.6
300	7.8	−7.5	0.6
350	11.0	−4.6	−1.5
400	9.9	−5.1	−2.1
500	5.9	−2.8	1.0
600	2.7	−4.1	2.9
700	3.3	−2.7	1.0
800	6.2	−2.8	3.6

To get a better understanding of why the left-turning cyclones first moved north and then turned left, vector wind profiles extending from 4° to 14° radius to the north of the cyclone are shown in Figs. 19a–d. During period LT3 (Fig. 19a), wind profiles show strong west to southwest winds in the upper troposphere at 6° and 8°, with westerly winds in excess of 20 m s^{-1} occurring at the 150–200-mb layer at 8°. What is most unusual about these profiles is that the westerly winds do not continue to increase with distance from the cyclone. Rather, they decrease dramatically and shift back to easterlies through much of the upper troposphere at 10° radius. Beyond the 10° radius, the mid- and upper-tropospheric westerlies return but are generally weak, ranging from 5 to 10 m s^{-1}. The anomalously strong westerly winds at 6° and 8° are believed to be associated with a tropical upper-tropospheric trough (Sadler 1976) of tropical or midlatitude origin.

The wind profiles for period LT4 in octant 1 (Fig. 19b) show that the upper-tropospheric westerlies at 6° and 8° have decreased, while the easterlies, which were previously located at 10° during period LT3, have shifted to westerlies. Note that the upper-level circulation that was present at period LT3 is no longer visible in the wind fields during period LT4. We believe that the upper-tropospheric trough has either moved off toward the northeast or has weakened by period LT4.

The wind profiles in period LT5 for octant 1 (Fig. 19c) show that the upper-tropospheric westerly winds at 6° continue to weaken. In addition, the winds in the layer between 300 and 500 mb at this radius have backed with time. Meanwhile, the west winds at 8° have increased again but do not prevent the cyclone from resuming a west-northwest course. The wind profiles during period LT6 (Fig. 19d) are very similar to the LT5 profiles except that the upper-tropospheric westerlies at 6° continue to weaken and shift back to easterlies.

f. Implications of results

The environmental wind fields at 6° radius in octants 2 and 3 are critical for distinguishing between conditions for nonrecurvature versus beginning recurvature. The time periods for west-northwest-moving nonrecurving cyclones as well as sharply recurving and gradually recurving cyclones prior to beginning recurvature all had one feature in common: the zonal winds in the middle and upper troposphere (300 mb and above) in octants 2 and 3 were from an easterly component. The cyclones that began to recurve or were moving on a course other than west-northwest (i.e., sharply recurving and gradually recurving cyclones after beginning recurvature during SR3 and 4, and GR3, 4, 5, and 6) all had positive zonal winds in the midtroposphere in these octants.

The 6° zonal profiles also identified characteristics that differentiated the beginning of sharp recurvature from the beginning of slow recurvature. Tropical cyclones began sharp recurvature when positive zonal winds penetrated the middle and upper troposphere 6° to the west, northwest, and north of the cyclone. Tropical cyclones typically began slow recurvature when weak positive zonal winds penetrate into the middle and upper troposphere in octant 2 and into the midtroposphere in octant 3.

The zonal wind fields at 8° radius are important for identifying tropical cyclones that might recurve. Prior to beginning sharp recurvature, the middle- and upper-tropospheric zonal winds at 8° in octants 1 and 2 changed from an easterly component to a westerly component. This same change was found for the gradually recurving cyclones except that the zonal winds tended to change from easterly to neutral in octant 2.

The following list summarizes the conditions that are necessary for recurvature.

- A tropical cyclone will remain on a west-northwest course for at least 36 h if the zonal winds in the midtroposphere at 8° radius to the north, northwest, and west of the storm's center are from an easterly component and (westerly) zonal winds in the upper troposphere do not exceed +5 m s^{-1}.
- A tropical cyclone will likely begin sharp recurvature within 12 h if the zonal winds in the middle and upper troposphere at 8° radius to the north and northwest of the storm's center shift from an easterly component to a westerly component.

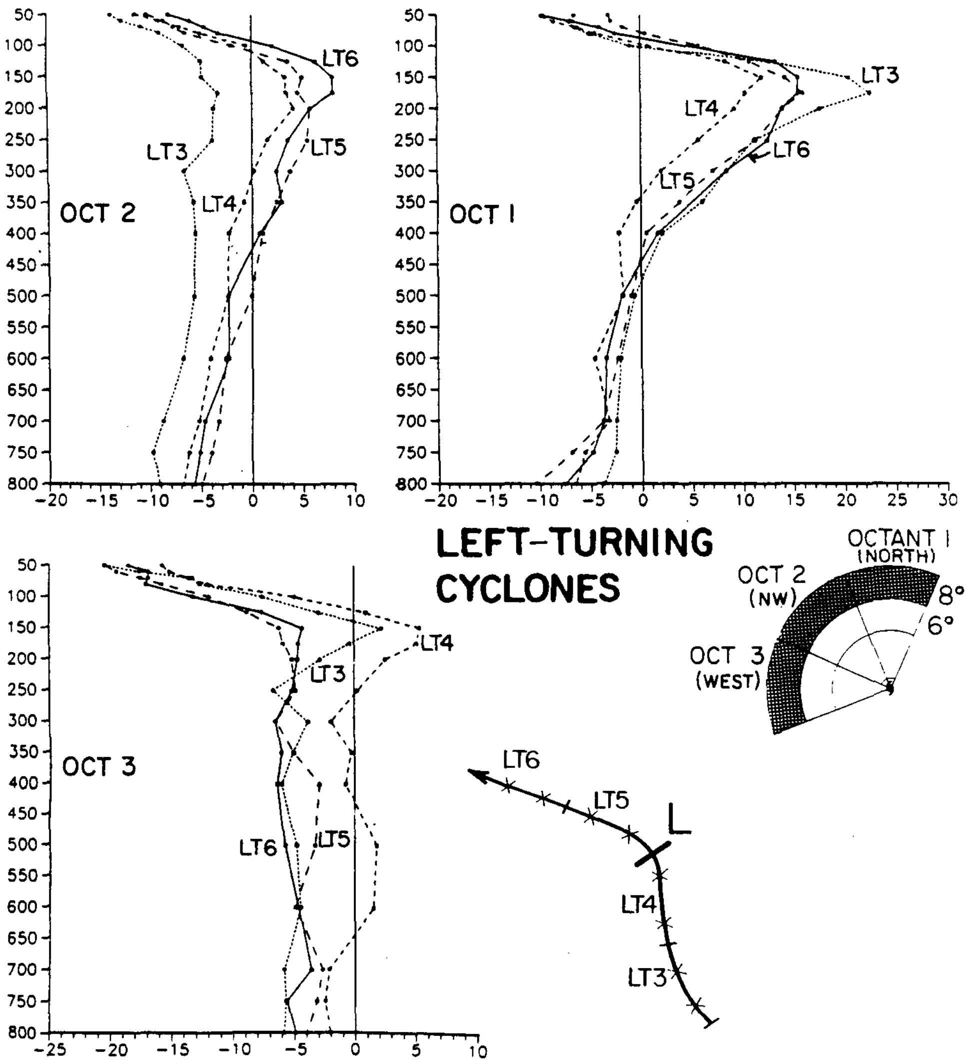


FIG. 18. Zonal wind profiles at 8° during the four left-turning cyclone periods in octant 1 (upper right), octant 2 (upper left), and octant 3 (lower left). Units are expressed as meters per second.

- A tropical cyclone could be expected to begin gradual recurvature within 12 h if the zonal winds at 8° radius to the northwest of the storm's center shift from an easterly component to a weak westerly component or become neutral throughout the middle and upper troposphere.
- A tropical cyclone will actually begin sharp recurvature when the zonal winds in the middle and upper troposphere 6° to the north, northwest, and west of the storm's center shift from an easterly component to a westerly component.
- A tropical cyclone will actually begin gradual recurvature when the zonal winds in the middle troposphere 6° to the northwest and west of the storm's center shift from an easterly component to a westerly component.

An additional tendency for both sharply recurving and gradually recurving cyclones is as follows. If the 200–500-mb-layer average zonal wind component at 6° radius to the northwest of the cyclone is from an easterly component, then the cyclone is moving on a west-northwest course; if, however, layer-averaged winds are from a westerly component, then the cyclone has already begun to recurve. Figure 20 shows the 200–500-mb zonal average winds at 6° and 8° radius for sharply recurving, gradually recurving, and nonrecurving cyclones during periods 1, 2, and 3. As can be seen, the 200–500-mb-layer zonal average flow at 6° for the sharply recurving and gradually recurving cyclones is from an easterly component prior to beginning recurvature. Once both the gradually recurving and sharply recurving cyclones begin to recurve, the layer-average zonal component shifts to the west. It is important to note that this same tendency does not apply at 8°.

Regarding motion changes for left-turning cyclones, during the first two time periods, LT3 and LT4, the

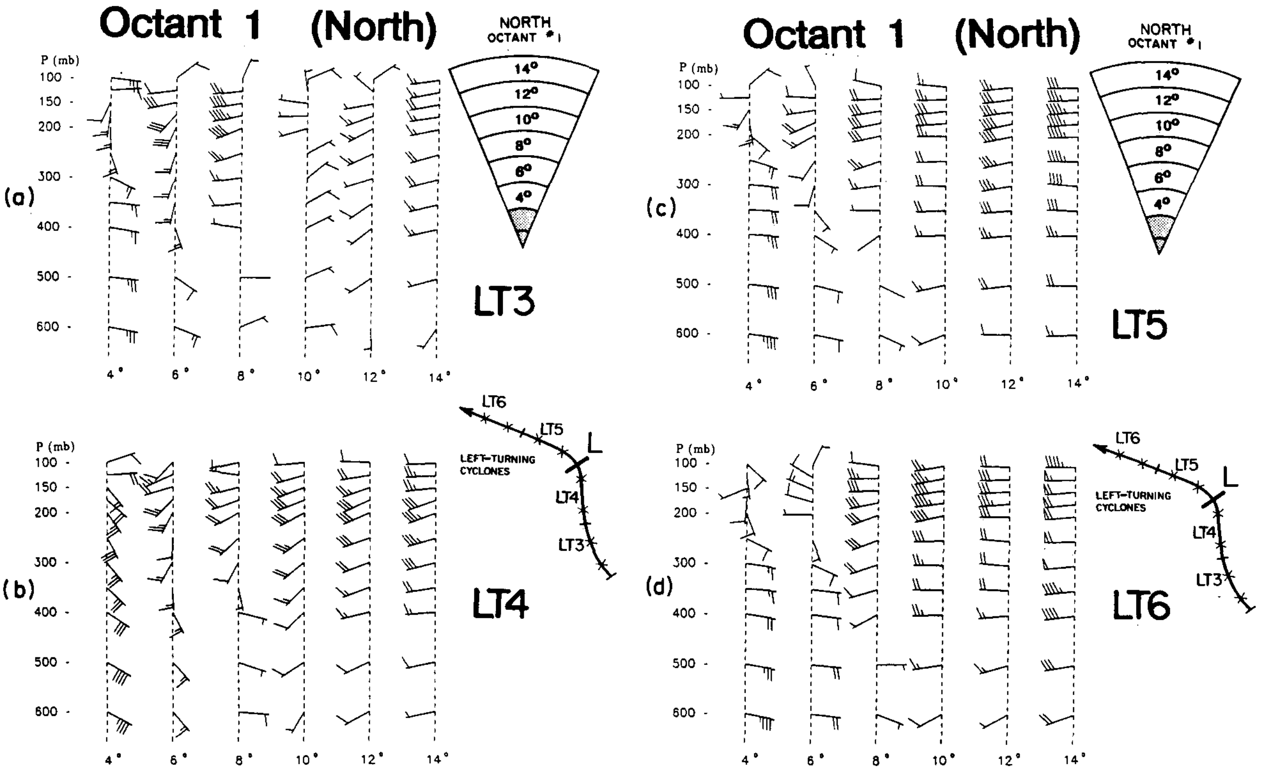


FIG. 19. (a)–(d) Vector wind profiles showing mid- and upper-tropospheric wind fields extending from 4° through 14° in octant 1 for each of the four left-turning time periods. Wind barbs plotted in standard meteorological format (kt).

cyclones were moving on a north-northwest course. During these time periods, strong southwesterly flow was evident in the middle through the upper troposphere at 6° and 8° radius in octant 1 (Fig. 19). When these cyclones resumed a west-northwest course (periods LT5 and LT6), the strong southwesterlies that were in octant 1 at 6° radius weakened and shifted back to an easterly component between 250 and 350 mb. In addition, the westerlies that were in octant 3 during the first two time periods have shifted back to easterlies (Fig. 18). It is likely that an upper-level trough of tropical or midlatitude origin is responsible for the anomalous westerly winds to the north and west of the cyclone. These winds interact with the circulation of the cyclone in such a way to cause the cyclone to move on a northerly course. However, once this feature bypasses to the north of the cyclone, easterly flow resumes and the cyclone takes on a west-northwest course.

A general characteristic of nearly all cyclone stratifications that moved westward during some portion of their lifetime is that they had negative (i.e., easterly) zonal winds throughout the 300–500-mb layer to the north, northwest, and west at 6° radius. Conversely, tropical cyclones that were either recurving or moving north or northeast tended to have positive zonal wind through the 300–500-mb layer in these same octants. Table 10 provides a summary of these results.

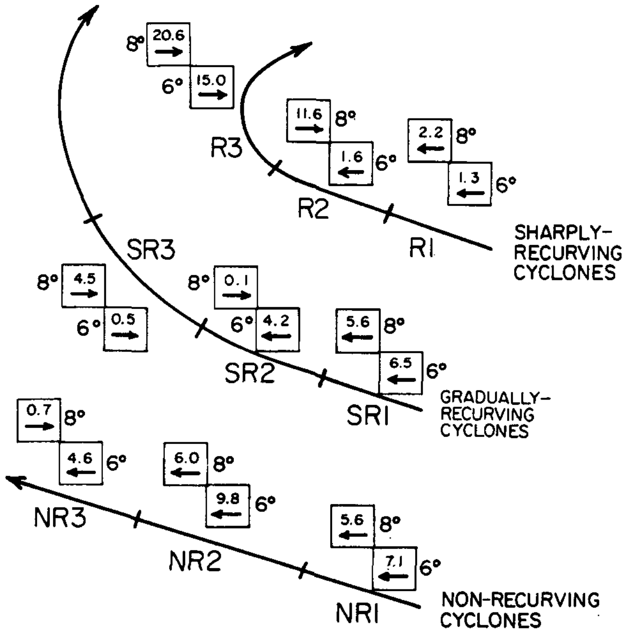


FIG. 20. Layer-average zonal winds for 200–500 mb at 6° and 8° radius in octant 2 for sharply recurving (top), gradually recurving (middle), and nonrecurving (bottom) cyclones at periods 1, 2, and 3. The arrow in each box represents direction. The small number above the arrow represents speed (m s^{-1}).

TABLE 10. Summary data for sign of zonal wind components in the 300–500-mb layer for specific stratifications, time periods, and octants.

Cyclone time periods	Was the zonal component of the wind, 6° from the cyclone's center, positive *at any level* in the 300–500-mb layer in octants 1, 2, or 3?	Was the cyclone moving on a west-northwest course (260°–320°) at this time?
Nonrecurving cyclones		
NR1	No	Yes
NR2	No	Yes
NR3	No	Yes
Sharply recurving cyclones		
SR0	No	Yes
SR1	No	Yes
SR2	No	Yes
SR3	Yes	No (moving N)
SR4	Yes	No (moving NE)
Gradually recurving cyclones		
GR1	No	Yes
GR2	No	Yes
GR3	Yes	No (moving NNW)
GR4	Yes	No (moving N)
GR5	Yes	No (moving NNE)
GR6	Yes	No (moving NE)
Left-turning cyclones		
LT3	Yes	No (moving NNW)
LT4	Yes	No (moving NNW)
LT5	Yes*	Yes
LT6	No	Yes

* At period LT5, the zonal wind at the 300-mb level in octant 1 was positive but the speed was only 0.9 m s^{-1}.

TABLE 12. Octant 2 radial belt zonal wind differences (m s^{-1}) for rejection of the null hypothesis that the two motion category populations are the same at the 0.05 level of significance.

Stratification	6° 500 mb	6° 200 mb	8° 500 mb	8° 200 mb
Sharply recurving minus straight motion (R2 − NR2)	2.0	3.0	1.5	2.2
Slow recurvature minus straight motion (SR2 − NR2)	2.9	4.3	1.1	1.4
Left turning minus north motion of sharp recurvature (L4 − R3)	2.3	3.4	2.0	3.0
Left turning minus north motion of slow recurvature (L4 − SR3)	3.1	4.7	2.6	4.8

4. Sampling reliability

There are a myriad of unrepresentative measurements (small and large) and instrumental inconsistencies that can occur in a large collection of rawinsonde data, especially in data collected near the centers of tropical cyclones. Some major data inadequacies arise due to the following. 1) Variable cyclone structure and surrounding flow. Every storm is unique and different in its characteristic, intensity, size, areal coverage of outer winds, etc. 2) Natural variability within storms due to convective features, etc. Winds are gusty and often unrepresentative when taken near convective-scale features. 3) Measurement inconsistencies. Every instrument has characteristic limitations and error sources. The sensing, transmitting, receiving, and processing of atmospheric data can sometimes introduce unrepresentative steering flow features. 4) Compositing limitations. Even if data were 100% accurate, some positioning and temporal unrepresentativeness are introduced into each composite analysis. A very large dataset is required to overcome or at least significantly diminish these inherent inconsistencies.

Data spread. To assess the degree of reliability and significance of the composite data, several basic statistical analyses were performed on the wind data composites. These tests were to determine the degree of scatter for individual parameter values about their means. The characteristic standard deviation of zonal or meridional winds in individual 2° radial belts–octants is about 4 m s^{-1} at 500 mb and about 6 m s^{-1} at 200 mb. Table 11 gives a typical example of the

TABLE 11. Number of rawinsonde reports at 500 and 200 mb in octant 2 of radial belts 6° and 8° for the four composite motion categories at the time period just before direction change.

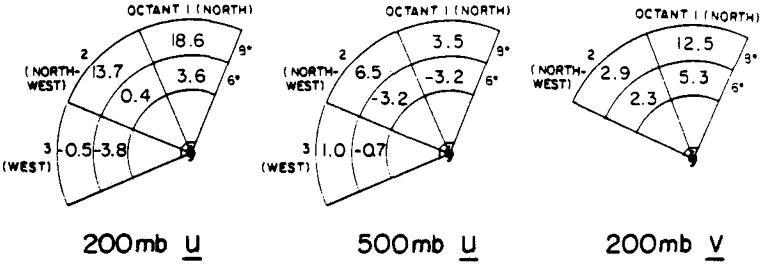
Stratification	Average number of soundings 6°	Average number of soundings 8°
Sharply recurving (R2)	18	35
Slowly recurving (SR2)	8	12
Nonrecurving (NR2)	134	169
Left turning (L4)	19	25
Sharp recurving motion north (R3)	38	46
Slow recurving moving north (SR3)	12	18

TABLE 13. Differences in octant 2 zonal winds (m s^{-1}) at 6° and 8° radial bands at 200 and 500 mb in comparative time periods before turning motion.

Differences between zonal winds	6° 500 mb	6° 200 mb	8° 500 mb	8° 200 mb
Sharply recurving minus straight motion (R2 − NR2)	8.1	24.8	13.0	18.2
Slow recurvature minus straight motion (SR2 − NR2)	8.2	5.0	7.9	4.1
Left turning minus north motion of sharp recurvature (L4 − R3)	−16.8	−18.8	−13.7	−17.1
Left turning minus north motion of slow recurvature (L4 − SR3)	−8.0	−2.1	−6.9	−3.1

Recurvature Number Equation

$$\sum_{i=\text{Oct }1}^{3} \frac{(u_{8^\circ}+u_{6^\circ})}{2}\,200\text{mb} + \sum_{i=\text{Oct }1}^{3} \frac{(u_{8^\circ}+u_{6^\circ})}{2}\,500\text{mb} + \sum_{i=\text{Oct }1}^{2} \frac{(v_{8^\circ}+v_{6^\circ})}{2}\,200\text{mb}$$



RN value calculated for the sharply-recurving time period of SR2:

[(18.6 + 3.6) + (13.7 + 0.4) + ((-0.5) + (-3.8))

+ (3.5 + (-3.2)) + (6.5 + (-3.2)) + (1.0 + (-0.7))

+ (12.5 + 5.3) + (2.9 + 2.3) 1/2 = ~ 30

FIG. 21. The equation used to calculate the RN values. An example of how the RN value is calculated is shown using wind fields from the sharply recurving dataset at period SR2.

number of rawinsonde reports in the 6° and 8° radial belts of octant 2 (northwest) for the period just before turning motion. Soundings vary from 8 to 169. Table 12 shows the individual octant and radial belt zonal wind differences one needs between different turning motion classes, such that one could reject the null hypothesis (at a 0.05 level of significance) that zonal winds in each group are the same. The observed mean zonal wind differences for the various different classes of turning motion are typically much larger than the wind difference shown in this table. For instance, the octant 2 (northwest of center) 6° and 8° radial belt mean zonal wind differences (m s^{-1}) between two rawinsonde composites of the time period (just before turning motion) are given in Table 13. These observed wind differences are much larger than the values shown in Table 12. We are confident that our measured individual octant radial band averages represent real differences and not sampling noise, particularly when we combine levels between 500 and 200 mb and use meridional winds at 200 mb to form the recurvature number (described in the following section).

5. Forecasting cyclone recurvature using a combination of 500- and 200-mb winds

The results of the previous section were adapted to a recurvature forecast scheme based on the mid- and upper-tropospheric wind fields observed northwest of the cyclone. This forecasting scheme is relatively simple and is designed to work using data available from standard computer analysis and prognostic wind fields. As noted in the preceding discussion, when westerlies penetrated to within a critical distance of the center of a cyclone, recurvature begins. It is proposed that by summing the zonal components of the wind fields at 500 and 200 mb and the 200-mb meridional component[4] of the wind at the same locations, a numerical value of the recurvature potential can be obtained. Conceptually, this derived numerical value, here termed the "recurvature number" (RN), would remain negative as long as the cyclone is embedded in easterly flow for the 500- and 200-mb levels. As westerlies start to appear northwest of the cyclone, the RN values tend to become less negative with time. As the westerlies increase in speed and penetrate closer to the cyclone, values become positive and should indicate a

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[4] The 200-mb meridional wind fields are used in the forecast scheme to help differentiate sharply recurving cyclones from gradually recurving cyclones after they have begun to recurve. The environmental winds north and northwest of sharply recurving cyclones were strongly from the southwest, while the winds north and northwest of gradually recurving cyclones were from a more west-southwesterly direction and were weaker in magnitude.

likely change in cyclone direction in the near future. An example calculation of an RN value is shown in Fig. 21.

Figure 22 shows mean RN values for sharply recurving, gradually recurving, left-turning, and nonrecurving time periods described in this study. Cyclones moving on a westerly course typically had negative RN values; when the cyclones were moving north or northeast, RN values were positive. Recurvature numbers of sharply recurving cyclones increased rapidly as the cyclones were recurving, while the values increased only gradually when the gradually recurving cyclones were recurving. Nonrecurving cyclones had varying, generally negative RN values during all three time periods.

Exceptions to the negative RN values for west-northwest motion occurred for two time periods: sharply recurving time period SR2, and left-turning period LT5. At period SR2, an RN value of +30 was computed, whereas prior to SR2, the RN values were negative. This sharp change indicates that environmental winds north and west of the cyclone take on positive components (zonal and meridional), thereby indicating that a possible change in the direction of the cyclone might occur. The RN value for the left-turning cyclones for period LT5 was also positive (i.e., +11), but prior to this time period, when the cyclones were moving north (period LT4), the RN value was larger in magnitude. As the left-turning cyclones went from a northerly to a westerly direction, the RN values decreased with time.

a. Data

To test the usefulness of recurvature numbers for actually predicting recurvature, RN values were calculated for an independent dataset consisting of 55 tropical cyclones that developed in the northwest Pacific during 1984, 1985, and the first six months of 1986. Environmental wind field data needed for calculating RN values were acquired from objective analysis fields generated by the Australian Bureau of Meteorology Research Centre (BMRC). The BMRC objective analyses included zonal and meridional winds at various levels throughout the troposphere. The wind field data were available on a 2.5° latitude–longitude grid, extending from 40°N to 20°S, and from 100°E to 180°. Figure 23 shows examples of the 500- and 200-mb BMRC wind field analyses.

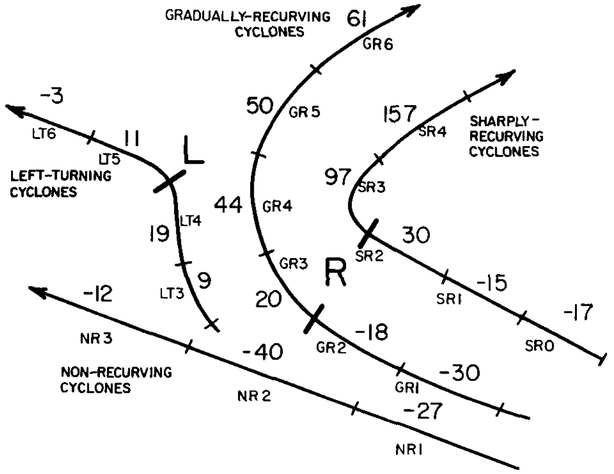

FIG. 22. The RN values for the sharply recurving, gradually recurving, left-turning, and nonrecurving cyclone time periods.

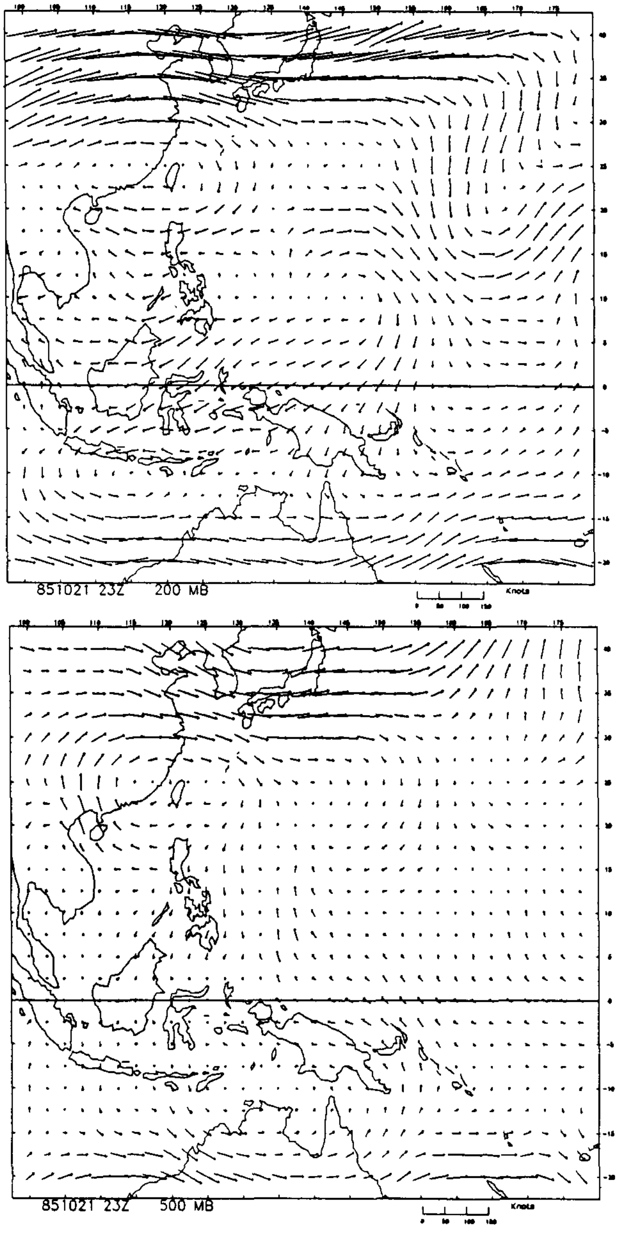

FIG. 23. An example of the 200- and 500-mb BMRC objective analysis wind fields.

TABLE 14. Example of the typical RN grid values extracted from the TCM-90 data.

RN grid for 90072512

		East longitude																			
	100+	10.0	12.5	15.0	17.5	20.0	22.5	25.0	27.5	30.0	32.5	35.0	37.5	40.0	42.5	45.0	47.5	50.0	52.5	55.0	57.5	60.0
Latitude	35.0	115	105	98	98	102	103	97	86	74	61	51	40	28	17	6	−9	−26	−36	−31	−10	15
	32.5	83	73	67	67	66	59	49	37	26	16	7	−4	−15	−25	−36	−47	−51	−42	−22	4	23
	30.0	44	39	36	31	22	10	0	−6	−11	−19	−29	−40	−50	−61	−67	−63	−45	−19	4	20	25
	27.5	10	8	3	−9	−22	−30	−32	−32	−34	−40	−50	−59	−67	−72	−65	−45	−17	7	22	27	22
	25.0	−13	−18	−28	−42	−51	−52	−47	−44	−46	−52	−59	−66	−67	−56	−36	−11	8	19	24	23	16
	22.5	−25	−34	−47	−55	−56	−52	−47	−48	−53	−57	−60	−60	−53	−32	−8	7	13	14	13	11	7
	20.0	−33	−42	−51	−51	−46	−41	−41	−44	−48	−49	−47	−41	−29	−12	3	7	4	1	−2	−3	−4
	17.5	−38	−44	−46	−41	−36	−35	−35	−34	−31	−28	−22	−14	−6	0	4	−0	−8	−14	−18	−18	−15
	15.0	−39	−40	−38	−34	−32	−32	−29	−22	−13	−7	−3	2	5	4	−0	−11	−23	−33	−36	−32	−25
	12.5	−34	−32	−29	−26	−23	−20	−15	−8	−2	−0	1	2	3	−1	−10	−26	−42	−50	−48	−39	−30
	10.0	−30	−27	−23	−19	−12	−6	−2	−2	−4	−7	−9	−8	−8	−15	−27	−45	−58	−59	−50	−39	−30
	7.5	−32	−30	−26	−21	−15	−11	−12	−18	−24	−28	−29	−29	−32	−41	−52	−63	−66	−58	−45	−36	−30
	5.0	−41	−41	−39	−36	−35	−38	−43	−50	−55	−56	−56	−58	−62	−69	−75	−74	−66	−53	−41	−35	−32

Since each RN value was calculated relative to the cyclone center, the position of the cyclone for each 12-h time interval had to be established relative to the 500- and 200-mb BMRC analysis fields. Once this was accomplished, a linear interpolation technique was employed on the BMRC objective analysis to find the zonal and meridional components of the wind fields, exactly 6° and 8° radius north, northwest, and west of the center of the cyclone. Results of this test show that the RN values relate fairly well to tropical cyclone motion.

To see if RN values could predict tropical cyclone direction on a real-time basis, the RN forecasting scheme was employed during the Tropical Cyclone Motion Experiment (TCM-90), which was conducted in the northwest Pacific from the island of Guam during the summer of 1990 (Elsberry 1990). During this experiment, recurvature numbers were calculated using data from the U.S. Navy NOGAPS analysis–prognostic wind fields. Since the analysis and prognostic wind fields were identical in format to the BMRC objective analysis, no major modifications of the RN forecasting scheme were necessary. Recurvature numbers were calculated for every grid point on the analysis and for the 24-, 48-, and 72-h prognostic position and fields instead of just for the cyclone's current position. This procedure was necessary simply because future cyclone positions were unknown. Table 14 provides an example of recurvature number grids.

During the experiment, tropical cyclone motions were forecasted using the recurvature numbers by the following procedure. The initial position (latitude and longitude) of the cyclone ($t = 0$) was found on the RN direction analysis grid. The cyclone was then simply advected, based on this RN direction, for 24 h, the speed of the cyclone being based on persistence and climatology. The position of the cyclone at the end of the first 24-h time period was then located on the 24-h RN forecast direction grid, a new direction was determined, and the cyclone again advected in this new direction for the next 24 h. This same procedure was repeated to find the location of the cyclone at 48 and 72 h after the initial forecast time.

Figure 24 shows two cyclones for which the recurvature numbers were used to forecast motion.[5] The first, Tropical Cyclone Yancy, moved on a west-northwest course throughout most of its lifetime, except when it was positioned east of Taiwan. During this time, a midlatitude trough was moving to a position north of the cyclone, and it was uncertain as to whether the cyclone would recurve or would resume motion to the west-northwest. The RN forecast made at 0000 UTC 18 August projected the cyclone to take on a west-northwest course during all three (24-, 48-, and 72-h) forecast periods. Although the cyclone did turn toward the north-northwest during the first 24-h time period, it resumed a west-northwest course during the second and third forecast periods.

The second tropical cyclone, Zola, had two significant track deviations during its lifetime. The first occurred at 1800 UTC 18 August when the cyclone turned sharply back toward the northwest from a previous northeast course. The RN forecast made 18 h earlier (0000 UTC 18 August; Fig. 25) predicted this track change. The second track deviation occurred when the cyclone actually underwent recurvature at 0000 UTC 22 August over southern Japan. The RN forecast made at 0000 UTC 19 August predicted the cyclone to move on a northwest course during the first

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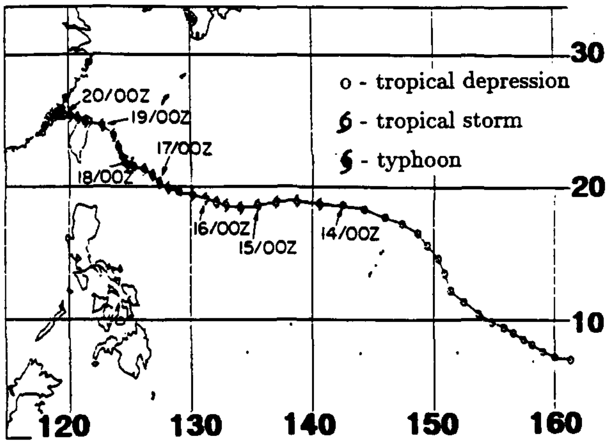
[5] Unfortunately, only two cyclones were forecasted using the RN forecasting scheme. This was due to computer ingest problems that developed at JTWC during the second part of the experiment (1–23 September). With the ingest system down, JTWC could not receive the NOGAPs data that were needed to run the forecast scheme.

Typhoon Yancy. August 14-20, 1990



Typhoon Zola. August 18-23, 1990

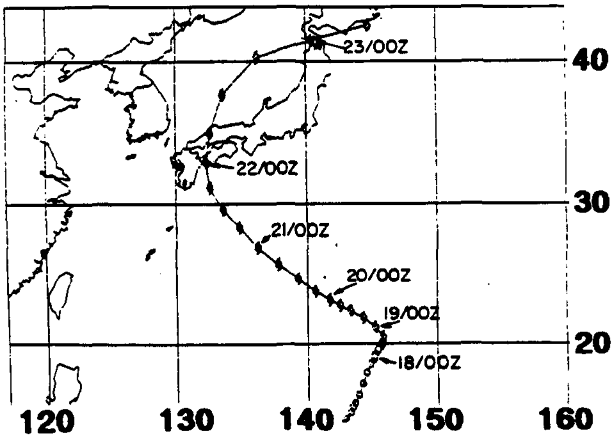


FIG. 24. Working best tracks of Typhoons Yancy (top) and Zola (bottom) during August of 1990.

48 h but then to gradually turn to the right at 72 h (0000 UTC 22 August). The RN forecast made at 0000 UTC 20 August again showed the cyclone moving northwest during the next 48 h, but by 72 h (i.e., 0000 UTC 23 August), the cyclone would have undergone recurvature. As can be seen in Fig. 25c, the cyclone actually underwent recurvature at 0000 UTC 22 August. The notable problem that the RN forecast scheme had in predicting the movement of Zola concerned speed. This problem was to be expected as the forecast speed of the cyclone was based on a mix of persistence and climatology. In retrospect, if the author had increased Zola's speed with time prior to recurvature, the forecast would have been quite close to the actual track verification.

b. *Critique of RN-based objective forecasting scheme*

Results of the objective recurvature number forecast for both storms were quite promising. The RN forecast for Yancy to move west-northwest, which was made while it was still east of Taiwan, was beneficial even though the cyclone initially moved on a north-northwest course during the first 24-h forecast period. It was hoped that the RN forecast would benefit the forecaster in this case by giving objective information to the unfavorable (for recurvature) environment northwest of the cyclone and that any change of course was likely to be of short duration.

The RN forecast of the two track deviations made by Typhoon Zola was also very favorable. The forecast for the first deviation demonstrated that as the recurvature numbers on the poleward side of the cyclone decreased with time the cyclone would turn left and resume a west-northwest course. The second track deviation by Zola was also predicted correctly, albeit the RN speed forecast was slow. The RN forecast demonstrated that as the recurvature numbers to the north of the cyclone increased with time the likelihood of the cyclone recurving to the northeast also increased.

6. Conclusions

Previous research related to tropical cyclone recurvature has shown that the environmental wind fields poleward of tropical cyclones are important for determining if the cyclones are going to remain on a west-northwest course or recurve. As was shown by George and Gray (1976), 200-mb westerly winds located 8°–20° radius north and west of recurving cyclones increased as the cyclone approached their point of recurvature. However, when Guard (1977) used the results of George and Gray's study to predict recurvature on a real-time basis, he found that their scheme overpredicted recurvature approximately 25% of the time. The likely reason why some of the cyclones in Guard's study did not recurve, even though the 200-mb wind fields were favorable for recurvature, is that westerly wind penetration was neither close enough nor deep enough to the cyclone center to facilitate recurvature. As was shown in section 3 of the present study, westerlies in the upper troposphere within 8° of the cyclone's center may have no effect on the direction of the cyclone. Rather, it is when the westerlies reached below the 300-mb level at 6° radius from the center of the cyclone that the cyclone actually begins to turn to the right and recurve. This study suggests that a refined emphasis should be given the mid- to upper-tropospheric wind fields for distinguishing recurvature versus nonrecurvature. Rather than use the wind fields at or below the 500-mb level, forecasters should study the manner in which the wind fields in the middle and upper troposphere (200, 300, and 400 mb) relate to subsequent changes in tropical cyclone motion.

The RN recurvature forecast scheme that is based on the environmental wind fields north and west of the cyclone showed promising results. We recommend this simple empirical approach to predicting tropical cyclone recurvature and hope that the scheme may be

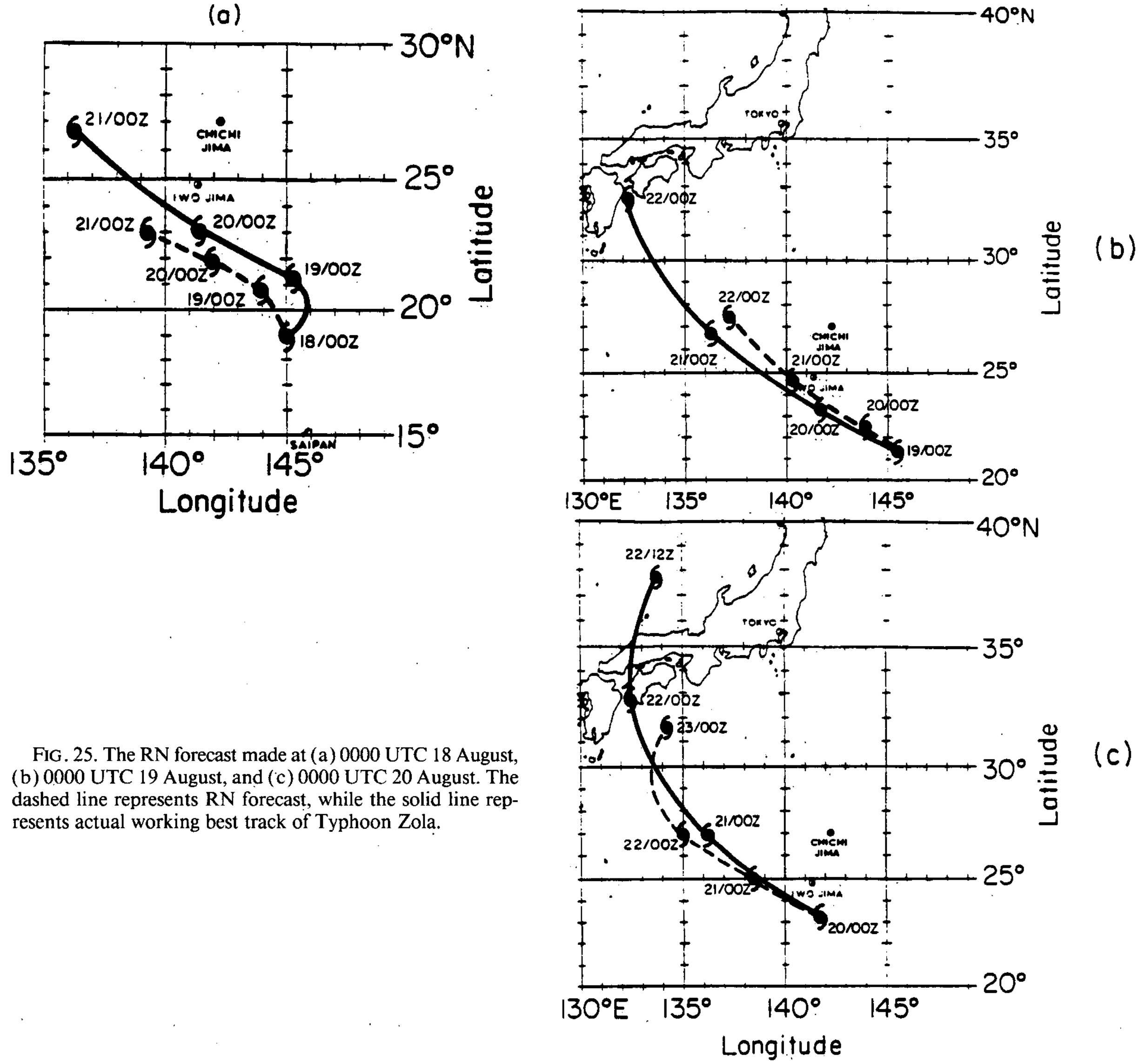


FIG. 25. The RN forecast made at (a) 0000 UTC 18 August, (b) 0000 UTC 19 August, and (c) 0000 UTC 20 August. The dashed line represents RN forecast, while the solid line represents actual working best track of Typhoon Zola.

of some assistance at cyclone forecasting centers in difficult recurvature–nonrecurvature forecast situations. It is important to note that this recurvature forecast scheme is based on historical information and has no complicated model assumptions related to motion and no computer analysis biases. The requirements for recurvature forecasting are thus reduced to the extent to which the mid- to upper-tropospheric wind fields at 6° and 8° radius to the north and west of the cyclone can be measured. Other information on the tropical cyclone, such as wind fields on the equatorial or east side of the cyclone, cyclone structure, extent of convection, and asymmetry, is not required for this scheme. These other pieces of information that most forecast models attempt to incorporate appear to add unneeded complexity to the recurvature forecast and may unnecessarily complicate decisions that the forecaster is required to make.

The next step in this study is to verify the extent to which this recurvature composite information can be used for individual forecast cases. The enhanced rawinsonde data network provided by the recent TCM-90 experiment (see Harr et al. 1991) is being extensively analyzed to determine the extent to which this rawinsonde composite information can be used for individual-case recurvature forecasts. If it is found that the mid- to upper-tropospheric wind fields are important for predicting individual cases of tropical cyclone motions, then more consideration might be given to expanded aircraft reconnaissance at the critical levels 6°–8° northwest of the cyclone to acquire data to improve operational track forecasting. For more background information on this research the reader is referred to the report of Hodanish (1991).

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