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DOPPLER RADAR INVESTIGATIONS OF THE INNER CORE OF TYPHOON SONGDA (2004) Polygonal / elliptical eyewalls, eye contraction, and small-scale spiral bands.

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1. INTRODUCTION

Inner core is one of the most important components of tropical cyclone. The most severe convective activity and devastating winds are concentrated in this region. Furthermore, the major energy generation and conversion processes take place within this region to drive the entire system. While the vorticity dynamics of inner core have been the subject of recent numerical and theoretical studies, it has yet to be explored in great observational detail. This paper documents the structural evolution of the inner core of Typhoon Songda (2004) before and during landfall on the Okinawa Island. The Doppler radar for Airport Weather (DRAW) on the Okinawa Island observed around the inner core over long periods because the typhoon center moves slowly enough to remain in the radar coverage. Therefore, the DRAW observation provided unique data set of high spatial and temporal resolution that has been used for analyzing the detailed inner-core structures.

2. STORM HISTORY (Fig. 1)

A tropical storm Songda began forming near the Marshall Islands region on 0000UTC 28 August 2004 and strengthened into a typhoon near 15.5N and 151.5E on 1200UTC 30 August. Songda continued to strengthen and moved west-northwestward, then northwestward. It crossed the Okinawa Island on approximately 1000UTC 5 September and reached the peak intensity with the lowest central pressure of 925hPa and wind speed of approximately 45ms^{-1}.

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The storm changed direction to northeastward across the East China Sea, crossed the northern part of Kyusyu Island around 0000UTC on 7 September, entered the Japan Sea, and caused damage along the Japan Sea coast. The storm weakened and was downgraded to a tropical storm by 1600UTC 7 September over the northern part of the Japan Sea and became an extratropical cyclone 14 hours later.

3. DATA

The data used in this study include (a) the Naha DRAW data and (b) the surface weather data at the Nago Meteorological Observatory. The locations where the data were taken are shown in Fig. 2.

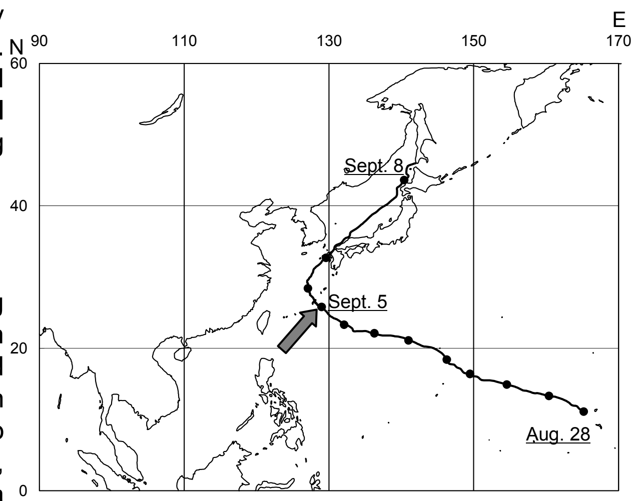

FIG. 1. Best track of Typhoon Songda between 28 August and 8 September 2004. The arrow shows the study area.

a. The Naha DRAW

The Doppler Radar for Airport Weather (DRAW) started its operation in 2003 as a wind shear detection and warning platform at Naha International Airport. It has a 120-km observation range, a 0.7° azimuth resolution, and a pulse length of 1.0 ms providing independent data points every 150 m in range. A volume scan update rate of 6 min and a 75-s time series of Doppler velocity near the surface can be obtained because the volume scan mode is regularly interrupted by the PPI scan of the lowest elevation, 0.8°, for the purpose of operational low-level wind shear detection.

b. Surface weather data

We used the routine surface weather data at the Nago Observatory, over which passage of the inner core of Songda was clearly identified with the Naha DRAW.

4. RESULTS

Radar echoes from the Okinawa weather surveillance radar reveal the presence of concentric eyewalls. Figure 3 shows an example at 1800 Japan standard time (JST) during landfall. The outer eyewall was not always completely closed and/or the inner and outer eyewalls were sometimes in contact with each other. At this time the inner eyewall was between 10- and 30-km radius and the outer eyewall between 70-and 130-km radius, with an approximately 40-km precipitation-free gap between the inner and outer eyewalls. In this study, we will focus on the region within the inner eyewall (i.e., the inner core).

a. Small-scale spiral bands

In order to enhance the reflectivity contrast in the inner core, a perturbation reflectivity field was calculated. The perturbation reflectivity field was derived by averaging the reflectivity on a small sample area (2-km range by 20-deg azimuth) and then subtracting the averaged reflectivity from the original. Figure 4 shows an example. The perturbation reflectivity field reveals many small-scale spiral structures spiraling outward from the eyewall, which are approximately similar to those shown by Gall et al. (1998) and Morrison et al. (2005) for several hurricanes. These bands are with a cross band width of perhaps 3-4 km and length of over 100 km.

Figure 5(a) shows the PPI image of the DRAW reflectivity at 1704JST around the time when passages of spiral bands were clearly identified over the Nago Observatory. The average band wavelength is approximately 7.0km and the width is approximately 3.0km. The Doppler velocity pattern is shown in Fig. 5(b). The effects of the passage of spiral bands over the Nago are shown in Fig. 6. Associated with the passages of bands, short time-scale (about 10min) perturbations are identified. The azimuth wind variations are around 6.0ms^{-1}. Note that the phases between reflectivity and velocity are not always consistent. The surface wind speed perturbations of the Nago Observatory were much smaller than the period of the band passages (not shown). The surface wind speed perturbations swaths may be attributable to sub-band scale.

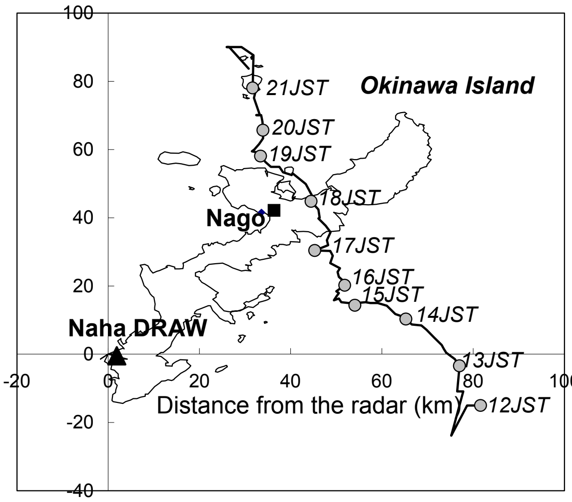

FIG. 2 Enlarged map around the study area including site names: the Naha DRAW (triangle) and the Nago Observatory (square). Bold line is the track of the typhoon center. Small circles indicate the locations of the typhoon center at 1-hour intervals.

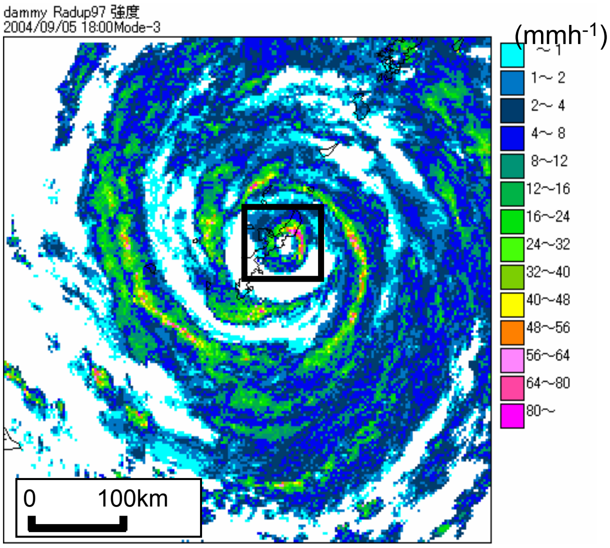

FIG. 3. Radar echo from the Okinawa Weather Surveillance Radar at 1800 JST 5 September 2004. The square indicates the inner-core region (target area).

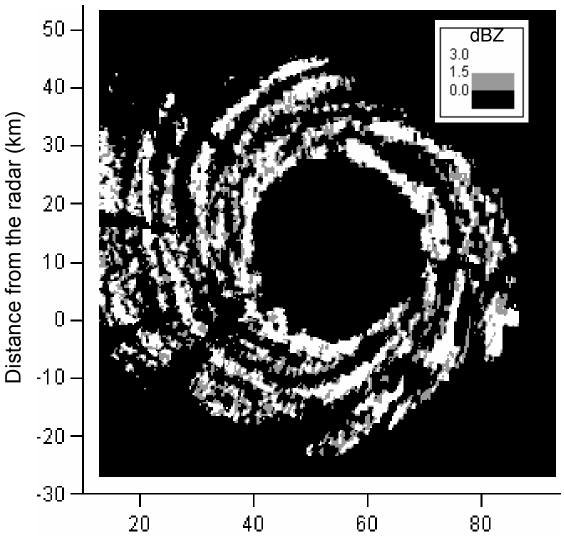

FIG. 4 Perturbation reflectivity field for the inner-core region of Songda (1203JST 5 September 2005, el=2.1).

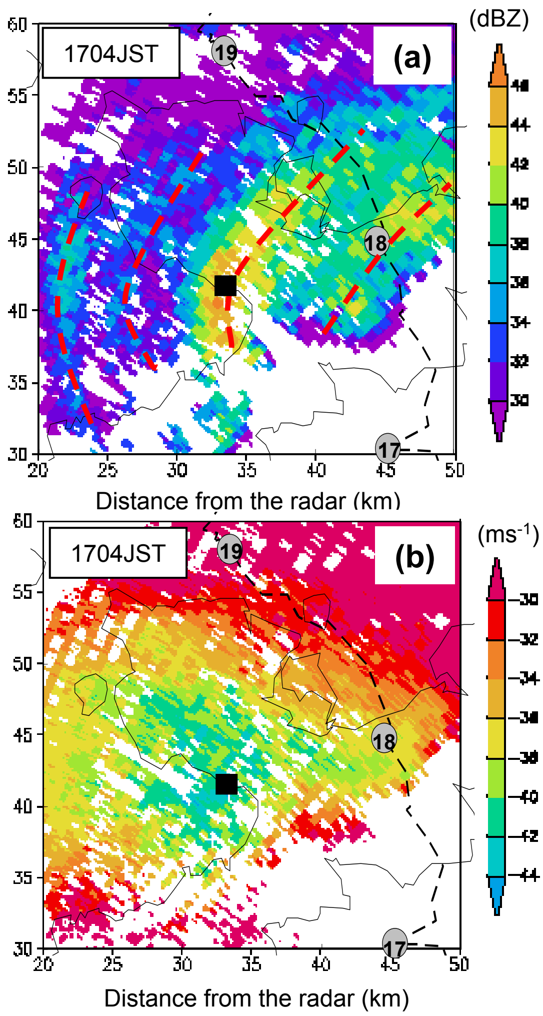

FIG. 5. PPI images at 1704JST. (a) Reflectivity and (b) Doppler velocity. The square indicates the location of the Nago Observatory. The thin dashed line is the track of the typhoon center. Small circles indicate the locations of the typhoon center at 1-hour intervals. The bold dashed lines in Fig. 5 (a) indicate the locations of bands.

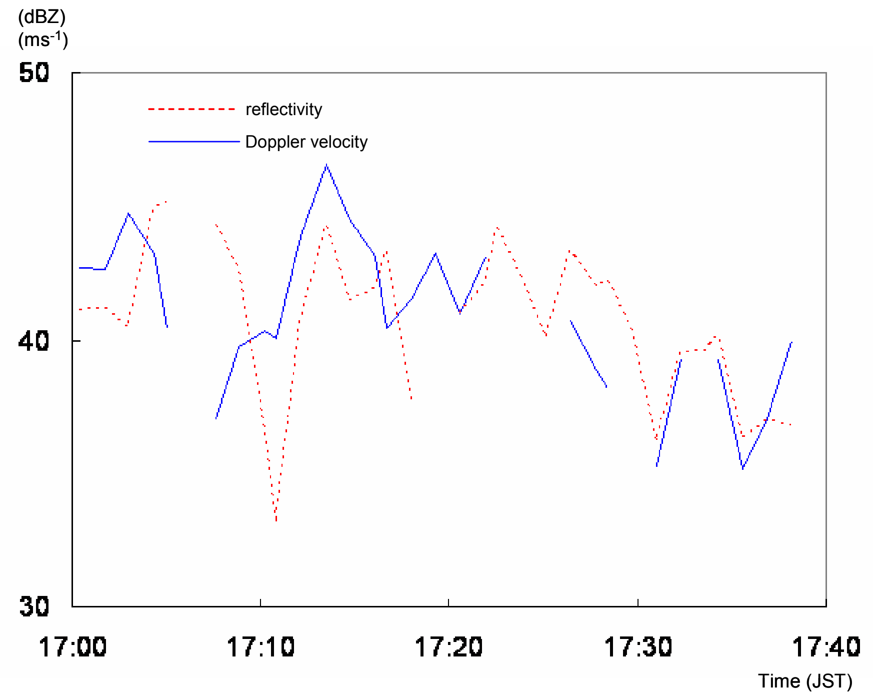

FIG. 6. The 75-sec time plots of radar reflectivity and Doppler velocity at 700m altitude (the lowest elevation is 0.8°) over the Nago Observatory. Note that the Doppler velocity data are absolute values.

b. Polygonal and elliptical eyewall structure

Polygonal eyewall structure is a common feature of most tropical cyclones. In order to quantify the eyewall shape, we introduce a quantity termed the equivalent circle - the circle with the same area as the eye. The inhomogeneous shape of the eye is represented by a length of difference between the radius of eye and the radius of equivalent circle as follows:

$$r_{anom}(\theta) \equiv \frac{R(\theta) - R_{eq}}{R_{eq}}$$

where R is the radius of eye and R_{eq} is the radius of equivalent circle.

Figure 7 shows the time series of r_{anom}. It is indicated that the eyewalls had rotational speeds of approximately 30ms^{-1} which is about 60-70% of maximum tangential velocities. The DRAW images indicate that the polygonal eyes ranging from squares to hexagons offshore are the dominate feature between 1300JST and 1500JST. Figure 8(a) indicates r_{anom} at 1400JST along line AB in FIG. 7. The outline of pentagonal eyewall is shown in FIG. 8(b), in relation to comparison of the r_{anom} property. Figure 9 is the same as FIG. 8 but for 1612JST (line CD in FIG. 7), and reveals that Songda had an elliptical eye. The eye was transformed to elliptical shape at 1500JST when the northwestern edge of the inner core made landfall at the Okinawa Island. The elliptical eye was observed until 1900JST when the inner core moved out of radar range.

c. Eye contraction and other prominent features

Figure 10 shows the time series of some variables indicating the eye contraction and other prominent features between 1200JST and 2200JST 5 September 2005. FIG.10(a) and (b) show inbound and outbound Doppler velocities and radar reflectivity, respectively. Bold lines are associated with the Okinawa Island and the terrain contours at 100-m intervals. In the northwestern eyewall, the tangential velocities at 917m AGL peaked at 56.7m s^{-1} at 1434JST, just before the landfall of the edge of the inner core made landfall on the Okinawa Island (FIG.10(a)). The radar reflectivity increased dramatically and the eye radius began to fluctuate around the same time (FIG.10(b)); it is also associated with the transition from polygonal to elliptical eyes. Note that the eye radius began to contract at 1600JST (at the landfall of the eye center) and reached the minimum size of 11.0 km at 1822JST.

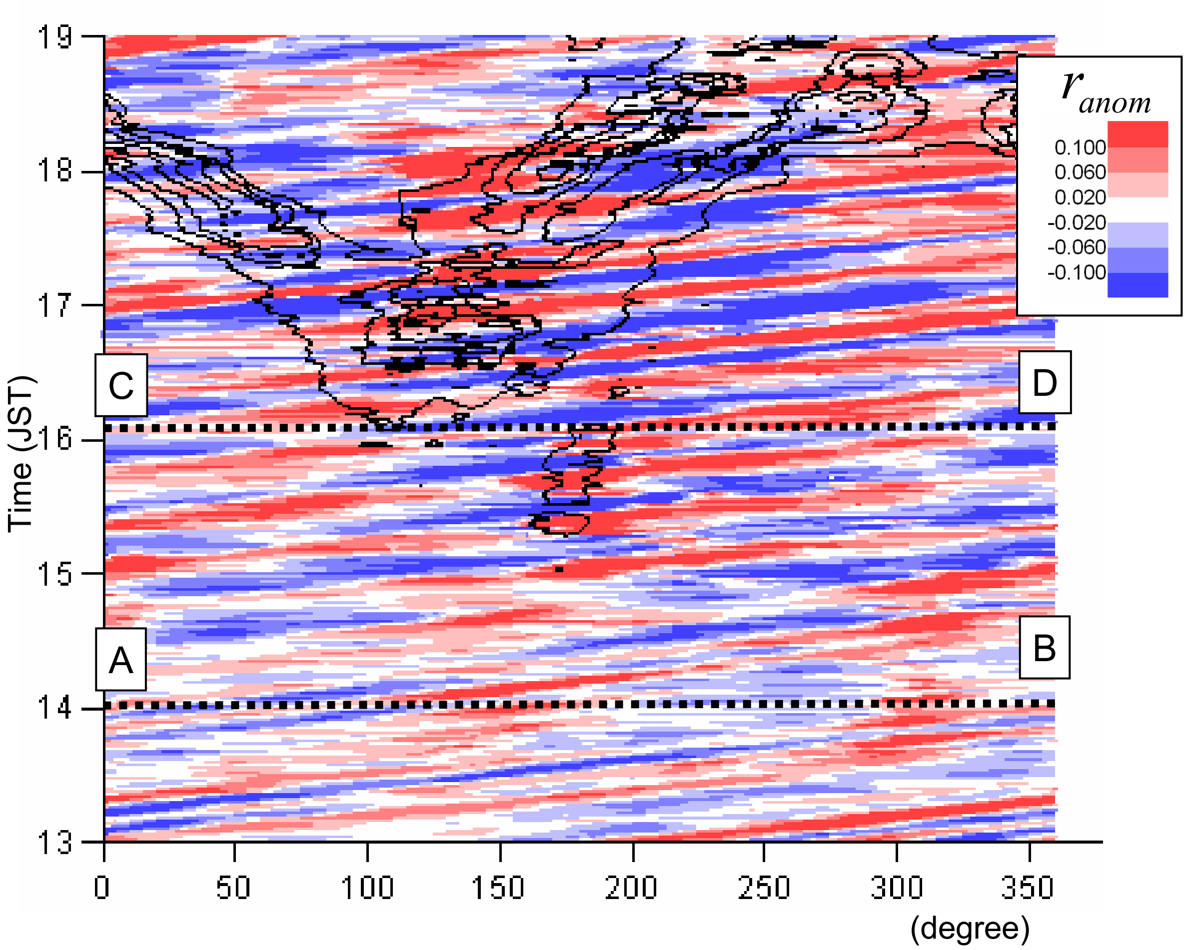

FIG. 7 Time series of r_{anom}. The horizontal axis indicates azimuth angle from eye center. Bold lines are associated with the Okinawa Island and the terrain contours at 100-m intervals.

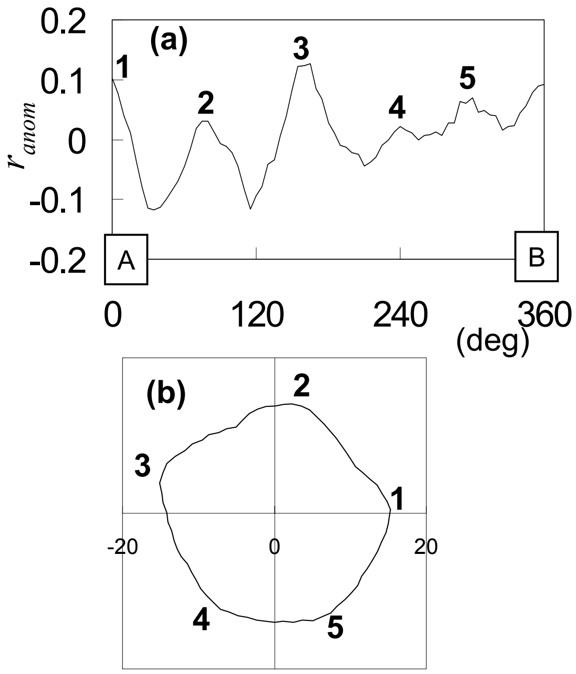

FIG. 8 (a) r_{anom} at 1400JST along line AB in FIG. 7. (b) The outline of eye at the same time. The integer numbers (from 1 to 5) indicate the apexes of the pentagon.

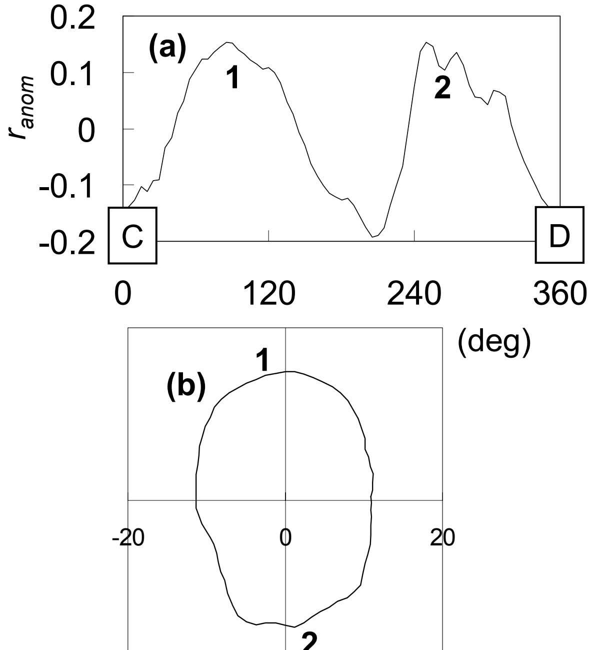

FIG. 9 Same as FIG. 8 but for 1612JST (line CD in FIG. 7). The integer numbers (from 1 to 2) indicate the apexes of the ellipse.

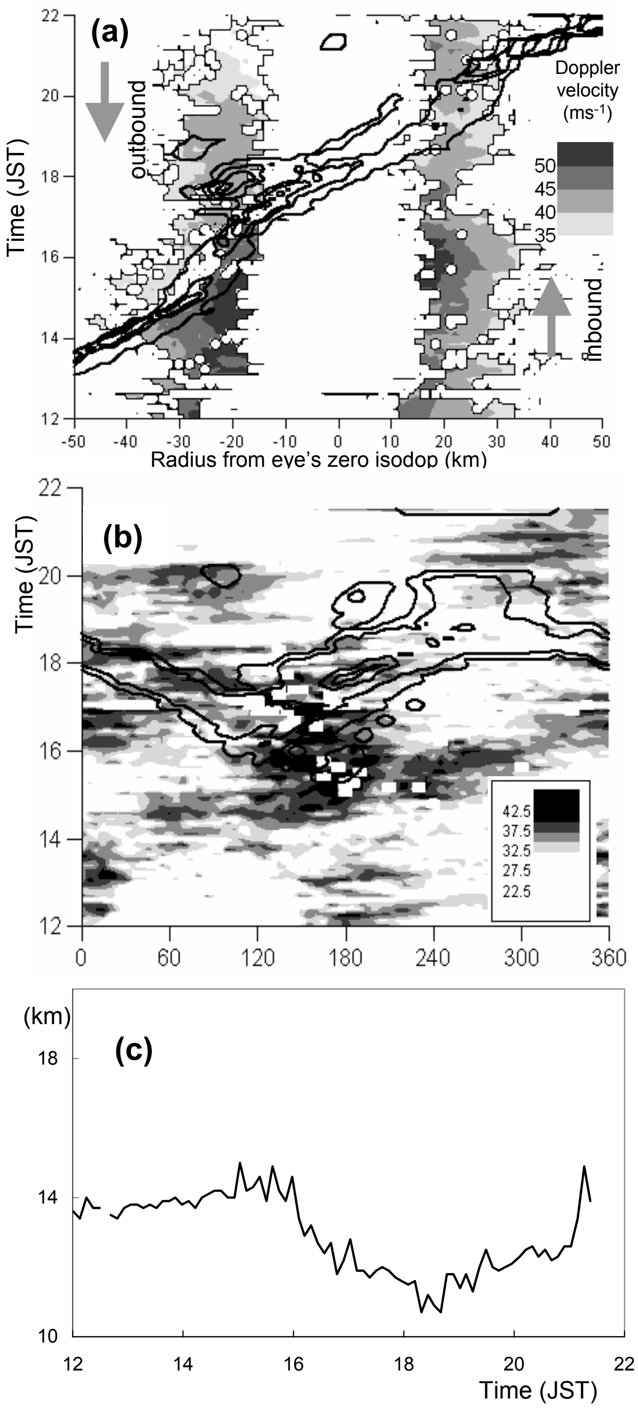

FIG.10 Time series of some variables indicating the eye contraction and other prominent features between 1200JST and 2200JST 5 September 2005. Bold lines in (a) and (b) are associated with the Okinawa Island and the terrain contours at 100-m intervals. (a) Inbound and outbound Doppler velocities between 1200JST and 2200JST 5 September 2005. (b) Radar reflectivity. The horizontal axis indicates azimuth angle from eye center. (c) Eye radius. Note that the eyes are sized by the equivalent circles.

5. DISCUSSION AND CONCLUSIONS

This paper documents the structural evolution of the inner core of Typhoon Songda (2004) before and during landfall on the Okinawa Island. The Doppler radar for Airport Weather (DRAW) on the Okinawa Island provided unique data set of high spatial and temporal resolution that has been used for analyzing the detailed inner-core structures. The major features of inner core evolution of Typhoon Songda are as follows.

1) The perturbation reflectivity field reveals many small-scale spiral structures spiraling outward from the eyewall, which are approximately similar to those shown by Gall et al. (1998).
2) Another interesting feature that has been observed in the eyewall region is the presence of polygonal and elliptical patterns in radar reflectivity. Songda revealed polygonal eye shapes ranging from squares to hexagons offshore, followed by an elliptical eye near the Okinawa Island. These eyewalls had rotational periods of approximately 60-70% of maximum tangential velocities.
3) Songda reached maximum intensity during the transition from polygonal to elliptical eyes. Around the same time, the radar reflectivity increased and a large asymmetry appeared in the inner-core. The eye began to contract at the landfall of the eye center.

The small-scale spiral structures are needed to compare various case studies and investigate the dynamics. The influence of topography on the inner-core transitions, such as eye shape, core intensification, and large asymmetry and intensification in radar reflectivity (resulting rainfall patterns) are also interesting topics for further research.

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