

Size of Tropical Cyclones as Inferred from *ERS-1* and *ERS-2* Data

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ABSTRACT

The sizes of the tropical cyclones (TCs) occurring over the western North Pacific (WNP) and the North Atlantic between 1991 and 1996 are estimated to establish a database for the study of the climatology of TC size and the physical processes responsible for the size changes of TCs. Wind data from the scatterometer onboard the European Remote-Sensing Satellites 1 and 2 (*ERS-1* and *ERS-2*) form the data source for defining the TC size. The size of a TC is defined as the mean radius at which the relative vorticity decreases to $1 \times 10^{-5} \text{ s}^{-1}$. The mean TC size is found to be 3.7° lat for WNP TCs and 3.0° lat for those in the North Atlantic. Such a difference in size between the two basins is statistically significant at the 95% confidence level. The mean TC size in the WNP is also found to vary seasonally, with a value larger in the late season (October and November) than in midsummer (July and August). These results generally agree with those from previous studies using other measures of size. The size changes (increasing or decreasing) of some TCs are also identified. The high-resolution surface wind data from the ERS satellites are shown to be a valuable tool in the study of TC sizes.

1. Introduction

The motion of a tropical cyclone (TC) is of concern to both researchers and weather forecasters. Many recent studies [see review by Elsberry and Abbey (1991)] have pointed out that the size of a TC may have a significant effect in modifying the movement of the TC, although very few studies have been made on the problem of TC size. Therefore, it is important to understand the physical processes that govern the changes in size of a TC, a topic that has not been addressed heretofore because of the lack of data. Before such a study can be undertaken, it is necessary to establish a database of TC size. This study is therefore an attempt to document the size distribution of TCs over the western North Pacific (WNP) and the North Atlantic using satellite-derived wind information. The results will then provide a basis for further investigation of size changes and their possible relationship to track changes.

Brand (1972) studied the geographic and seasonal variations of very large and very small TCs, using the average radius of the outer closed isobar (ROCI) as a measurement of TC size, by examining 24 yr of typhoon data (1945–68). This definition of TC size was also used by Merrill (1984) in his study of TC size. The database used by Merrill consists of 183 Atlantic TCs (1722 position records) and 201 WNP TCs (2576 position rec-

ords). He found that climatologically the mean size of the WNP and Atlantic TCs is 4.4° and 3.0° lat respectively. The typical size of TCs varies seasonally and regionally and is only weakly correlated with cyclone intensity. Using more than 8500 radiosonde soundings over the WNP and the West Indies, Frank and Gray (1980) found that the frequency of 15 m s^{-1} wind occurrence around TCs increases with TC size, which is defined as the mean ROCI, and this relationship is more pronounced for more intense TCs. A right-side maximum in this frequency due to the asymmetry of moving TCs was also identified. Weatherford and Gray (1988a,b) studied the typhoon structure using aircraft reconnaissance from 66 TCs and examined the variation of the radial extent of 15 and 25 m s^{-1} winds (*R-15* and *R-25*). They found that the TCs at higher latitude have generally greater values of *R-15* and *R-25* than those at lower latitude with similar minimum central sea level pressure (MSLP). Furthermore, the *R-15* and *R-25* values are strongly correlated with the outer core wind strength (OCS), defined as the mean tangential winds of the 1° – 2.5° region but are only weakly correlated with cyclone intensity, measured as MSLP. Hawkins and Black (1983) evaluated the ability of the Seasat scatterometer data in detecting gale force winds (GFW) near TCs and found large asymmetries in the GFW.

As TCs spend most of their lifetime over the ocean, data from traditional sources are very sparse. However, the advance in meteorological satellites can provide high-resolution satellite-derived wind information. For example, the scatterometer on the *Seasat-A* satellite

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launched in 1978 was able to measure wind speed and direction over the ocean. The first passive Special Sensor Microwave/Imager (SSM/I) of the Defense Meteorology Satellite Program (DMSP) was introduced in 1987 to measure ocean surface wind speed for winds less than 50 kt in rain-free areas (Goodberlet et al. 1989). Then two satellites, the European Remote-Sensing Satellites 1 and 2 (*ERS-1* and *ERS-2*) were launched in 1991 and 1995, respectively. These latter satellites are also capable of measuring both surface wind speed and direction over the ocean. Recently, the National Aeronautics and Space Administration scatterometer (NSCAT) onboard the Japanese Advanced Earth Observing Satellite (ADEOS) was launched in August 1996. Unfortunately, ADEOS failed in June 1997. Other scatterometers such as QuickSCAT and SeaWinds will soon be launched. All these scatterometers provide a high-resolution near-surface wind field over the ocean so that it should be possible to make use of information from these satellites to define TC size. To assess this possibility, the *ERS-1* and *ERS-2* datasets are examined in this study, which represents the first attempt to use satellite data systematically in the study of TC size. The objectives of the present study are as follows:

- 1) to study the feasibility of using the ERS wind data to define the size of a TC, and
- 2) to develop a climatology of the size distribution of TCs over the WNP and the North Atlantic.

2. Data

a. Scatterometer wind data

The *ERS-1* and *ERS-2* satellites were launched on 17 July 1991 and 21 April 1995, respectively. The *ERS-1* satellite ceased operation in June 1996 and the *ERS-2* satellite should be operating until at least 1999 so that more data from *ERS-2* will be available. The onboard wind scatterometer provides measurements of near-surface wind speed and direction. The *ERS-1* and *ERS-2* data are available for the period August 1991–May 1996 and April 1996–December 1996, respectively. The Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER) offline products form the data source in this study.

The ERS satellites traverse the earth in a sun-synchronous, near-polar, quasi-circular repeating orbit, which allows global and repetitive measurements to be made. A typical scan geometry of the scatterometer over the WNP in a period of 1 day is shown in Fig. 1.

The measurement principle of the wind scatterometer is based on advanced microwave techniques. The sea surface is illuminated by microwave from the three antennas of the scatterometer. Three measurements of the backscattered signals from small ripples generated by the surface wind are made in each of the 19 resolution cells to the right of the satellite track resulting in a swath 500 km wide. The resolution cells are 50 km in diameter

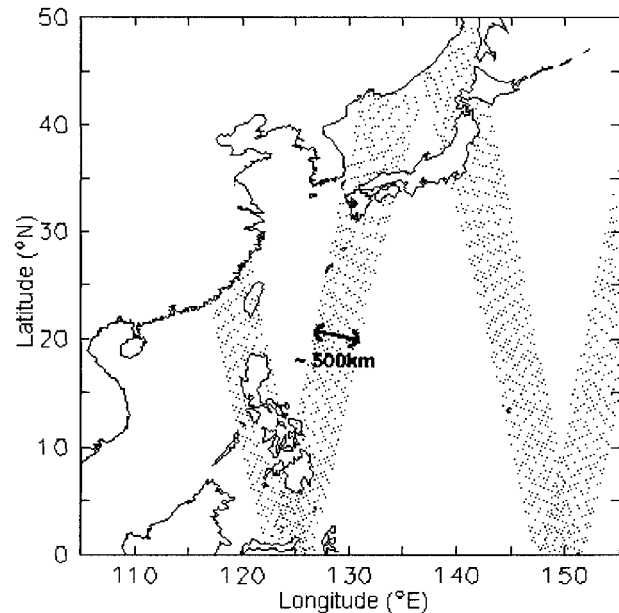


FIG. 1. Typical scan geometry of the ERS scatterometer during a period of 1 day. Area with ERS data is shaded.

and are centered at the nodes on a 25-km grid (Fig. 2). The wind data have an effective resolution of 50 km and correspond to 10-m height winds. As the back-scattered signal depends on the energy in these ripples, which is influenced by the surface wind, the wind speed and direction can be estimated using the C-band model, named CMOD_IFR2 (Quilfen and Bentamy 1994), which relates the measured backscattered signal to wind speed, wind direction, and incidence angles of the measurements. The two most probable solutions returned from the model have similar speeds but are 180° out of phase in direction. These directional ambiguities encountered in the model are then resolved by the ambiguity removal scheme (Quilfen and Cavanié 1991; Stoffelen and Anderson 1997).

The accuracy of the wind speed and direction derived from the scatterometer has been estimated by comparison with buoy wind measurements from the National Oceanic and Atmospheric Administration (NOAA) (Quilfen and Bentamy 1994). The scatterometer wind data were found to be in good agreement with those from buoys. The root-mean-square difference between scatterometer and NOAA buoy wind estimates is about 1.2 m s^{-1} for wind speed and 15° for wind direction. However, high wind speeds ($>18 \text{ m s}^{-1}$) are underestimated and the scatterometer also tends to overestimate low wind speed. Ebuchi and Graber (1998) found that the wind vectors from the IFREMER offline products and the Jet Propulsion Laboratory (JPL) value-added products show artificial directivity relative to the antenna beam directions and the directivity varies with the incident angle and wind speed. It is considered that this

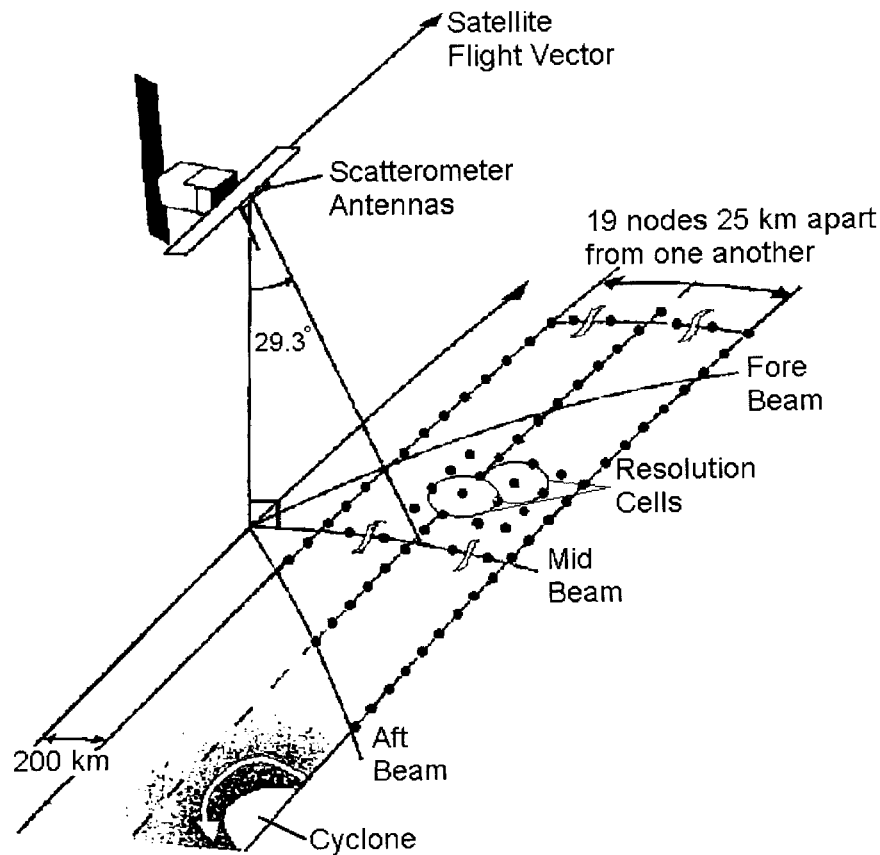


FIG. 2. Scan geometry of the ERS wind scatterometer (from IFREMER 1996). Dots (nodes) indicate the measurement points.

artificial directivity is caused by the errors in the model function used to derive the wind vectors.

The TC environment is characterized by strong winds and speed gradients as well as heavy rain. The remote sensing of surface wind in TCs using a wind scatterometer is discussed by Quilfen et al. (1998). As buoy measurements of high wind speed ($>18 \text{ m s}^{-1}$) are very sparse, the C-band model has very few such measurements for calibration so that the derived C-band model in this wind regime may not have the correct shape. The high winds in TCs are therefore likely to be underestimated. Moreover, the effective resolution of 50 km of the scatterometer wind data cannot resolve the high wind speed gradients of a TC. However, estimates of TC size in this study should not be significantly affected by such an underestimation since the winds in the outer regions are generally well below 20 m s^{-1} . The ERS and NSCAT data have been used operationally by the Joint Typhoon Warning Center (JTWC) to identify the gale winds areas, to determine the intensity of TCs at or below tropical storm intensity (17 m s^{-1}), and to locate the centers of poorly organized TCs (JTWC 1995; Edson 1997).

b. TC positions

The 6-hourly best-track positions of TCs with at least tropical storm intensity, which occurred between 1991 and 1996 over the WNP and the North Atlantic, are obtained from the JTWC and the National Hurricane Center (NHC, now known as the Tropical Prediction Center), respectively. These positions serve as a guide in identifying swaths that covered the TCs and for estimating the TC center at the time of the satellite pass. See section 3 for details.

3. Methodology

a. Selection of data

The dates and positions of each TC occurring within the period of study are identified first and the corresponding ERS data covering the TCs within a 30° lat square are extracted. Due to the scan geometry of the scatterometer coverage (see Fig. 1), it is not surprising that the TCs were not always covered by the swaths. In some cases, the swath covered the center of the TC (Fig. 3a), while in others only part of the TC can be captured (Fig. 3b). As the scatterometer wind data are underes-

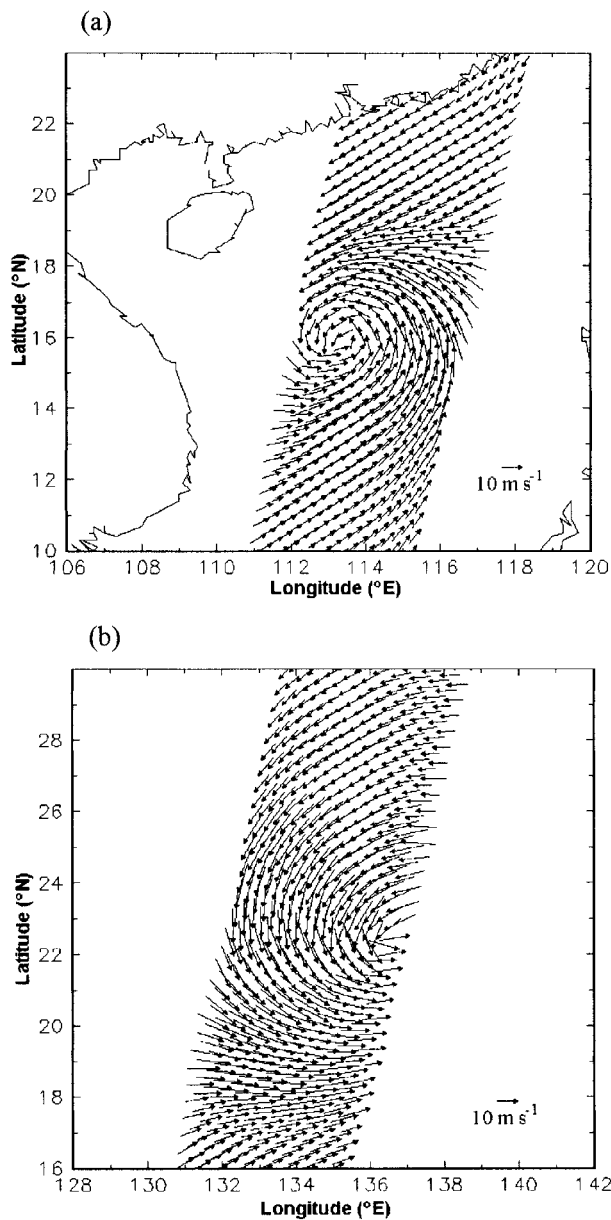


FIG. 3. Two situations in which the swath covers (a) the center and (b) part of the TC.

timated for high wind speed, the wind data within 1° lat of the center are not used. For those swaths not covering the TC center, the criterion for selecting the swaths requires the distance between the TC center and the edge of the swath to be $<2^\circ$ lat. In addition, the following points are considered in the selection of data.

- 1) Directivity of the wind vector: Since the directions of the wind vectors at the inner cells 1–3 (i.e., low incidence angles) are less accurate (Quilfen and Bentamy 1994) and show systematic preference relative to the antenna beam directions (Ebuchi and Graber 1998), the wind vectors at cells 1–3 are not used in

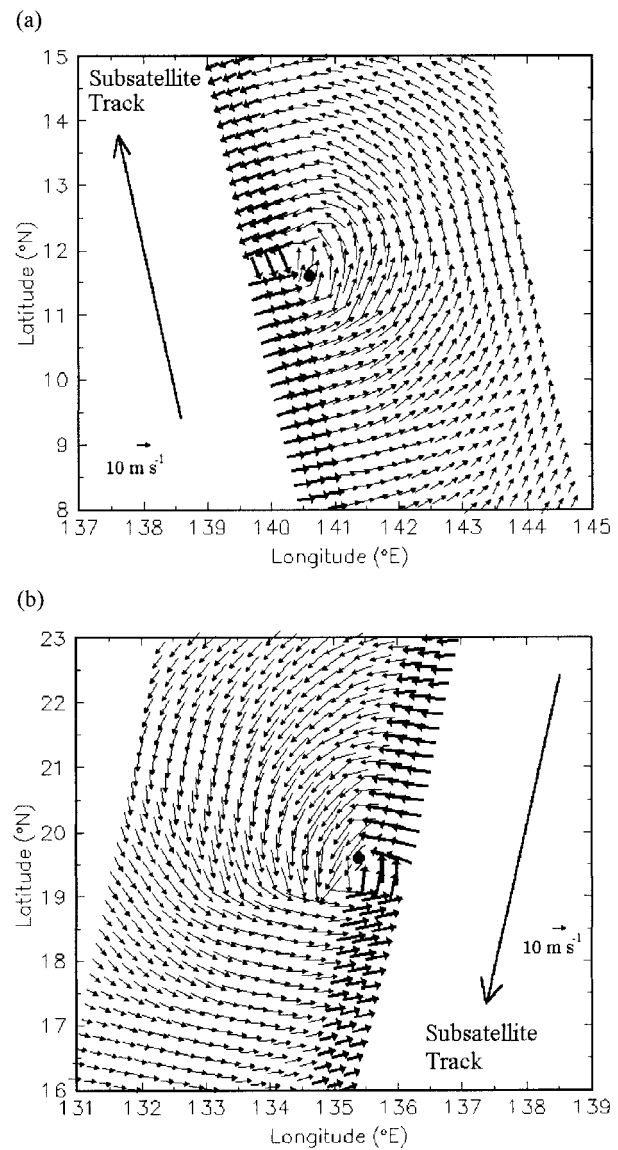


FIG. 4. Wind fields of (a) Typhoon Robyn (1310 UTC 4 Aug 1993) and (b) Typhoon Herb (0135 UTC 30 Jul 1996) as revealed by the ERS satellite. Bold arrows represent wind vectors at inner cells (1–3) and typhoon symbol indicates the TC center.

the construction of the relative vorticity field. Figures 4a and 4b show that the wind vectors at inner cells cannot reveal the cyclonic wind fields near the TC centers and are aligned in the midbeam direction.

- 2) Discontinuity of the wind field: Figure 5 shows the wind field of a TC located at about 19.8°N , 116.5°E . The winds in the area around 18.0°N , 115°E are aligned in the midbeam direction and therefore discontinuities of wind direction are present in the neighboring area. It is considered that the directivity of the wind vector may cause discontinuities of wind direction in some cases. The relative vorticity field

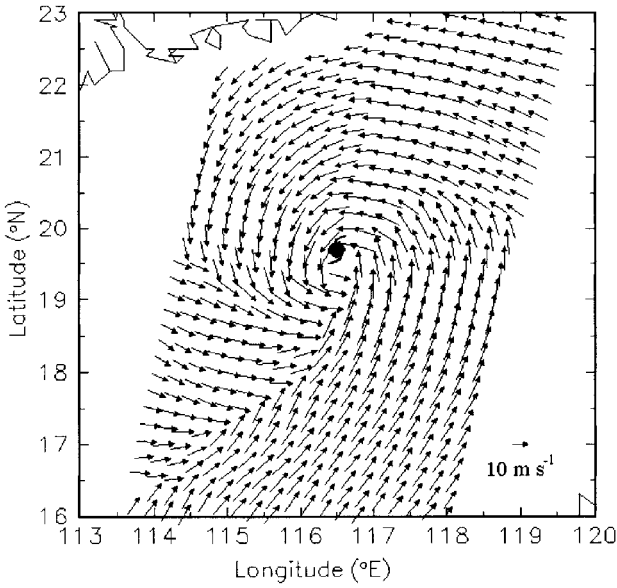


FIG. 5. Wind field of Typhoon Tasha showing a discontinuity south-southwest of the center (0240 UTC 19 Aug 1993). Typhoon symbol indicates the TC center.

the wind speed is low ($<3 \text{ m s}^{-1}$). In addition, if a TC is close to a land area or islands, some portions of the TC circulation are over the land area and therefore the wind data are unavailable. If the area of missing data is large, this swath of data is not used in the calculation of TC size.

b. Definition of TC size

The size of a TC is difficult to define objectively. Two definitions, the ROCI and the average radius of 15 or 17 m s^{-1} of surface winds ($R-15$ or $R-17$), are currently used by researchers and operational weather forecasters. The identification and forecast of the radial extent of gale force winds ($R-17$) are important to shipping and public safety, and therefore an operational requirement. However the $R-15$ or $R-17$ of a TC represents only a part of its circulation. In this study, a new definition of TC size is proposed. The relative vorticity associated with the TC is positive and decreases from the center. Hence, the boundary of the cyclone circulation may be defined as the radius at which the relative vorticity decreases to zero from the center. In this study, the size of a TC is defined as the mean radius at which the relative vorticity decreases to $1 \times 10^{-5} \text{ s}^{-1}$ from the center. This value is chosen rather than 0 because the zero contour is not always closed due to the relative vorticity associated with the environmental flow around the TC.

around this area may be distorted and therefore these data are not used.

- 3) Missing data: Invalid measurements of the wind vectors are found at some data points at which either the maximum likelihood estimator (MLE) is out of range, or one or more of the backscattered signal measurements from the three beams is missing, or

For each swath covering the TC (see example in Fig. 6a), the wind vectors at cells 1–3 are removed and the swath width is reduced to about 425 km. The wind speed

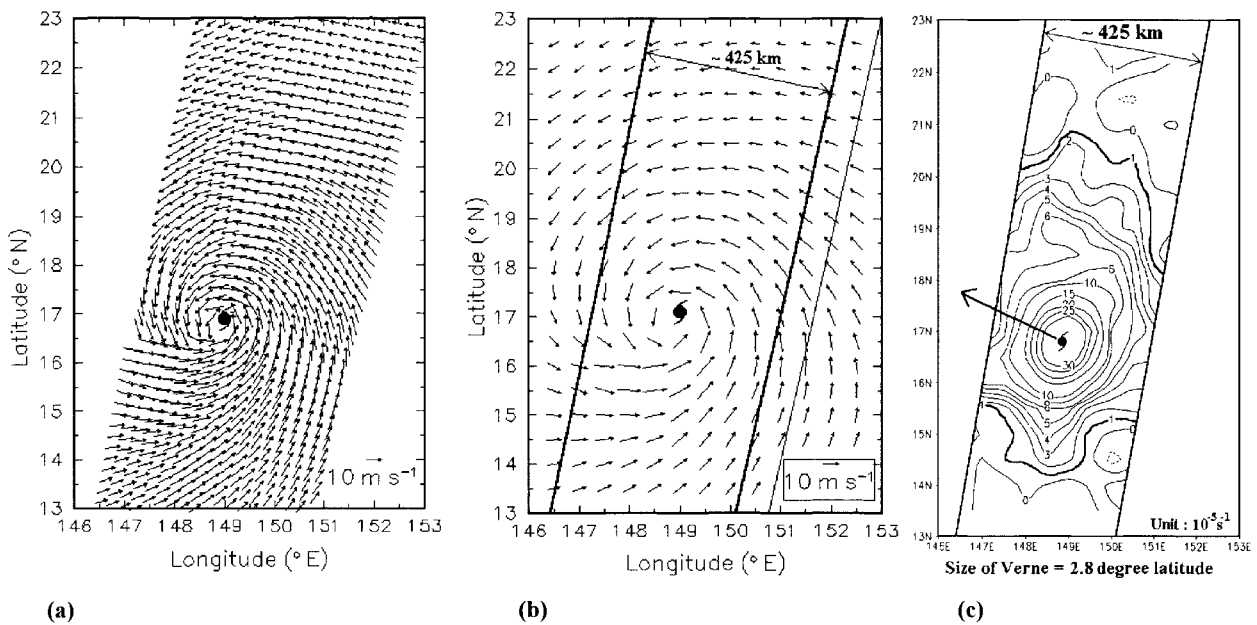


FIG. 6. Example of estimation of the size of a TC, in this case, Tropical Storm Verne at 0024 UTC 9 Nov 1991. (a) Wind field revealed from original ERS data. (b) Wind field after interpolated to a $0.5^\circ \text{ lat} \times 0.5^\circ \text{ long}$ square grid. (c) Relative vorticity field with a contour level of $1 \times 10^{-5} \text{ s}^{-1}$. The arrow shows the direction of the storm. Typhoon symbol indicates the TC center.

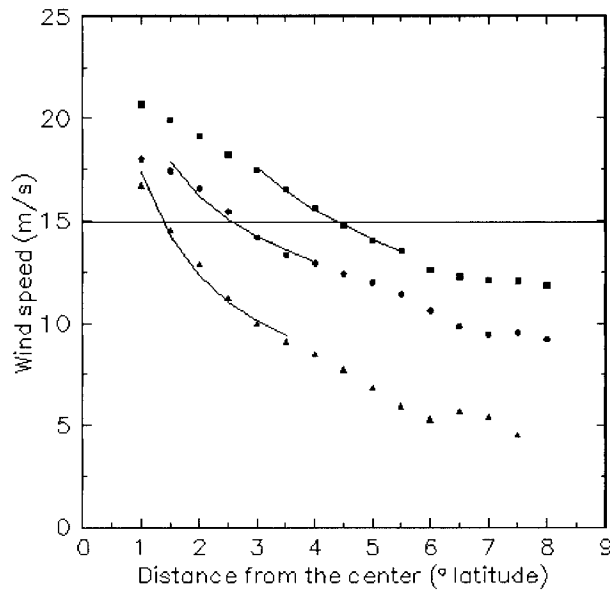


FIG. 7. Typical total wind profiles of TCs.

and direction from the ERS dataset are converted to the zonal and meridional components, which are then interpolated to a $0.5^\circ \text{ lat} \times 0.5^\circ \text{ long}$ square grid (Fig. 6b). Although the area changes slightly with latitude, this method of interpolation should not affect the results significantly because of the small grid size ($\sim 50 \text{ km}$) and that most of TCs are between 10°N and 30°N . The relative vorticity associated with the TC is then calculated using the finite difference method. The values of the relative vorticity are contoured at intervals of $1 \times 10^{-5} \text{ s}^{-1}$ (Fig. 6c). The size of a TC is then defined as the average distance (over points separated by an azimuthal angle of 5°) between the center and the $1 \times 10^{-5} \text{ s}^{-1}$ contour. The positions of the TCs corresponding to each swath are determined using one of the following methods. If the swath covers the center of the TC, the position of the TC is given by the location of maximum relative vorticity calculated from the ERS winds. Otherwise, the position of the TC is determined by linear interpolation in time of its best-track positions.

The R -15s of the TCs (studied by Frank and Gray 1980) are also estimated for comparison. The azimuthally averaged winds between 1° and 8° lat from the center at intervals of 0.5° lat are obtained by averaging the winds within each 0.5° lat wide ring belt (0.75° – 1.25° lat radial area for the first ring belt). Typical wind profiles of TCs are shown in Fig. 7.

Outside the radius of maximum wind (RMW), the TC behaves like a Rankine vortex described by

$$v = cr^{-x}, \quad (1)$$

where v is the tangential wind speed and r is the distance from the center of the TC. Since the tangential winds are only slightly smaller than the total winds (Frank 1977), the total winds are used to fit the Rankine vortex.

TABLE 1. Number of TCs with ERS coverage occurring over WNP and the North Atlantic and the number of cases. Numbers in parentheses indicate the total number of TCs with at least tropical storm intensity.

	WNP	North Atlantic
Number of TCs with ERS coverage	84 (187)	21 (61)
Number of cases (R -15)	185	54
Number of cases (size)	136	45

The coefficient and the exponent in 1) are obtained using a simple linear regression technique. Six points with wind speeds closest to 15 m s^{-1} are used in the regression as shown in Fig. 7. The R -15 is then obtained using (1).

4. Climatology of TC size and size change patterns

The number of TCs of at least tropical storm intensity with ERS coverage occurring over the WNP and the North Atlantic as well as the number of cases in which a successful estimation of size or R -15 that can be made are listed in Table 1. The relative small number of cases found in the North Atlantic is due to the fact that the average annual number of Atlantic TCs is much smaller than that in the WNP. In some regions of a TC such as rainbands, the wind directions can change rapidly and the scatterometer may not compute the wind directions correctly. In this case, the relative vorticity field may not be well defined and therefore the size of the TC cannot be obtained although its R -15 may still be estimated. This explains why the number of cases of estimating size is smaller than that of R -15. Based on this dataset, the asymmetries of TCs, the relationship between R -15 and size, the overall distributions of the sizes and the R -15s of the WNP and the Atlantic TCs and the seasonal variation of the sizes of the WNP TCs will be discussed. The size changes of selected TCs will also be examined.

a. Asymmetries of TCs

It is well known that asymmetries of surface winds with stronger winds on the right/left side with respect to the direction of motion exist in TCs in the Northern/Southern Hemisphere (Frank and Gray 1980; Holland 1980). The ERS swaths are generally north–south oriented. If the swath covers the center of a TC, the northern and southern portions of the TC can be viewed by the ERS scatterometer. Therefore the asymmetries of westward- or eastward-moving TCs can be better revealed by scatterometer data (Figs. 8a and 8b). For the swaths that cover the sides of the TCs, only the eastern or western portions of the TCs can be revealed. Therefore, the ability of ERS data to map TC asymmetries is limited in some cases. Many of the TCs in the database are observed to have asymmetric surface wind patterns.

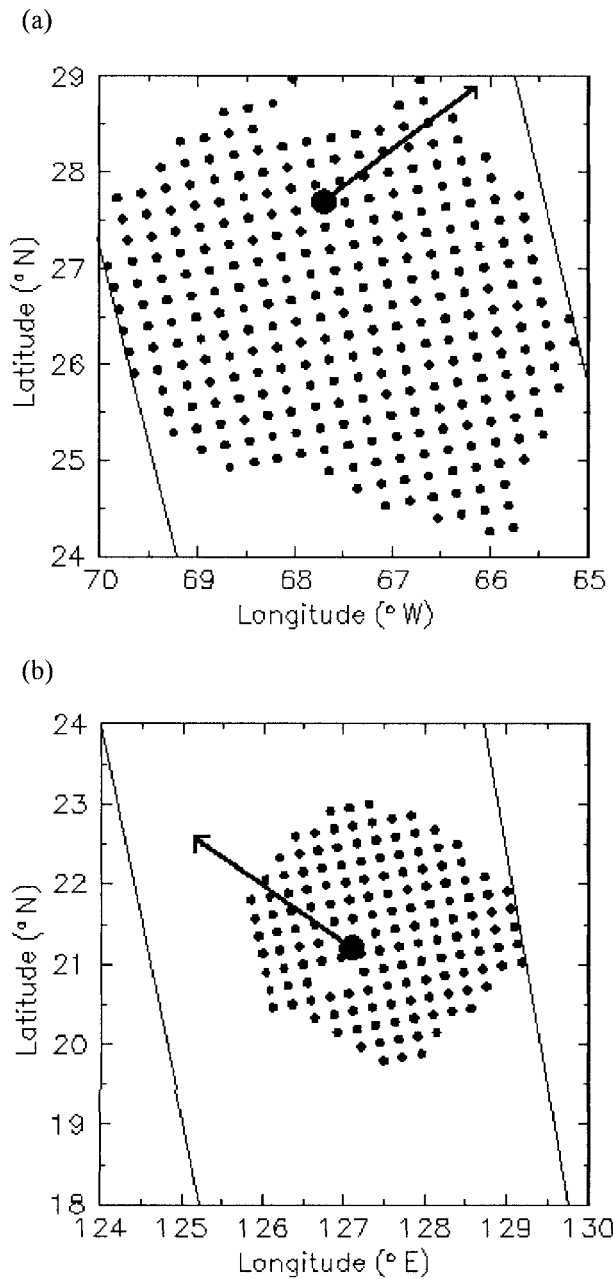


FIG. 8. Areal extent of winds above 15 m s^{-1} of (a) Hurricane Lili and (b) Typhoon Yancy. Small dots represent winds $>15 \text{ m s}^{-1}$. Large dot and arrow indicate the center and the direction of motion of the TC, respectively.

Similar asymmetries in TCs revealed by the ERS scatterometer are also found by Quilfen et al. (1998).

b. Relation between R-15 and size

In this study, the size estimated from relative vorticity is used as a measure of the areal extent of the TC circulation. Cases in which both $R-15$ and size can be estimated are compared to identify the correlation be-

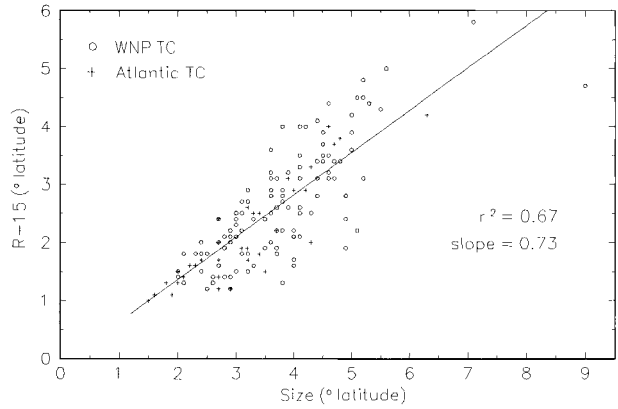


FIG. 9. Scatter diagram of $R-15$ vs size. Line indicates the regression line.

tween $R-15$ and size. The scatter diagram of $R-15$ versus size (Fig. 9) suggests that in general a TC with a larger circulation has a larger radial extent of 15 m s^{-1} winds and the correlation coefficient is found to be 0.82. In general, a change in size is accompanied by a change in $R-15$.

c. Overall distribution of sizes and R-15s of TCs

The percentage frequency distributions of the sizes and the $R-15$ s of the TCs occurring over the WNP and the North Atlantic in the period of study suggest that in general the TCs over the WNP have a broader spectrum of sizes and $R-15$ s (Figs. 10 and 11). The average size of the TCs is larger in the WNP than in the North Atlantic by about 0.7° lat (Table 2), which means that the average area enclosed by the circulation of WNP TCs is about 1.5 times larger than that of Atlantic TCs. This difference of mean TC sizes between the two basins is statistically significant at the 95% confidence level based on Student's t -test. Although the definition of the size of a TC used here is not equivalent to that using

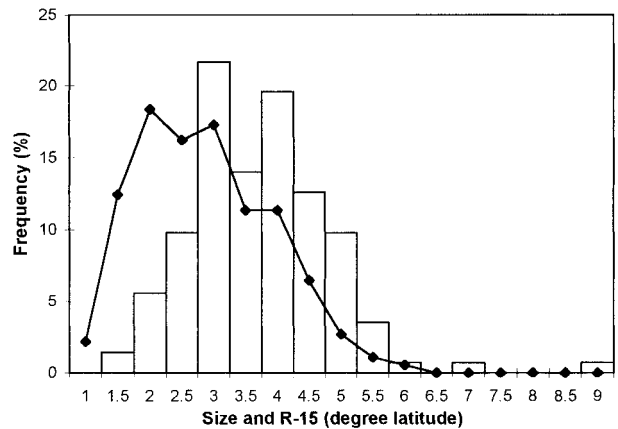


FIG. 10. Percentage frequency distribution of sizes and $R-15$ s of WNP TCs. Bars and line represent size and $R-15$, respectively.

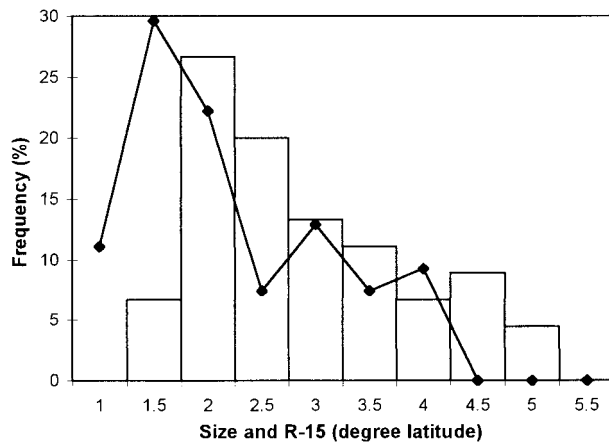


FIG. 11. As in Fig. 10 but for Atlantic TCs.

ROC1, the larger mean size of WNP TCs found in this study agrees with the results of Merrill (1984). This consistency and the high correlation between size inferred from the relative vorticity and from *R*-15 (see previous subsection) suggest the validity of using the present definition of size.

d. Seasonal variation of TC sizes

Because of a relatively small number of cases for the North Atlantic basin, only the seasonal variation of TC sizes over the WNP is discussed. The monthly mean TC size between July and November is shown in Fig. 12. It should be pointed out that Typhoon Gladys in August 1991, which was generated by a monsoon gyre (JTWC 1991), was excluded in the calculation of the mean size of August TCs because of its extreme size (>9° lat).¹ The mean size of August TCs is found to be smaller (statistically significance: 95%) than that of either September, October, or November TCs. The same is true for July TCs except for its relationship with September TCs. It may be concluded that the mean size of late-season (October and November) TCs is significantly larger than that of midsummer (July and August) TCs. Similar results are obtained for the seasonal variation of *R*-15s of TCs (not shown). Brand (1972) and Merrill (1984) also found a minimum mean TC size in midsummer and a maximum mean TC size in October in the WNP.

e. Size change patterns

As the scatterometer swaths provide only intermittent coverage of the TCs, the size changes of most TCs cannot be described completely throughout their life-

TABLE 2. Mean TC size obtained from this study and that from Merrill (1984). The corresponding standard deviation is in parentheses. Unit: ° lat

Basin	This study		Merrill (1984)
	Vorticity	<i>R</i> -15	Mean
WNP	3.7 (1.1)	2.9 (1.1)	4.4 (2.0)
Atlantic	3.0 (1.1)	2.2 (0.9)	3.0 (1.4)

time. However, the size changes during parts of their life cycle can be identified. The following section describes the size changes (increasing or decreasing) of some TCs.

1) SIZE INCREASING WITH TIME

Typhoon Seth reached tropical storm intensity at about 0100 UTC (ddhh) while tracking west-northwestward. Seth intensified rapidly and peaked at about 0318 UTC. It then started to slow down and turned west-southwestward on 6 November 1991 (JTWC 1991). Seth was first viewed by the scatterometer pass at 0300 UTC and its size was 2.4° lat. The next four passes showed that the size of Seth increased to 4.4° lat 0814 UTC and then decreased to 3.8° lat 1002 UTC (Fig. 13).

2) SIZE DECREASING WITH TIME

Typhoon Verne generally moved west-northwestward before slowing its forward speed at about 2106 UTC. Then it made an anticlockwise loop in the Philippine

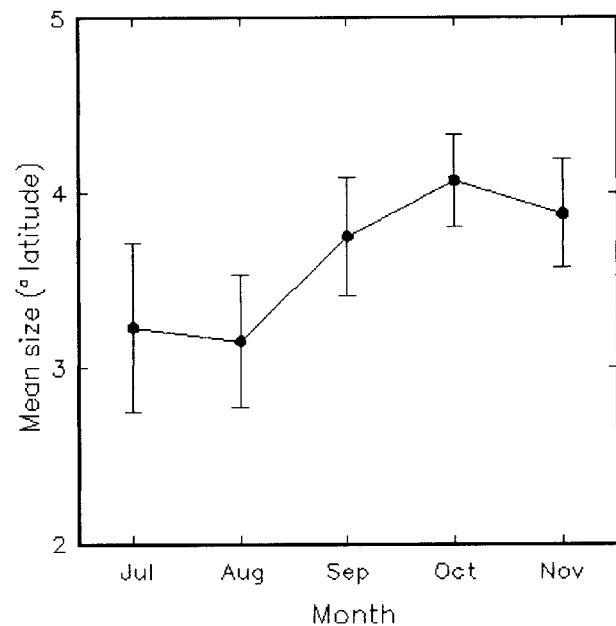


FIG. 12. Monthly mean TC sizes for the WNP TCs (vertical bars represent the 95% confidence interval).

¹ The inclusion of Gladys does not change the results qualitatively if the median value of the size of August TCs is considered instead of the mean.

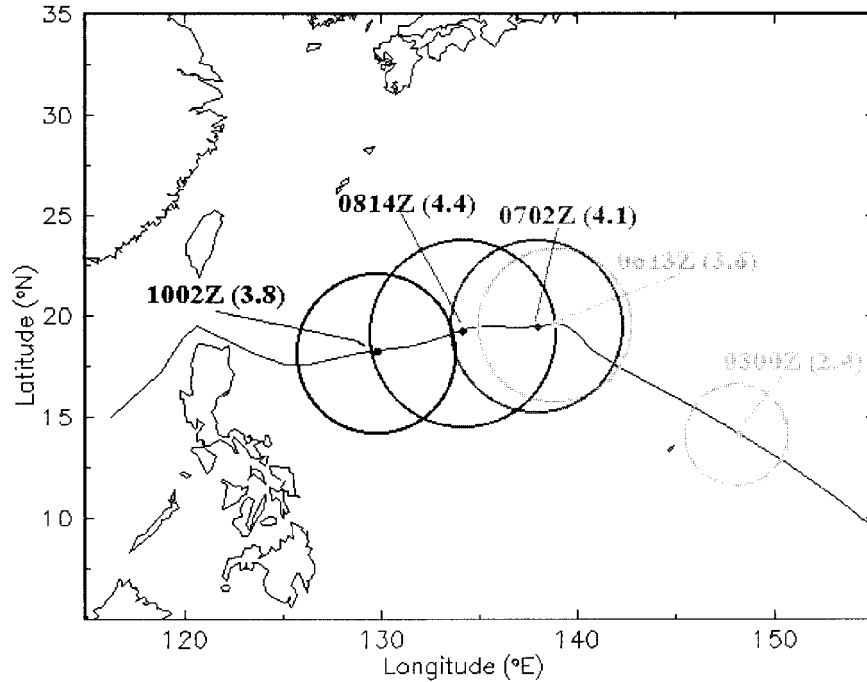


FIG. 13. Size change of Typhoon Seth as indicated by the circles that have a radius (indicated in parentheses) equal to the average radius at which the relative vorticity decreases to $1 \times 10^{-5} \text{ s}^{-1}$ from the center. The date and time in UTC are also indicated.

Sea (JTWC 1994). The size of Verne decreased slightly from 4.4° lat 2302 UTC to 3.8° lat 2901 UTC as viewed from the four *ERS-1* scatterometer passes in 1994 (Fig. 14). At the same time, the intensity of Verne changed from 90 kt at 2300 UTC to 115 kt at 2318 UTC and then gradually to 50 kt at 2818 UTC.

While such size change results appear to be expected

or trivial, they demonstrate the possibility of using scatterometer data to monitor the temporal variation of TC size, which could never be achieved from conventional data sources.

5. Summary and discussion

a. Summary

This study utilizes *ERS-1* and *ERS-2* wind scatterometer data to estimate the sizes and the radii of 15 m s^{-1} winds (*R-15s*) of the tropical cyclones (TCs) occurring over the western North Pacific (WNP) and the North Atlantic between 1991 and 1996. The size of a TC is defined as the mean radius at which the relative vorticity decreases to $1 \times 10^{-5} \text{ s}^{-1}$ from the center.

During the period of study, 239 and 181 estimates of *R-15s* and sizes of the TCs are made, respectively. The relatively small number of cases is due to the intrinsic scan geometry of the sensors and the relatively narrow swaths. Based on these cases, the mean and the standard deviation of TC sizes are found to be 3.7° and 1.1° lat for WNP TCs, and 3.0° and 1.1° lat for those in the North Atlantic. This represents a 0.7° lat size difference between WNP and Atlantic TCs. The mean TC size in the WNP is found to vary seasonally, being larger during the late season (October and November) and smaller during midsummer (July and August). The above results generally agree with those from previous studies. In addition, the *R-15* of a TC is found to be highly cor-

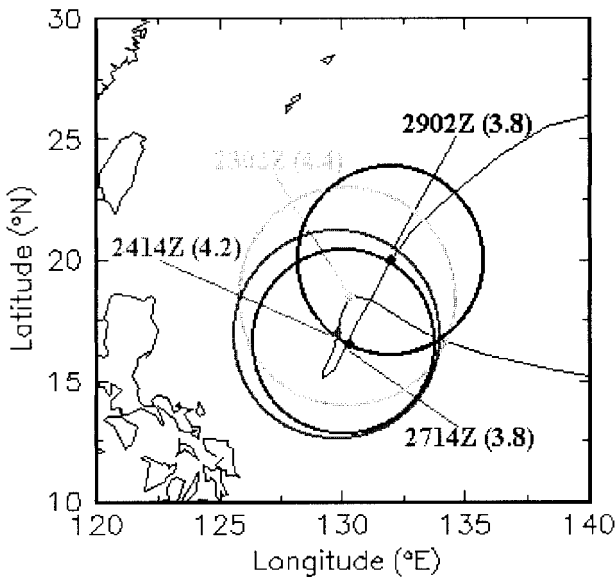


FIG. 14. As in Fig. 13 except for Typhoon Verne.

related with its size (based on relative vorticity). Asymmetries in TCs can also be revealed by the ERS scatterometers.

b. Discussion

The ERS data have been demonstrated to be useful in the study of TC size. The results in section 4 also suggest that the scatterometer wind data are able, to some degree, to monitor the size change of TCs. However, there are some limitations of the utilization of ERS data in the study of TC size. First, the TCs are not always covered by the swaths. Therefore the daily size change may not be monitored. Second, the swaths cover only parts of the TCs. As a result, the influence of the asymmetry of TCs may not be included in the calculation of TC size. Third, the errors in the model function deriving the wind vectors cause directional preference of the wind vectors relative to the beam directions. An improvement of the model function is required to solve this problem. Nevertheless the ERS scatterometer data represent a unique data source in the study of TC size. The SSM/I data provide another source of satellite-derived wind data. This dataset is not used in this study although its swath (1400 km in width) is wider because this passive microwave radiometer measures only scalar winds over the ocean and the measurements are contaminated by rain and heavy cloud cover, which are always associated with TCs (Goodberlet et al. 1989). Comparing with SSM/I data, the C-band scatterometer (onboard the ERS satellites) data are not too seriously contaminated by heavy rain (Quilfen et al. 1998). The NSCAT scatterometer data, which have a swath width (1200 km) twice as the ERS data, provide better coverage of the TCs, but unfortunately the satellite carrying this scatterometer failed in June 1997 and this dataset is available only for the period September 1996–May 1997. Therefore this short-period dataset is not used in this study.

The mean size of late-season TCs is found to be larger than that during midsummer and further studies are required to investigate the synoptic conditions favorable for the occurrences of large or small TCs. Moreover the physical processes governing the size change of a TC are not known yet.

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