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THESIS

WESTERN NORTH PACIFIC TROPICAL CYCLONE WIND STRUCTURE AND STRUCTURE CHANGES

by

Michael Robert Fisher

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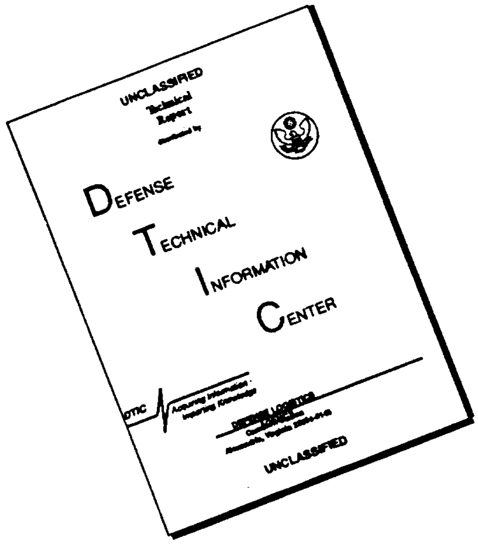

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Subjective and objective analyses of near-surface winds are utilized to estimate tropical cyclone (TC) size over a region of the western North Pacific. An empirical outer wind profile assuming partial conservation of angular momentum is utilized to determine the radial extent of cyclonic winds, which may be defined as the TC size in four categories. The first method uses the radii of either 30-kt or 35-kt wind in the Joint Typhoon Warning Center (JTWC) warnings during 1989-1994 to estimate the size categories each 6 h. A second subjective method based on satellite imagery has more cases of large and midget TCs than the first method. A multi-quadric interpolation (MQI) of composited wind observations over +/- 12 h is tested as a more objective method of estimating the 30-kt or 35-kt wind radii. For two case studies, these MQI-derived size estimates generally agree with the first method, although the MQI values varied more in time depending on the data distribution. It is concluded that a combination of the second and third methods could provide supporting data for estimating the outer wind profiles for the JTWC wind warnings.

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WESTERN NORTH PACIFIC TROPICAL CYCLONE WIND STRUCTURE AND STRUCTURE CHANGES

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ABSTRACT

Subjective and objective analyses of near-surface winds are utilized to estimate tropical cyclone (TC) size over a region of the western North Pacific. An empirical outer wind profile assuming partial conservation of angular momentum is utilized to determine the radial extent of cyclonic winds, which may be defined as the TC size in four categories. The first method uses the radii of either 30-kt or 35-kt wind in the Joint Typhoon Warning Center (JTWC) warnings during 1989-1994 to estimate the size categories each 6 h. A second subjective method based on satellite imagery has more cases of large and midget TCs than the first method. A multi-quadric interpolation (MQI) of composited wind observations over +/- 12 h is tested as a more objective method of estimating the 30-kt or 35-kt wind radii. For two case studies, these MQI-derived size estimates generally agree with the first method, although the MQI values varied more in time depending on the data distribution. It is concluded that a combination of the second and third methods could provide supporting data for estimating the outer wind profiles for the JTWC wind warnings.

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I. INTRODUCTION

Setting of critical wind warnings and beginning of various disaster preparedness activities are essential to minimize loss of lives and property owing to potential high winds, excessive rainfall, and storm surge in the Tropical Cyclone (TC). The timing of the warnings depends on the distance to the TC center, translation speed, and the wind structure in the TC vortex. For example, a threshold such as gale-force wind will be surpassed earlier for a large TC than for a midget TC if the TCs are following the same track.

The analysis of critical wind radii at the Joint Typhoon Warning Center (JTWC) is hampered by inadequate data. Monitoring of the TC wind structure is based on observations such as low-level cloud-drift winds from geostationary satellite visible and infrared instrumentation, a few rawinsonde soundings, and ship and shore station reports. Analyses of such observations of the low-level wind structure in TCs are required for improved TC warnings of critical threshold wind values, such as the 35-kt and 50-kt wind radii. This TC size determination is important to the warning process throughout the TC life cycle, and is particularly important for accurate forecasts of onset winds in the 0-36 h time frame. The contribution of the track error growth to critical wind warning errors at a location gets larger than the contribution from wind radii errors after about 24 to 36 h (C. Guard, personal communication, 1996).

A size estimate is also important for understanding whether significant deviations of the motion from the steering current will be expected. Improved synthetic wind observations in dynamical track prediction models, improved ocean forcing estimates, and understanding of the relationships between the TC vortex and the environment during formation and throughout the life cycle are imperative to enhance current prediction techniques.

One objective of this research is to understand wind structure and structure change during the life cycle of a TC. A working hypothesis is that the TC outer wind structure at formation time is the primary determinant of the outer wind structure throughout the life cycle. Thus, the goal is to estimate the magnitude of the TC outer wind structure changes and the circumstances in which such changes occur. Another goal is to relate inner-core intensity changes to the outer wind structure changes.

Two TC size definitions are: radius at which the winds are above a certain speed such as 35 kt (17 m s^{-1},or earlier, the 30 kt or 15 m s^{-1}), and the average radius of the outer closed isobar (ROCI) on the surface pressure analysis. The first of these size classifications is presently used at JTWC. Another definition of the size of the TC is implied by a proposed wind profile by Carr and Elsberry (1994,1997). They define a radial extent of the cyclonic tangential winds that may be thought of as a size specification. The term "growth" in this thesis refers to an expansion of the cyclonic circulation. Three methods for estimating TC size will be investigated and compared.

II. TROPICAL CYCLONE SIZE ESTIMATES BASED ON JTWC WIND RADII

A. METHODOLOGY

Carr and Elsberry (1994, 1997) proposed a tangential wind profile model for estimating R_0^{850} (radius of zero cyclonic wind at 850 mb) for subsequent tropical cyclone size estimates. This model is based on partial conservation of absolute angular momentum, and thus best applies at outer radii where the frictional losses of momentum are not as large. They inserted initially symmetric vortices with various angular momentum profiles into a nondivergent, barotropic model and found significantly different beta-effect propagation speeds. The Carr and Elsberry wind profile relationship is

$$V=\frac{M}{r^x}-\frac{1}{2}f_0 r, \tag{2.1}$$

where

$$M=\frac{1}{2}f_0 R_0^{1+x}. \tag{2.2}$$

Here, V is the tangential wind velocity at the 850 mb level, r is the radius from the center, R_0 is the radius of zero cyclonic wind, f_0 is the Coriolis parameter at the latitude of the tropical storm, and M is the angular momentum at the radius R_0. A complete derivation of these equations is provided in Appendix C of Carr and Elsberry (1994). The value of the "x" exponent is set to 0.4 when these equations are used at low levels. They demonstrate that the exponent value x = 0.4 is reasonably accurate throughout the TC and is in approximate agreement with observed TC tangential wind profiles. They also illustrate in Appendix C the differences in the tangential wind profiles as the exponent value of "x" is varied from 0.3

to 0.5. As these differences are mainly found within 300 km of the TC center, they have almost no effect on the beta-effect propagation speed, which depends on the outer wind structure.

The objective of this chapter is to describe the outer wind structure of western North Pacific TCs with the Carr and Elsberry angular momentum model (Eqs. 2.1 and 2.2). Given x=0.4 in Eq. (2.1), a specific (V, r) value is all that is required to solve for M, and then R_0 may be determined via Eq. (2.2). Specifically, the wind radii in the JTWC warning messages each 6 h will be inserted in Eq. (2.1) to calculate the constant M, and then solve for R_o in Eq.(2.2), which specifies the complete model wind profile. The JTWC specified a radius of 30-kt winds prior to 1992 and a radius of 35-kt winds after 1992. Although the JTWC radii strictly apply at the surface, the R_0 estimate will be assumed to also apply at 850 mb. Therefore, the R_0^{850} value obtained from JTWC specifications of the R_{30} or R_{35} wind radii and the Coriolis parameter f_0 value at the time of the current analysis may be input into the beta-effect propagation (BEP) speed model (Fig. 2.1) from Carr and Elsberry (1994) to obtain a TC size estimate. Because the angular momentum model is a function of the radial extent R_0 and the cyclone latitude, the BEP speed may be expressed as a function of these two parameters. Carr and Elsberry then define four broad categories of TC sizes based on the magnitudes of these BEP speeds. The four TC size categories (midget, small, average, and large) were defined as BEP speeds of less than 0.5 m s^{-1}, 0.5 to 1.0 m s^{-1}, 1.0 to 2.0 m s^{-1}, and greater than 2.0 m s^{-1}, respectively.

The TC sizes in these four categories derived from the JTWC wind radii values will be compared in Chapters III and IV with other TC size estimates.

B. DATA

Only those western North Pacific tropical storms attaining tropical cyclone intensity of greater than 30 kt (prior to 1992) or 35 kt (1992 and subsequent years) have the desired wind radii values. Data from TC number 16 of 1989 through TC number 39 of 1994 were utilized in the size estimation procedure based on JTWC wind radii specifications with the following exceptions: TC number 24 of 1991; TC numbers 22 and 26 of 1992; TC numbers 8, 30, and 35 of 1993, and TC numbers 15 and 36 of 1994 were omitted due to missing radii files. Therefore, 165 of 173 (95.4%) storms during the period were employed for this TC size estimation method. The Coriolis parameter was calculated from the storm latitude in the JTWC best-track file.

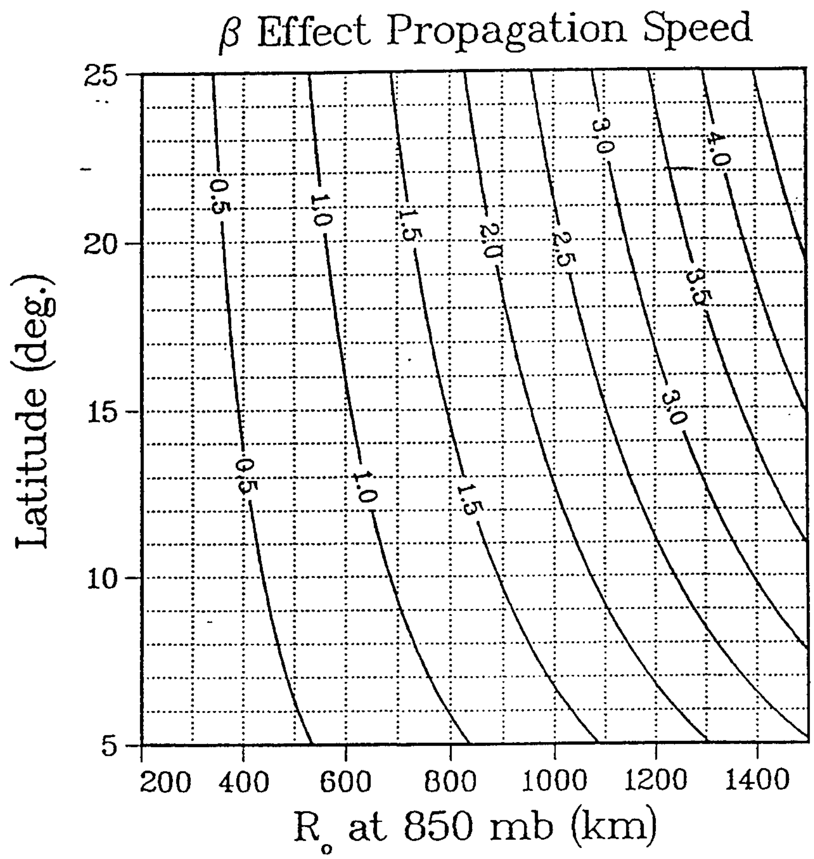

Fig. 2.1 Beta-induced propagation speed (m s^{-1}) as a function of latitude and outer radius at 850 mb based on angular momentum profiles (Carr and Elsberry 1994).

The JTWC specification of R_{30}/R_{35} winds describes the radii of both the dangerous semi-circle and the less dangerous semi-circle. Here, the average radius between the dangerous and less dangerous semicircles was used in the R_0 determination. That is, the asymmetry associated with the increased (decreased) winds to the right (left) of the storm motion arising from addition of a vortex and a basic flow is assumed to be removed by this average of the two wind radii prior to input into the angular momentum equations above. Special processing of the archived JTWC wind radii data is described in the Appendix.

C. CHARACTERISTICS OF JTWC WIND RADII ESTIMATES

Merrill (1984) demonstrates with individual cases that the strength of a TC can change even though its intensity (maximum wind) and size (radius of outer closed isobar--ROCI) remain constant. Merrill suggests changes in the TC wind field at radii of 100-300 km may have different controls and effects than either intensification or growth (increase in ROCI). For the purposes of this study, the life cycle was subdivided into the increasing intensity phase and the decreasing intensity phase. That is, the TC size estimates will be examined separately for the intensification and decaying phases to see if these were periods of growth in size as well.

1. Size and Intensity Correlation During Intensification Phase

To illustrate quantitatively the behavior of R_0^{850} during the TC intensification stage, R_0^{850} was computed using the partial conservation of angular momentum model (Eqs. 2.1 and 2.2). Specifically, R_0^{850} was computed from the first report of R_{30} or R_{35} until the time the TCs attained a maximum intensity as specified by JTWC. As illustrated in Fig. 2.2, examples of R_0^{850} plots versus intensity may be compared for various TCs. When the TC has just surpassed the 30-kt or 35-kt criterion, the R_0 estimate is relatively small. As the TC intensifies, the R_0 estimate increases. For about 40 % of the TCs, no further increase in R_0 is observed after the intensity reaches a value in the range of 50-60 kt. Examples of these near-constant R_0 values after an early growth phase are shown in Fig. 2.2a. The remaining 60 % of the TCs demonstrated growth in R_0^{850} throughout the intensification phase, as illustrated in Fig. 2.3a. It is not clear whether a conceptual model of increasing size during TC intensification was the basis for the behavior in Fig. 2.3a, or whether sufficient wind observations were always available to define the R_{30} and R_{35} radii. Thus, the increasing R_0 values in Fig. 2.3a may arise from the tendency of JTWC forecasters to increase the R_{30} (R_{50} or R_{100}) during TC intensification, or it may reflect actual variations in nature. Of those 40% of the cases in which R_0 did not continue to grow throughout the intensification phase, about 60% had a contracting R_0 with an increase in intensity and about 40% had a relatively constant R_0 with an increase in intensity. The TC intensity at which the increasing R_0 trend stopped, and either remained constant or contracted (Fig. 2.4), is of considerable interest for

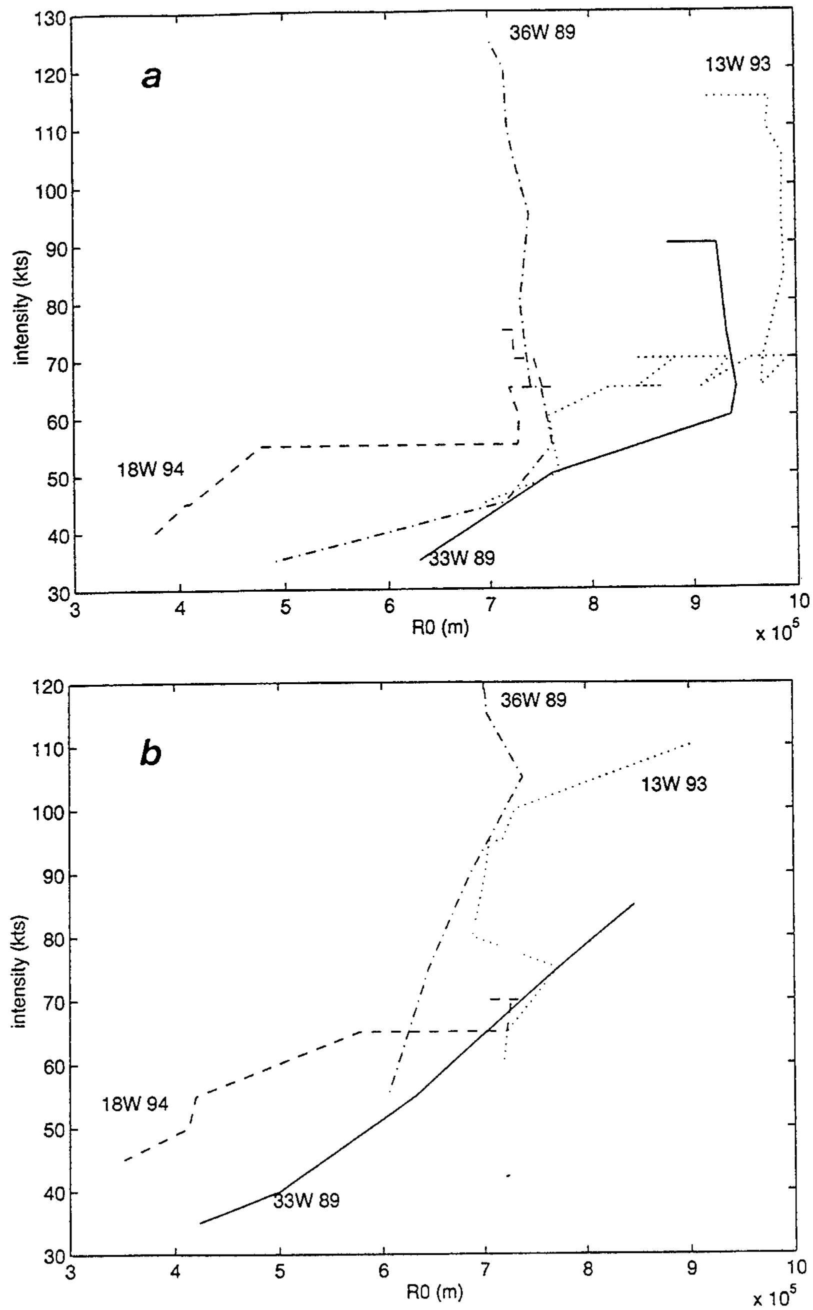

Fig. 2.2(a) R_0^{850} (10^5 meters) versus TC intensity (kt) during the intensification phase for TCs in which a near-constant R_0 phase follows an increasing R_0 phase as the TC intensifies to about 45-65 kt. The TC number (W indicates western North Pacific) and year (19XX) are given along each curve. Each trace begins at the smallest intensity and ends at maximum intensity along the curve. (b) As in (a), except during the decay phase of the same TCs, so that the trace begins at maximum intensity and ends at minimum intensity along the curve.

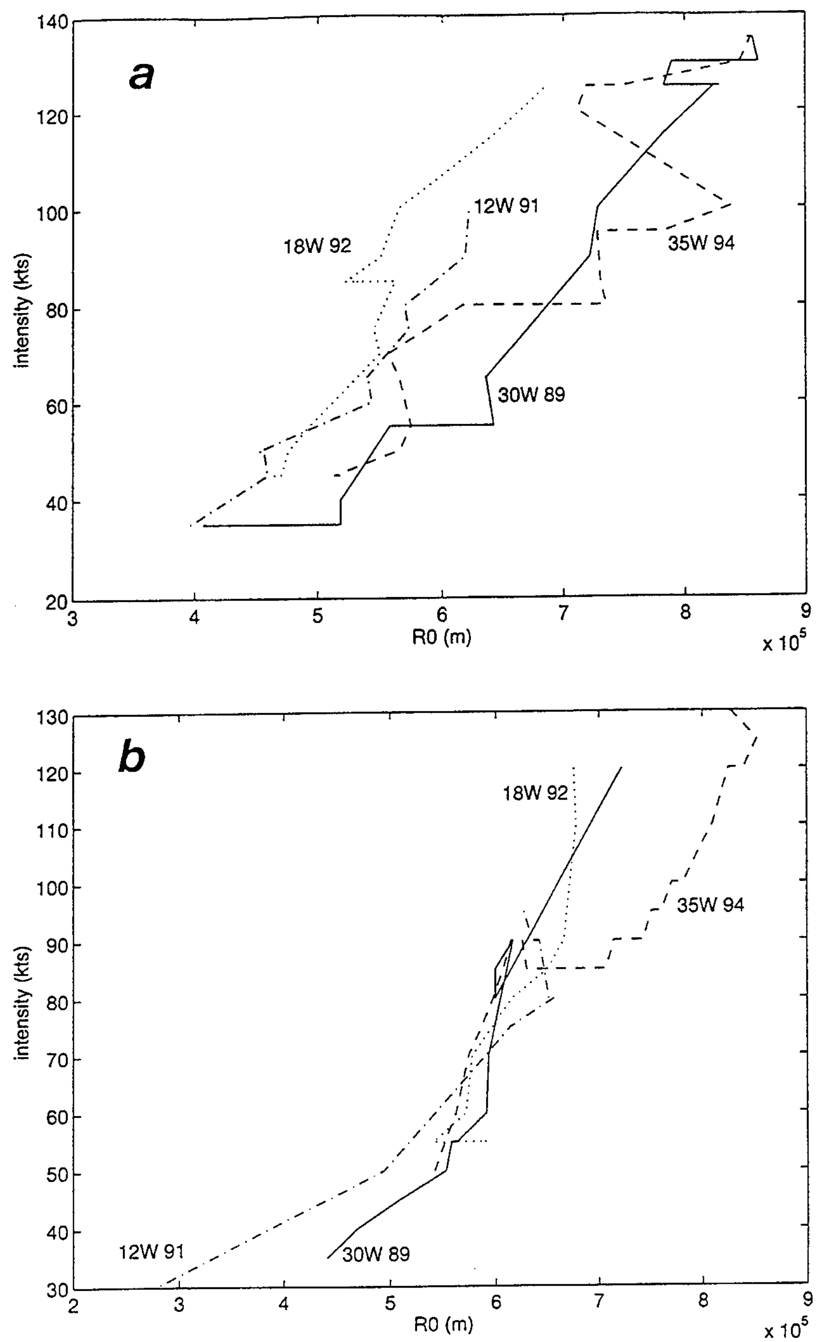

Fig. 2.3(a) As in Fig. 2.2(a), except for TCs that had continued increases in R_0 throughout the intensification phase. (b) As in (a), except during the decay phase of the same TCs.

warnings. The range of TC intensities at which the majority of the R_0 trend changes occur is between 41-70 kt (Fig. 2.5). The majority of the TCs that had a change in R_0 trend at higher intensities tended to then have a decrease in R_0 during the remainder of the intensification phase. Other methods for checking these R_0 trends will be described in the following chapters.

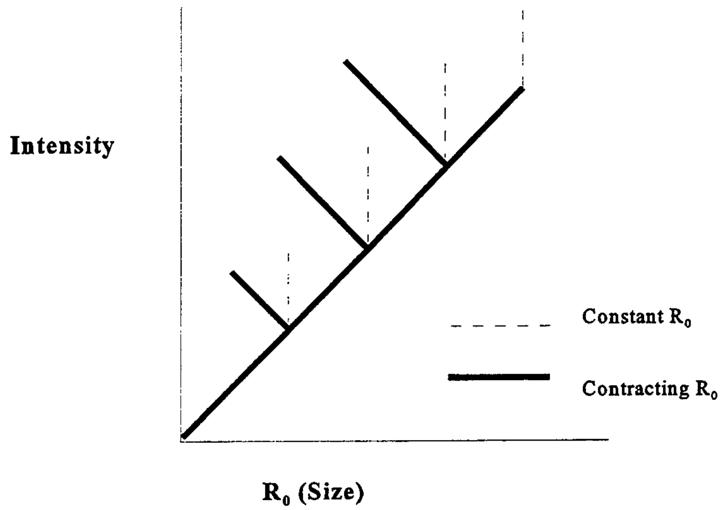

Fig. 2.4 Schematic of the change from an increasing R_0 trend with intensity increase for those cases where R_0 did not continue to grow throughout the intensification phase, and thus have either a contracting (solid) or constant (dashed)R_0.

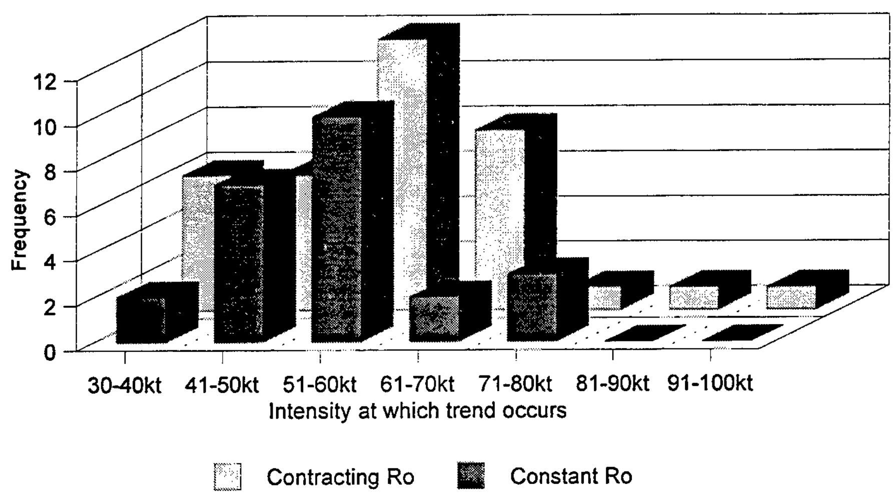

Fig. 2.5 Frequency of TC cases in which R_0 (size) either remained relatively constant (front column) or contracted (back column) during the intensification phase as in Fig. 2.4 stratified by the intensity at which the R_0 trend change occurred.

2. Size and Intensity Correlation During Decaying Phase

Merrill's conceptual model has the TC size (specifically the ROCI) continuing to increase after maximum intensity (i.e., during decay). Thus, it is during the decay phase that the cyclone reaches it greatest size, and then begins to contract as the maximum winds diminish. Forecaster "lore" is that TCs spread out as they move into midlatitudes, which may be because the TC is moving into a stronger environmental flow so that the size of the gale-force winds increases. About 29 % of the TCs from TC 16 of 1989 through TC 39 of 1994 demonstrated this characteristic during the decay phase. The other R_0 trends were that about 6 % demonstrated a constant R_0 and the majority (about 65 %) had a decrease in R_0 during the decay phase. Based on this sample of approximately five years, the expected tendency for the radial extent of the tangential winds associated with a TC to always increase as the TC moves into the midlatitudes may be doubtful.

III. TROPICAL CYCLONE SIZE ESTIMATES BASED ON SATELLITE IMAGERY

A. METHODOLOGY

Carr and Elsberry (1994) proposed a satellite imagery-based technique for estimating R_0^{850} (radius of zero cyclonic wind at 850 mb) for subsequent tropical cyclone (TC) size estimates. As part of a reproducibility test (Carr et al. 1995), Mark Boothe generated a data base of TC size estimates using primarily satellite IR imagery. Extraction of this data base consisted of four basic steps.

The first step in this subjective interpretation of satellite imagery was to estimate the average radius in degrees latitude of the curved cloud banding features associated directly with the tropical cyclone being analyzed. The entire 360 degree cloud pattern around the TC center associated with the TC circulation had to be considered. That is, the R_0^{850} radius was estimated by weighing the prominent banding features related to the structure of the TC. Therefore, the external cloud features associated with the monsoon trough were excluded. Although the cloud band distinctions were made primarily without hindsight because of the rules of the reproducibility test (Carr et al.1995), the sequence of past imagery assisted in distinguishing those cases in which a TC had moved into a prominent banding feature external to the TC structure.

Given the subjective nature of the radii estimates based on the cloud pattern, these estimates of the horizontal extent of the TC cyclonic circulation were only recorded to the nearest one-half of a degree of latitude. As indicated in Chapter II, Carr and Elsberry (1994) proposed a tangential wind profile based on partial conservation of angular momentum that they inserted into a nondivergent, barotropic model to estimate the beta-effect propagation speed. Because tangential wind profile given by the angular momentum model is a function of the radial extent R_0 and the cyclone latitude, the BEP speed may be expressed as a function of these two parameters. Thus, the R_0^{850} value obtained from the satellite imagery and the Coriolis parameter f_0 value at the time of the current analysis were input into the BEP speed model (Fig. 2.1) from Carr and Elsberry (1994) to obtain beta-effect propagation

(BEP) speeds.

Carr and Elsberry (1994) also defined the TC size in four categories (midget, small, average, and large) in terms of the magnitude of the BEP speed (less than 0.5 m s^{-1}, 0.5 to 1.0 m s^{-1}, 1.0-2.0 m s^{-1} and greater than 2.0 m s^{-1}, respectively). Based on the BEP magnitude derived from the satellite imagery values of R_0^{850} and f_0, these definitions of Carr and Elsberry (1994) were used by Mark Boothe to assign TC sizes in these four categories as part of the reproducibility test (Carr et al. 1995).

B. DATA

Tropical cyclone number 4W of 1990 through TC number 30 W of 1993 were utilized in the reproducibility test. Generally, the time period was June through October with some gaps, especially during August-September 1990. There were 54 storm matches between the reproducibility test storms and those cases in Chapter II.

C. COMPARISON WITH SIZE ESTIMATES FROM JTWC WIND RADII

The size estimates based on the satellite method are compared with those from the JTWC wind radii for those TCs and day time groups (DTG) where both values are available. As indicated above, the satellite-based estimates are only available for those TCs and DTGs in the 1989-1994 JTWC data set that were used in 1990-1993 reproducibility test (Carr et al. 1995). Thus, a much reduced data set is available. In general, the satellite-derived size estimates are in agreement with the JTWC wind radii method (Fig. 3.1). However, the size estimates (R_0 values) from the satellite imagery indicate a considerably greater number of *large* TCs relative to the JTWC wind radii based size estimates. The explanation may be that high-level cloud features associated with the *large* TCs obscure or conceal the low-level cloud features, especially when relying primarily on infrared (IR) imagery rather than visible imagery. For example, an apparent extension of the circulation beyond R_0^{850} may occur by measuring the outflow of high-level cirrus clouds versus the outlying low-level cumulus lines that are taken to define the radial extent of the cyclone.

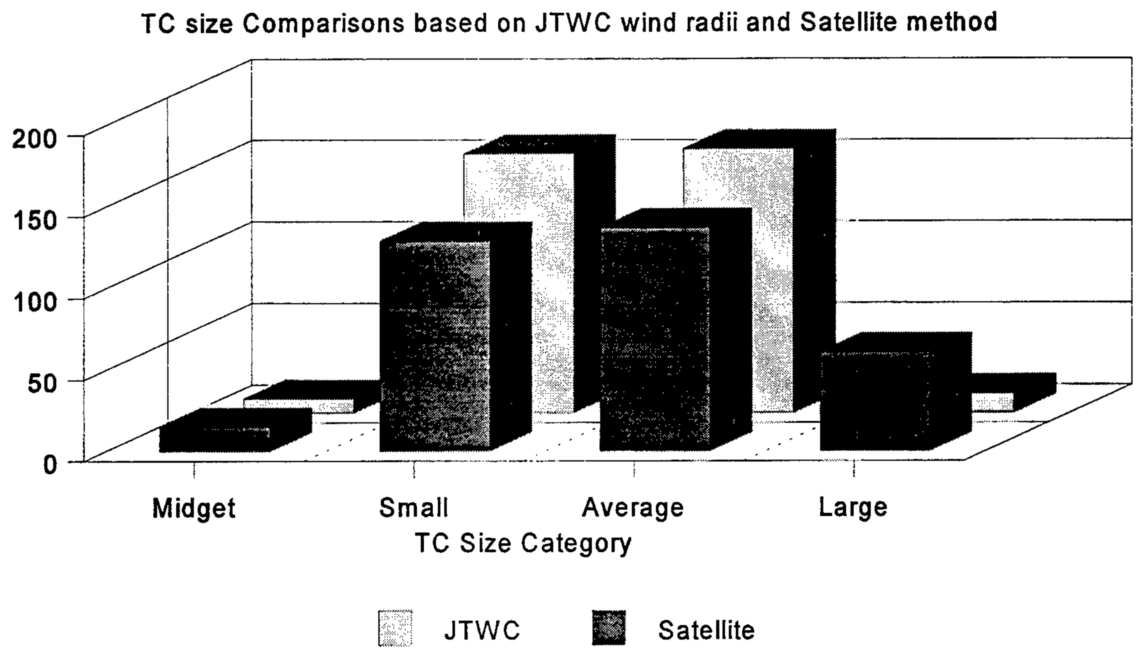

Fig. 3.1 Comparisons of the frequency in four TC size categories based on the JTWC-specified R_{30} or R_{35} wind radii (back column in each size category; see insert) and the corresponding satellite-derived R_0 (front columns).

To illustrate these differences in size categorizations, a contingency table (Table 3.1) is constructed for the two size estimation methods. For example, when a size estimate derived from JTWC wind radii is in the *midget* category, the satellite-derived method resulted in the following size categories: 1 *midget*, 7 *small*, and 1 *average*. Conversely, the 15 *midget* TC size estimates derived from satellite imagery had JTWC wind radii derived size estimates in the following size categories: 1 *midget* and 14 *small.*

The more numerous (61) *large* TC categorizations by the satellite method than the nine *large* cases from JTWC radii method (Fig. 3.1) were distributed to the *average* (39) and *small* (13) categories. Similarly, the *average* TC size categorizations by the satellite method tended to be biased toward the low side (47 *small* cases versus only 3 *large* cases) in the JTWC wind radii method. As indicated above, the 15 *midget* size categories based on satellite imagery were predominately in the *small* category based on the JTWC wind radii. Similarly, the *small* size categorizations by the satellite method were more likely to be put in the *average* category (37 cases) than in the *midget* category (7 cases).

Table 3.1 Contingency table of size estimates in four categories based on JTWC wind radii (rows) and corresponding estimates from satellite imagery (columns).

Satellite Imagery

JTWC	Large	Average	Small	Midget
Large	9	3	0	0
Average	39	86	37	0
Small	13	47	85	14
Midget	0	1	7	1

IV. TROPICAL CYCLONE SIZE ESTIMATES BASED ON MULTIQUADRIC INTERPOLATION OF COMPOSITED WIND OBSERVATIONS

A. METHODOLOGY

Since the operational sources of near-surface winds are typically limited in the tropics, especially in the vicinity of tropical cyclones, a compositing in time and height will be used to enhance the data base. An objective analysis technique is then implemented to provide the near-surface wind structure around the TC to estimate the radial extent of the 30-kt (R_{30}) or the 35-kt (R_{35}) winds. The first-guess field for the multiquadric interpolation (MQI) analysis will be the Naval Operational Global Analysis and Prediction System (NOGAPS) analysis and the composited wind observations will be analyzed as increments to this first-guess field. As in Chapter II, knowing the R_{30}/R_{35} values permits a calculation of R_0 and subsequent size category assignment based on the BEP model in Fig. 2.1.

B. DATA COMPOSITING

Observed winds to demonstrate this method of TC size estimation were extracted from the Tropical Cyclone Motion (TCM-93) field experiment data base (Carr and Jeffries 1993). Tropical cyclone numbers 10 through 15 during TCM-93 were utilized, which is all TCs from 0000 UTC 20 July to 1200 UTC 13 August 1993. Data compositing in time (+/- 12 h) is used to increase the data base for an analysis in the area 10^0 S - 45^0 N, 120^0 E - 160^0 E. Specifically, three types of wind data were composited over five 6-h synoptic times: Conventional surface winds from land and ship stations (SFCOBS), rawinsonde winds at 850 mb (SOUNDINGS), and satellite-derived, low-level cloud-drift winds assigned to 850 mb (SATWINDS). Although the density of observations varied in time (i.e., every 12 h or every 6 h, and for SFCOBS every 3 h), compositing of these data greatly enhanced the density of data in the previously sparse-data region around a TC.

Near-surface wind observations were composited by shifting the observations at prior and subsequent times to the central time, using the JTWC best-track positions as the reference points at each of the five 6-h synoptic times. For example, all the available wind data +/- 6 h and +/- 12 h from a central observation time of tau = 00 h were repositioned relative to the best-track positions at tau = -12, -06, 00, 06, 12 h as illustrated in Fig. 4.1. If the TC moved steadily westward at 10 kt for the entire 24-h period, an observation at -12 h (-6 h) would be displaced 120 n mi (60 n mi) to the west, and an observation at +12 h (+6 h) would be displaced 120 n mi (60 n mi) to the east. The limited number of wind observations associated with a TC for a day-time group (DTG) is illustrated in Fig. 4.2a. The increased data density that is produced with this compositing technique is demonstrated in Fig. 4.2b.

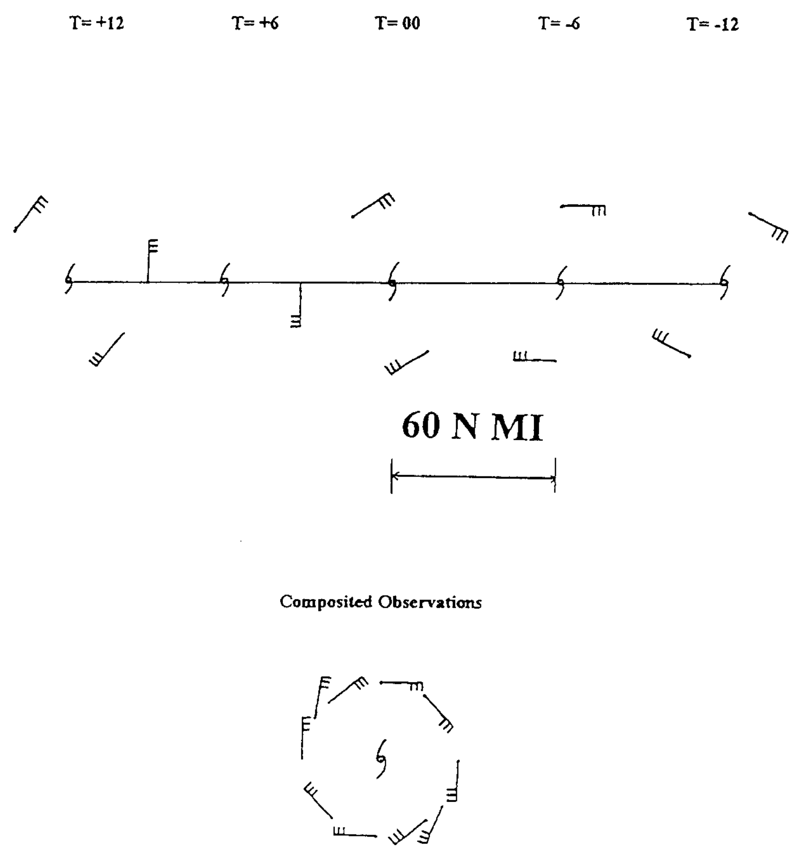

Fig. 4.1 Schematic of composited wind observations at +/- 6 h and +/- 12 h relative to TC best-track center about tau = 00 h for a TC moving westward at 10 kt for a 24-h period.

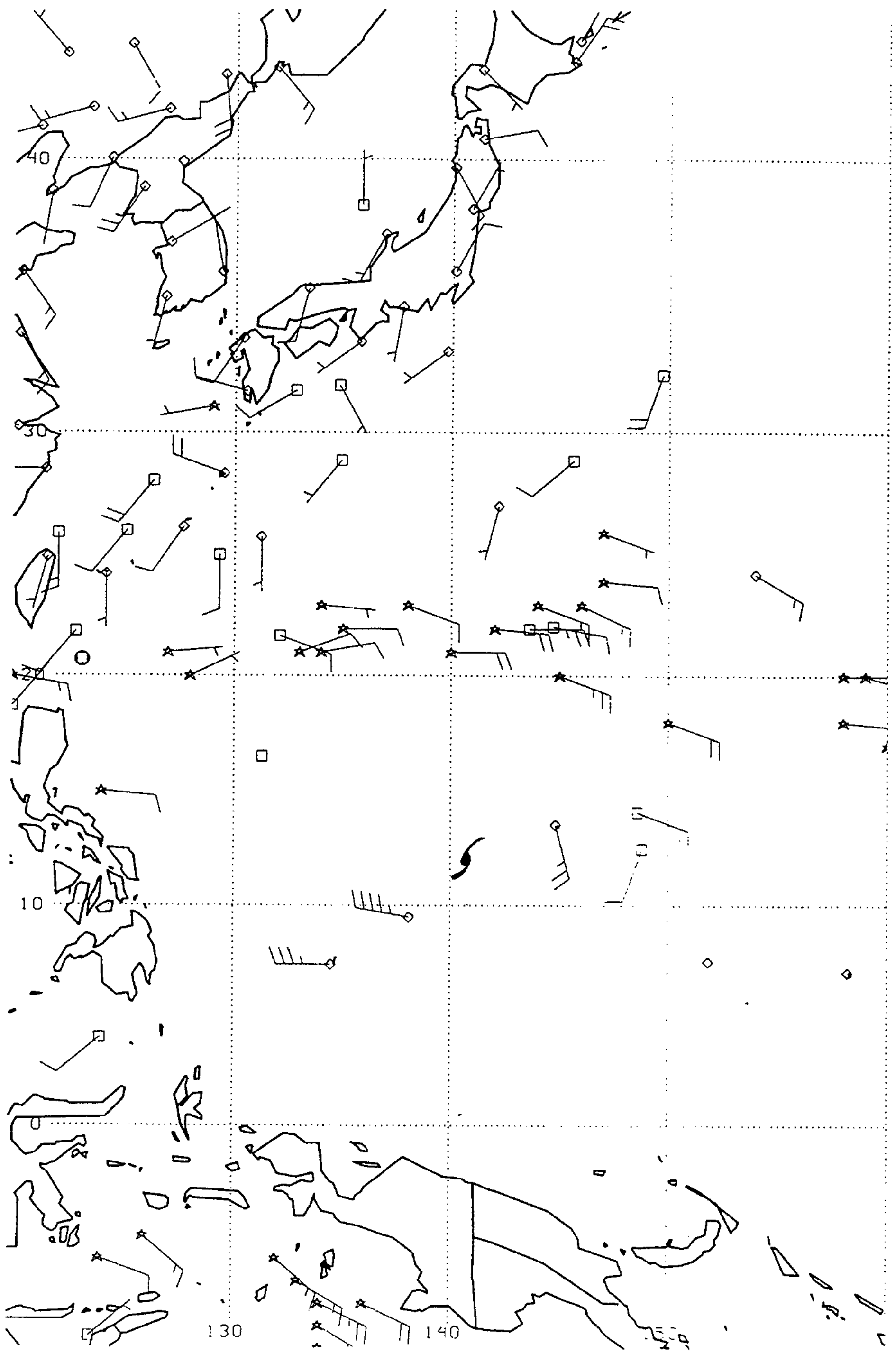

Figure 4.2(a) Wind observations available at 1200 UTC 4 August 1993. Diamond-headed winds represent SOUNDING data at 850 mb, square-headed winds represent SFCOBS, and the star-headed winds represent SATWINDS. A long (short) wind barb indicates 10 kt (5 kt).

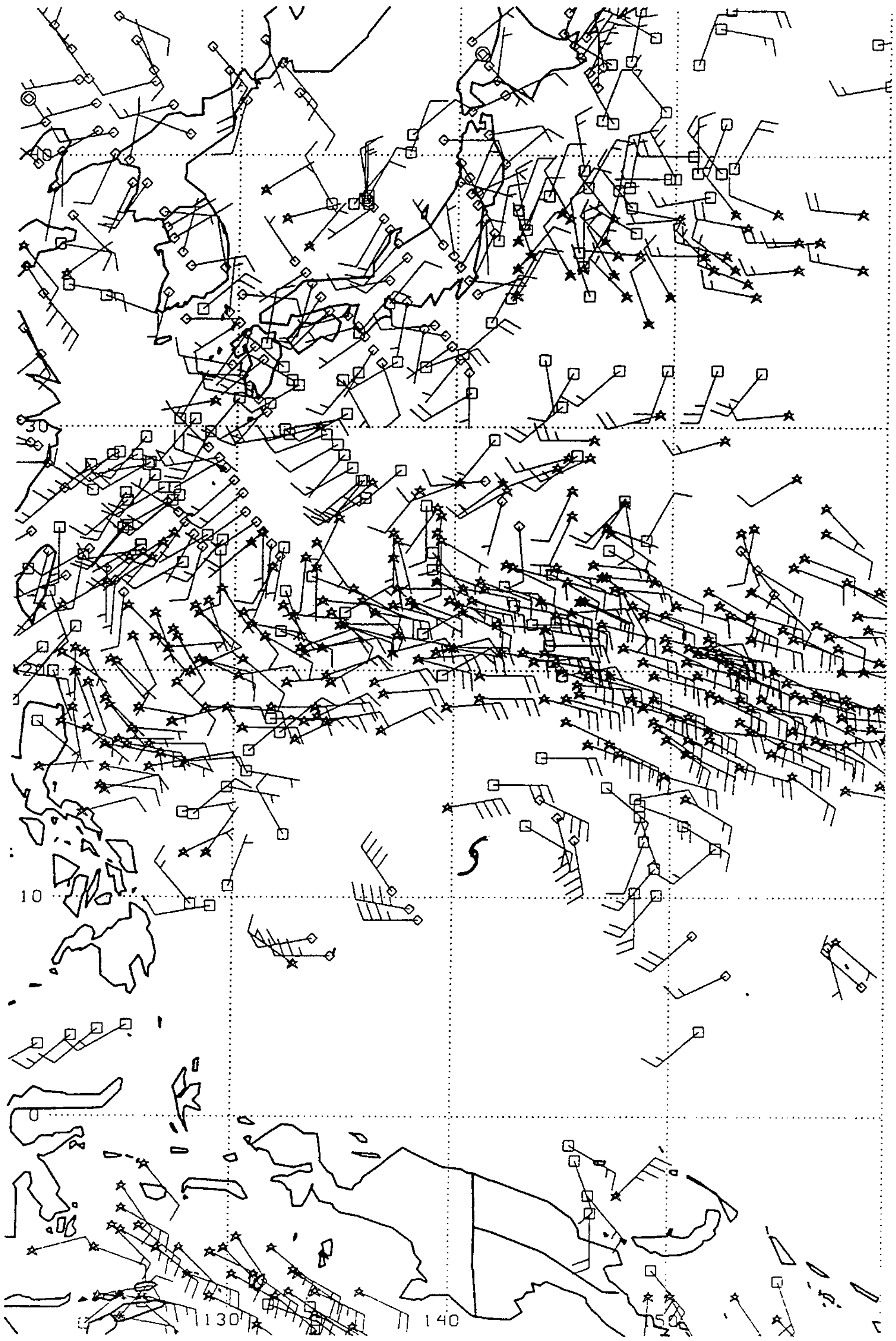

Fig. 4.2(b) Composite of wind observations in (a) and corresponding data sets +/- 6 h and +/- 12 h translated to the time of (a) by repositioning relative to center of TC Robyn.

C. OBJECTIVE ANALYSIS

The multiquadric interpolation (MQI) technique of Nuss and Titley (1994) was chosen for this analysis because it is designed to draw very closely to the observations. The MQI fits surfaces through all observations in such a way that values can be interpolated to any point in a domain, which in this case is a 0.5^0 lat./long. grid. The MQI code described by Jeffries (1995) was adopted here to analyze the composited wind observations. As described in Jeffries (1995), the user may control the weight given to the observations and the first-guess field (operational NOGAPS 850 mb wind analysis) via a smoothing parameter. How closely the MQI analysis is fit to the wind observations is governed by this smoothing parameter. The smoothing value of 0.005 adopted by Jeffries (1995) was tested for this research. As illustrated in Fig. 4.3a, the MQI with a smoothing parameter equal to 0.1 drew more closely to the first-guess field (NOGAPS). For example, the MQI analysis departs significantly from the observations and reflects more of the first-guess field west of the TC. Conversely, the MQI with a smoothing parameter equal to 0.005 drew more closely to the composited wind observations (Fig. 4.3b). Thus, the smoothing parameter was set to 0.005, as in Jeffries (1995).

D. MQI ANALYSIS

The MQI size estimation technique was performed on TCs Nathan (10W), Ofelia (11W), Percy (12W), Robyn (13W), Steve (14W) of 1993, and TCs Page and Fred (3W and 19W of 1994). A total of 220 wind analysis was produced for these seven TCs. Based on the objective analysis with the MQI technique, the average radius of critical winds around the tropical cyclone center may be estimated. For example, either the R_{20}, R_{25}, $R_{30,}$ or the R_{35} value may be used to estimate R_0^{850}. The Coriolis value f_0 value at the time of the current analysis, which was also required for estimating the BEP speed from Fig. 2.1 from Carr and Elsberry (1994), was taken at the JTWC best-track latitude. Based on the BEP magnitudes derived from the MQI wind radii values of R_0^{850} and f_0, TC sizes in four categories were assigned as described in Chapters II and III.

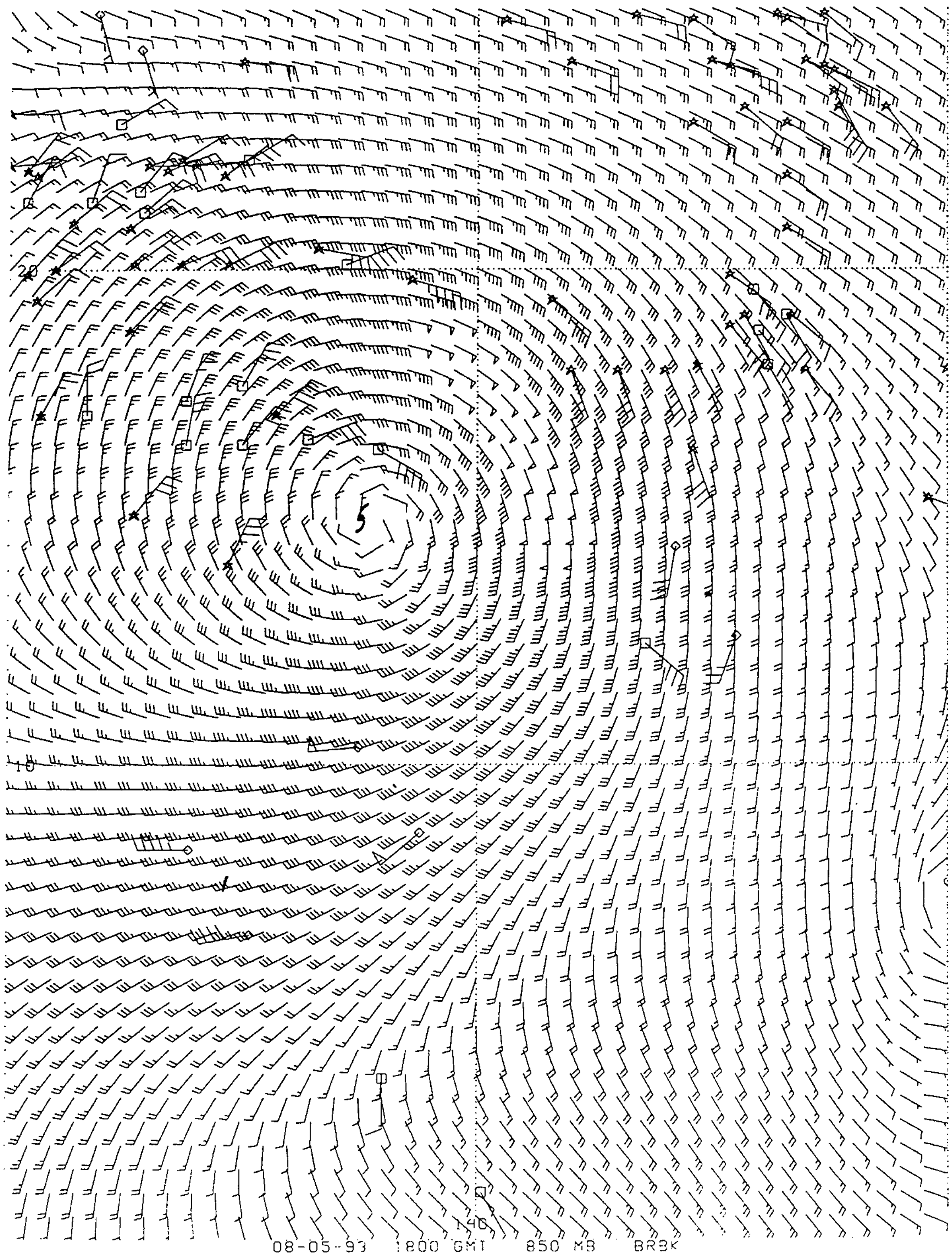

Figure 4.3 MQI analysis in the area 0^0 - 25^0 N, 130° E - 150° E at 1800 UTC 5 August 1993 with composited observations (longer wind barbs) overlaid, using a smoothing parameter of (a) 0.1 and (b) 0.005. See Fig. 4.2 for meaning of wind barbs.

Figure 4.3(b) as in (a) using a smoothing parameter of 0.005.

The MQI method for estimating TC size during the life cycle of a TC appears to work best when the analyses are conducted on larger TCs where sufficient observations exist for the MQI analysis. For example, a R_{20}, R_{25}, R_{30}, or R_{35} value and subsequent R_o^{850} may be readily extracted throughout the life cycle for larger TCs such as Robyn (13W 1993) and Fred (19W 1994) as in Figs. 4.4 and 4.5, respectively. The TCM-93 was underway during the development stage of TC Robyn. Thus, additional data from reconnaissance aircraft provided adequate tracking throughout the Robyn life cycle. A suitable R_{35} value for the TC size estimates via the MQI analysis was available as early as 0000 UTC 3 August 1993, which is just 18 h after the TC reached an intensity of 35 kt. The MQI analyses each 12 h provided R_{35} values (size estimates) until Robyn reached maximum intensity of 120 kt at about 1200 UTC 7 August 1993.

One limitation of the MQI analysis of composited wind observation method is the lack of realism that exists in the inner structure of the TC owing to the absence of adequate observations to define the increase to a maximum wind value, and then a decrease to zero in the eye. When sufficient outer wind observations are available, and are well distributed in all quadrants, the hyperboloid surfaces of the MQI technique will fit the outer winds reasonably well. However, the inner-core region is not well resolved with observations. Therefore, the fitted surface must adjust across the center to wind components from the opposite direction. This will produce a decrease in wind speed through zero, with the decrease beginning somewhere inside the innermost observations at each azimuth. Consequently, the radius of maximum winds (r_m) will be at too large a radius and the maximum wind (v_m) will be too small. Thus, the actual inner-core wind structure will not be represented as demonstrated by the radius of the inner 35-kt isotach associated with Robyn (Fig. 4.4d).

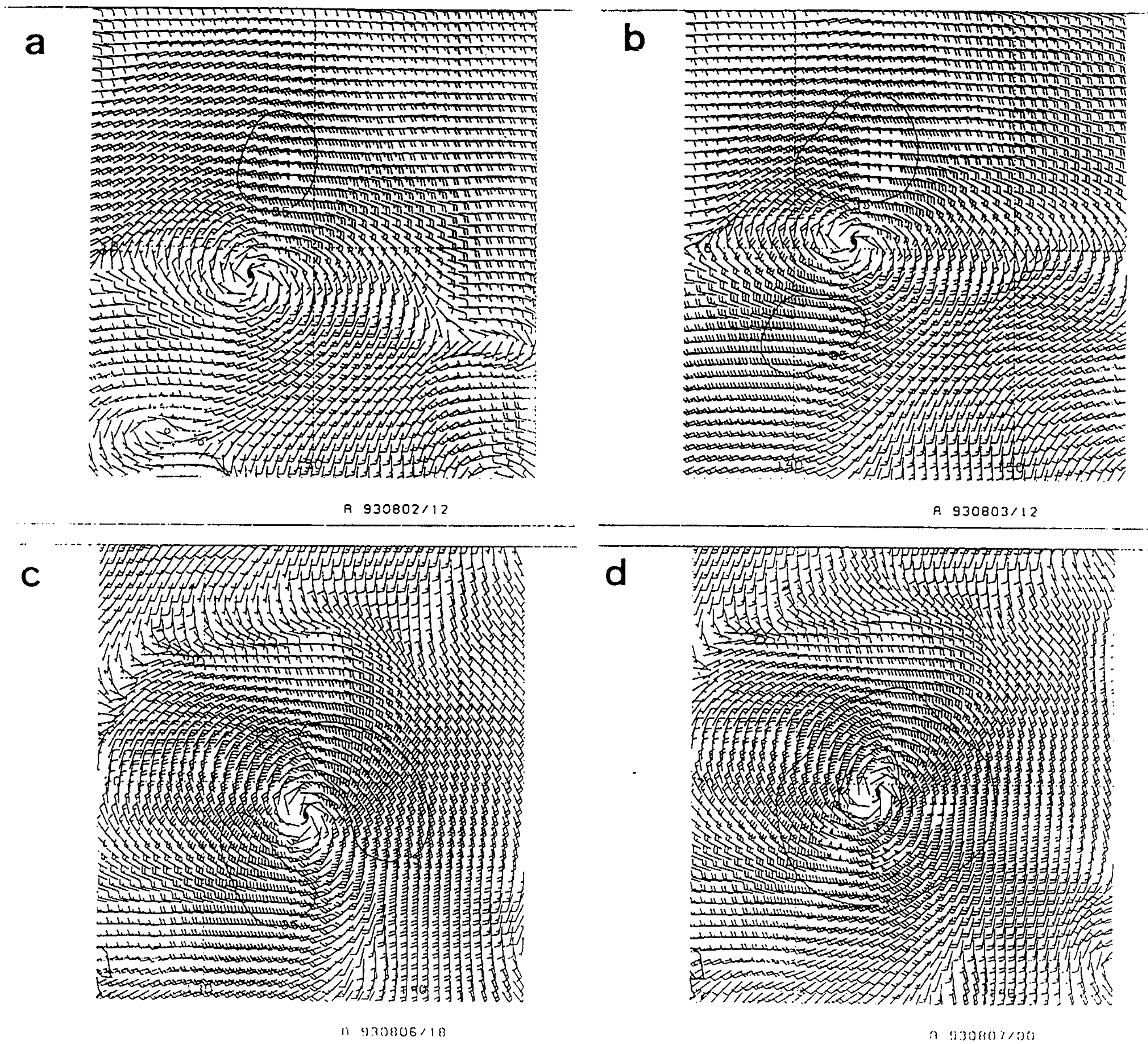

Figure 4.4 MQI composited wind analysis at 850 mb field with 35- kt isotach (solid) near Robyn (13W 1993) for (a) 1200 UTC 2 August, (b) 1200 UTC 3 August, (c) 0600 UTC 6 August, and (d) 0000 UTC 7 August 1993.

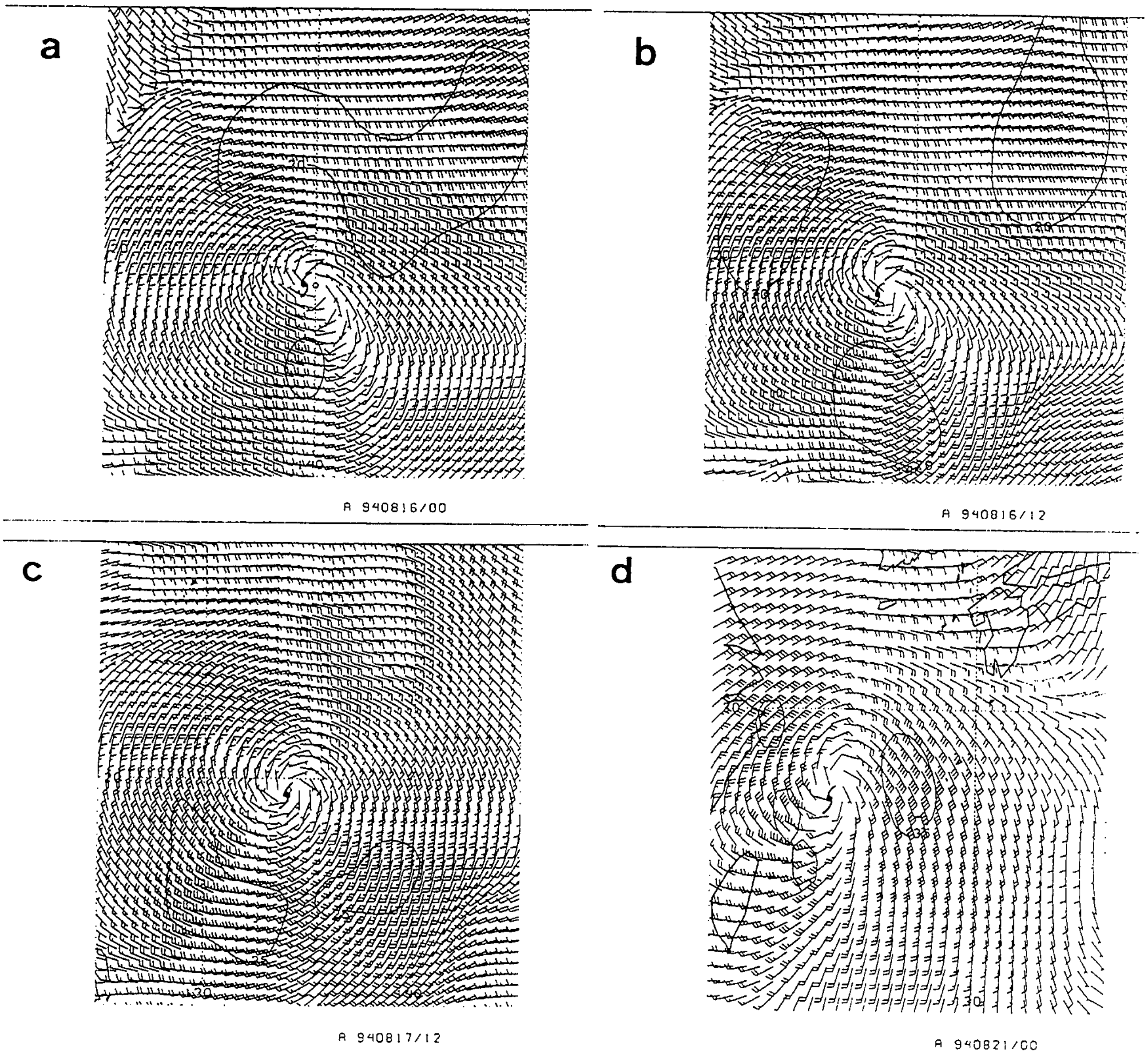

Figure 4.5 MQI composited wind analysis at 850 mb field with 20- kt isotach (solid) near Fred (19W 1994) for (a) 0000 UTC 16 August, and (b) 1200 UTC 16 August, and for 25-kt isotach at (c) 1200 UTC 17 August, and for 35-kt isotach at (d) 0000 UTC 21 August 1994.

Finally, the R_{35} or R_{30} analysis of smaller TCs via MQI may be especially limited in regions with less dense, or non-uniform, wind observations. To illustrate, TC Nathan (10W 1993) was a weak storm that formed inside and interacted with a large-scale cyclonic vortex called a monsoon gyre circulation. Although a 35-kt isotach is on one side (Fig. 4.6), the lack of symmetry prevents an accurate approximation of the average value of R_{35} and subsequent estimate of R_0^{850}. Similar MQI limitations were demonstrated with the interaction of the well-established monsoon gyre that was associated with the formation and motion of two very small storms: Ofelia (11W 1993) and Percy (12W 1993). Specifically, the resultant MQI analyses of TS Ofelia and TC Percy did not produce an adequate isotach analysis that defined maximum winds on two sides, and thus a size estimate could not be made for comparison with the other size estimation techniques.

Another case of a smaller TC was Steve (14W 1993). The maximum intensity achieved by Steve was 65 kt at about 0000 UTC 10 August 1993 (Fig. 4.7b). A possible explanation for the weak cyclonic winds to the northwest of Steve may be an interaction of TC Robyn's cyclonic flow as illustrated in Figs. 4.7a-c.

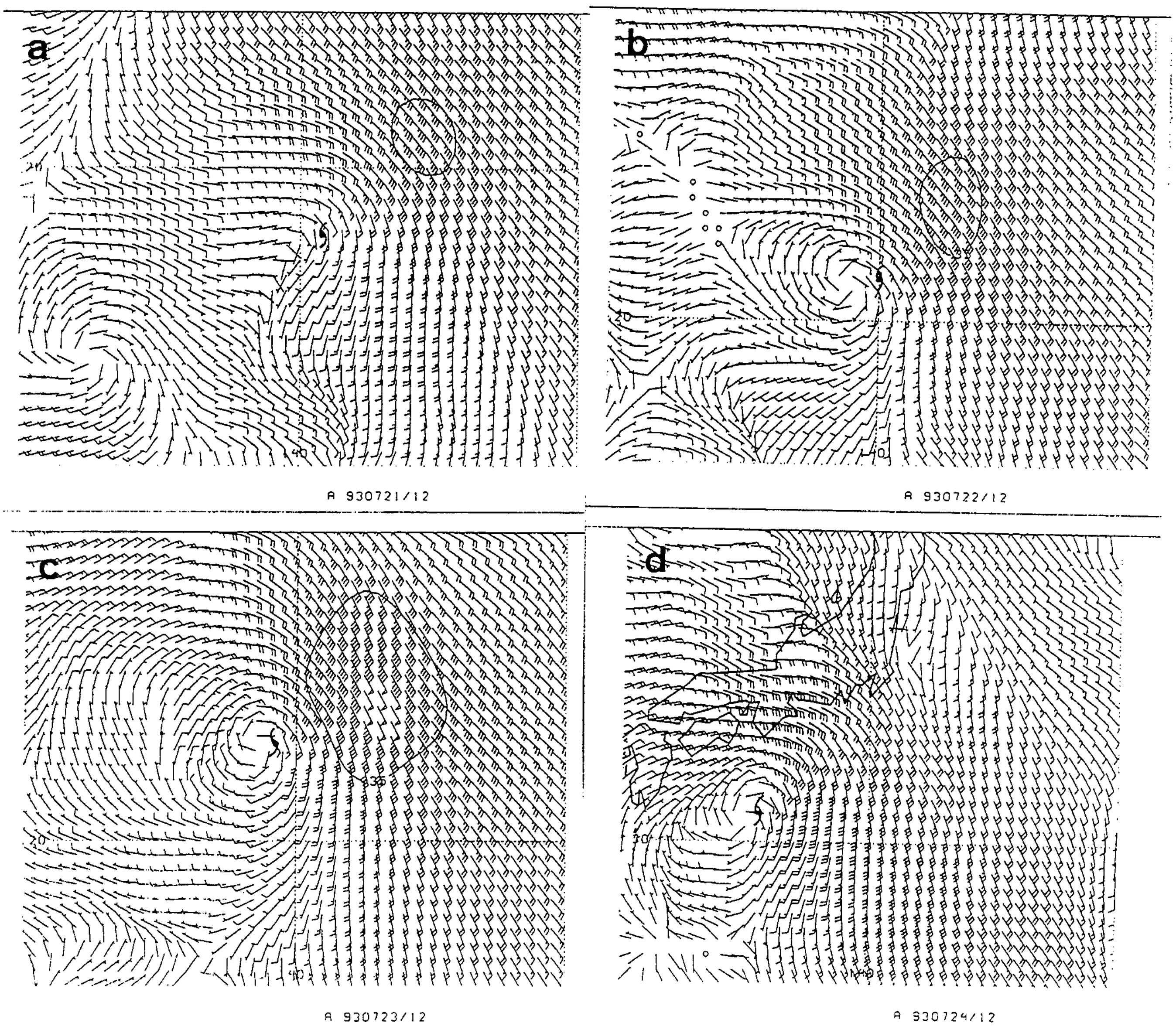

Figure 4.6 MQI composited wind analysis at 850 mb with 35-kt isotach (solid) surrounding Nathan (10W 1993) for 1200 UTC (a) 21, (b) 22, (c) 23, and (d) 24 July 1993.

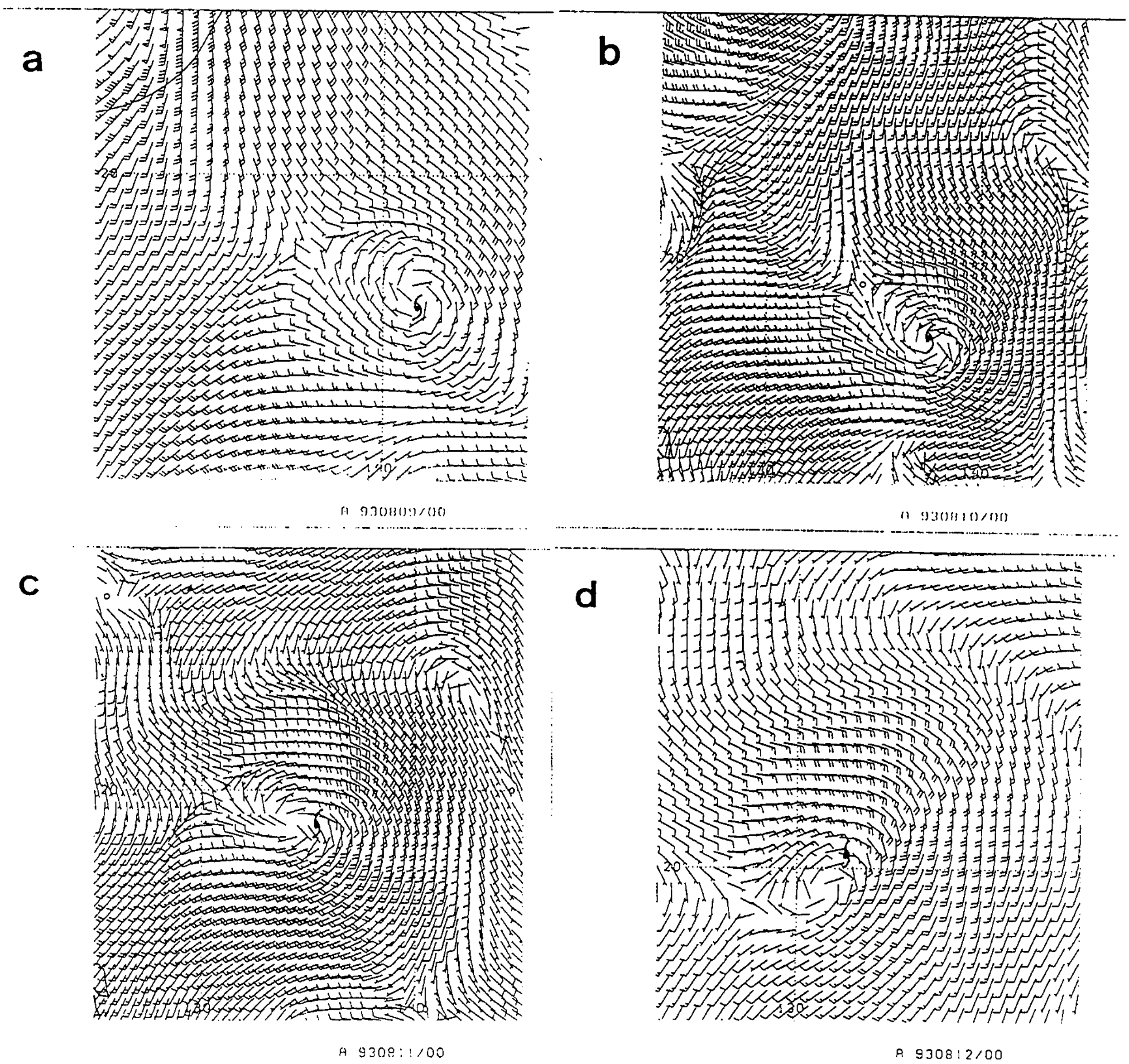

Figure 4.7 MQI composited wind analysis at 850 mb with 35-kt isotach (solid) near Steve (14W 1993) for 0000 UTC (a) 9, (b)10, (c)11, and (d)12 August 1993.

E. COMPARISON WITH SIZE ESTIMATES FROM JTWC WIND RADII AND SATELLITE-DERIVED WIND RADII ESTIMATES

Only a few case studies were carried out with the composite observations method because of the effort necessary to collect the various types of observations and to perform the MQI analysis. These case studies will be summarized in this section by comparison with the corresponding R_0 estimates based on JTWC wind radii (Chapter II) and satellite imagery (Chapter III).

1. TC Robyn (13W 1993)

The three TC size categorization methods as a function of intensity during the intensification phase for Robyn are in general agreement (Fig. 4.8). For example, the R_0 size estimation from the MQI analysis and JTWC wind radii for TC Robyn are nearly identical at maximum intensity as demonstrated in Fig. 4.8a. Similarly, the R_0 size estimates from JTWC wind radii and MQI analysis are very similar during the decay phase of TC Robyn (Fig. 4.8b). The satellite-derived R_0 estimate agrees fairly well with JTWC wind estimates in several instances during the intensification phase, especially during the intensity increase from 70 kt to 85 kt. During the decay phase of Robyn, the R_0 size estimates from satellite imagery are larger relative to JTWC wind and MQI analysis estimates. This may be due to over-estimating the R_0 associated with restricting the use of satellite imagery to primarily IR as previously discussed in Chapter III.

2. TC Fred (19W 1994)

Comparisons of the three TC size categorization methods for TC Fred are illustrated in Fig. 4.9. Size estimates from the MQI analysis and satellite-derived estimates are in close agreement during the intensification phase (Fig. 4.9a). Since the satellite method of obtaining R_0 is independent of the MQI analysis of composited wind observations to obtain R_{30}/R_{35} and then estimate R_0 based on the partial conservation of angular momentum equations (Eq. 2.1 and 2.2), the relatively close agreement between these two methods is a preliminary validation of both methods. As TC Fred intensified, the threshold wind value used to calculate R_0 was progressively increased from R_{20} to R_{25} to R_{30}. Even with this range of threshold values, the sequence of R_0 values derived from the angular momentum model varied consistently in time, and agreed with the trend from the satellite method. That is, the ability to use the R_{20} during the early intensification stage of TC Fred and then switch to the R_{25} and R_{30} values as Fred matures greatly extends the application of the composited winds method (Fig. 4.5). Although both the satellite-derived and JTWC wind radii estimates involve subjectivity and assumptions, the similar size change trends in this case is a favorable sign.

F. CONCLUSION

Unlike the previous size estimation methods, this method is more objective in nature. At least for TC Robyn, this method does not illustrate size-intensity correlation tendency as in those size estimates based on JTWC specifications. This is illustrated in Fig. 4.8 by the nearly constant R_{35} values during the entire life cycle of Robyn (13W 1993). That is, the radial extent of the 35-kt (R_{35}) winds remains relatively constant (Fig. 4.4) from the early stages of initial intensity increase to maximum intensity.

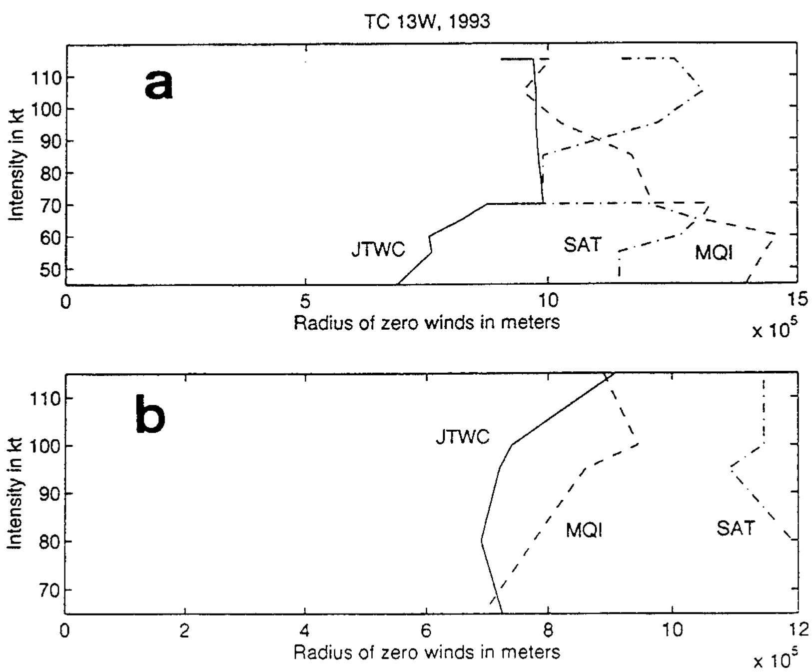

Figure 4.8 Comparison of TC size estimates based on JTWC wind radii (solid), satellite-derived (dash-dot), and MQI composited wind analysis (dashed) for Robyn (TC 19W 1993) during the (a) increasing intensity phase, and (b) decreasing intensity phase.

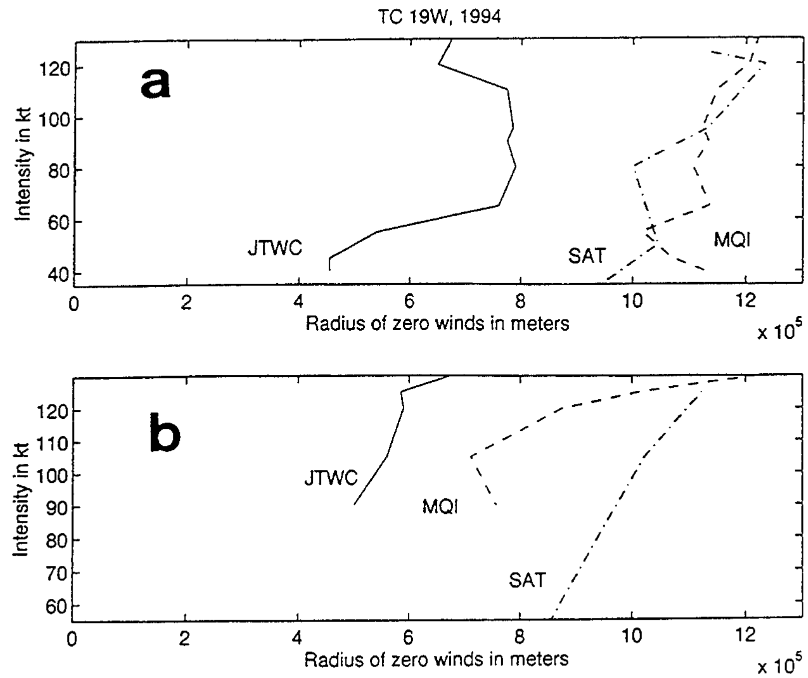

Figure 4.9 As in Fig. 4.8, except for TC Fred (19W 1994).

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Three methods for obtaining an estimate of western North Pacific tropical cyclone (TC) size are intercompared. In contrast to earlier size definitions involving the radius of outer closed isobar or gale-force wind radius, the size is defined here as the radius of zero cyclonic wind at 850 mb.

The first size estimation method utilized the proposed tangential wind profile model of Carr and Elsberry (1994, 1997), who also defined four size categories in terms of the magnitude of the beta-effect propagation (BEP) speed. This profile is based on partial conservation of absolute angular momentum and contains constants that may be evaluated using the JTWC specified 30-kt or 35-kt wind radii (R_{30}/R_{35}) as archived in the JTWC Automated Tropical Cyclone Forecasting data base. An average of the dangerous and less-dangerous semicircle wind radii was used to characterize the symmetrical near-surface winds of each TC. One assumption is that the exponent in the angular momentum equations (Eqs. 2.1 and 2.2) is equal to 0.4 at lower levels away from the TC center. With this assumption and either the R_{30} or R_{35} value, a complete wind profile can be described, which includes the R_0 value.

The second size estimation method from Carr and Elsberry (1994) is based on the outer curved bands in satellite imagery (primarily IR) to estimate R_0^{850}. As in the first method, this estimate can be converted to a TC size in one of four categories (midget, small, average, or large) in terms of the BEP speed. Whereas the satellite-based method produces more large and slightly more midget TCs than the JTWC wind radii method, fewer small and average TC size occurrences are found.

The third estimation method makes use of the MQI interpolation that provides an analysis of low-level winds from rawinsondes, ship reports, and satellite-derived cumulus cloud-drift data. The assumption here is that these observations may be composited over a +/- 12 h to provide a better data distribution. The MQI analysis provides an objective estimate of the R_{30}/R_{35} value, and then a R_0^{850} estimate from the angular momentum profile, and finally a size characterization in one of the four categories.

The +/- 12 h data compositing method clearly does improve coverage of wind observations around a TC. However, a data-sparse area exists near the center of western North Pacific TCs because aircraft reconnaissance is not available, satellite cloud-drift wind extractions at low levels are not possible under a cirrus overcast, and ships avoid the central region. The MQI analysis of composited wind observations worked well for larger TCs where a greater number of observations exist. However, a problem still exists for small storms or for storm intensities just over 35 kt. This is especially true when the background flow is strong and obscures the TC vortex circulation. Additionally, the MQI method can not interpolate inward from the outer region with composited wind observations into the central data void to obtain R_{30} or R_{35} values in lieu of 30-kt or 35-kt observations. Thus, a realistic description of the inner structure of a TC is not possible with the MQI size estimation method with typically available observations. When no ground truth is available, a combination of the MQI and satellite methods may provide more support for the JTWC wind radii estimation.

Since real ground-truth observations are not available in most cases, only an intercomparison for overall consistency is made among these three size estimation methods via several case studies. These case studies provide a preliminary validation of the partial conservation of angular momentum profile of Carr and Elsberry (1994), because the MQI method tends to provide similar size estimates as the independent satellite-derived size estimates. Although only a few case studies with all three methods are available, general agreement is found among all three of the size estimation methods.

B. RECOMMENDATIONS

To further test the validity of the MQI method for estimating TC size, this study should be extended to include other observations, such as high-resolution, visible cumulus cloud-drift winds. High-density, low-level cloud-tracked winds from GOES-8 are being generated for the Atlantic hurricane region by the University of Wisconsin and are readily available 1 h after synoptic time via the INTERNET, as are other low-level TC wind structure products. Additionally, this study should be extended to include more cases with TCs from 1995 to the present. The size estimation method should use DMSP SSM/I or ERS-1 scatterometer observations to estimate R_{30} or R_{35} via a two-dimensional field of the R_{30} or R_{35} isotachs. To make the MQI analysis more useful (i.e., more real-time) to the forecaster, a composite of the wind observations over a +/- 6 h vice a +/- 12 h period should be considered. That is, a more timely analysis of wind structure would be available by waiting only 6 h to receive the latest observations.

A climatology and persistence track forecast technique is being developed that is tailored to individual synoptic patterns and regions that are used by Carr and Elsberry (1994) to describe the structure of the environment. Therefore, incorporating these TC size estimates as predictors in a statistical track prediction technique may result in smaller errors, and thus improve wind warnings for the hazardous tropical cyclone.

APPENDIX

SUMMARY OF CORRECTIONS OF THE JOINT TYPHOON WARNING CENTER (JTWC) AUTOMATED TROPICAL CYCLONE FORECASTING DATA SETS

One of the data sources utilized in this research is maintained on the Automated Tropical Cyclone Forecasting (ATCF) System by the Joint Typhoon Warning Center (JTWC). The period of ATCF data investigated was all tropical cyclones from number 16 in 1989 through 1995. Information is stored in a series by files named according to the format <X><tcid>.dat where

X=a denotes the objective aid track/intensity forecast file

X=b denotes the official best track file

X=f denotes the fix file

X=r denotes the official wind radius and intensity forecast file

For example, rwp0195.dat contains the wind radius and intensity forecasts for Western Pacific (wp) tropical cyclone 01 in 1995. For convenience, the nomenclature X-deck is used when referring to a group of these files. For example, the files containing the wind radius/intensity forecasts information are called "r-decks."

During analysis of the r-deck files, a number of errors and false entries were discovered. This is not surprising since there is presently no routine post-storm analysis and examination of the r-decks as there is for the a-, b-, and f-decks. A listing of the types of errors found and the corrective measures taken is provided here for other researchers who may access these files.

1. Wind radii/intensity forecasts were found for day time groups (DTG) when the TC was not in a warning status as reported in the appropriate Annual TC Report (ATCR). These are most likely preliminary forecasts, perhaps when a Tropical Cyclone Formation Alert (TCFA) was in effect, that should not have been saved in the r-deck database. These

unofficial forecasts were deleted.

2. Wind radii/intensity forecasts occasionally were saved out of chronological order. These were moved to the proper chronological position.

3. More than one tau=00 (initial warning time since 00 represents the number of hours past the initial time) entry appeared for the official JTWC-analyzed wind radii and intensity of the TC, especially in the fall of 1992. These duplicate entries seem to be a result of a software update to the ATCF. One entry would have the form tau = '0' and the other tau = '00.' The duplication seemed to occur when the forecaster had already created and saved a wind radii/intensity forecast, and later decided to update it. The software that merges the updated forecast into the r-deck properly over-writes the radii/intensity forecasts for tau > 0, but produces one entry with the form tau='0' and another with the form tau='00.' Corrective measures in this situation were as follows:

a. If the radii/intensity analysis values on the two tau=00 lines were identical, one of the lines was simply deleted. This was apparently a case in which the forecaster updated either the radii or intensity forecasts, but did not change the analysis time values.

b. If the analysis intensity values were different, this means that the intensity value sent to Fleet Numerical Meteorology and Oceanography Center (FNMOC) for the purpose of running certain objective track/intensity forecast aids was different from the intensity value put into the official warning. In this case, the entry called "WRNG" in the a-deck for that TC was checked since the first intensity entry on this line is the intensity that JTWC actually issued in the warning. The tau=00 line in the r-deck that had a different intensity was then deleted.

c. If the analysis intensity values were the same, but the wind radii analysis values were different, the only definitive way to determine which entry is the official value is from the text of the warning message from JTWC for that TC and DTG. However, the text is not saved by the ATCF system. In these cases, the tau=00 entry was retained that seemed most consistent with the trend given by the tau=12 h and tau=24 h forecasts.

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