The Structure of Polygonal Eye of a Typhoon*

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Abstract

A distinct polygonal eye was observed for 15 hrs in the PPI image of typhoon 8019 WYNNE. The shape of radar eye of approximately 30 km diameter was variably square, pentagonal and hexagonal, and rotated counterclockwise around its center. The period of rotation was 41–43 minutes for the pentagon and hexagon compared with 47–50 minutes for the square. The period decreases (tangential velocity increases) as number of corner of polygon becomes larger. The pentagonal shape occurs most frequently and persists for 111 minutes, contrary to 12 minutes for square shape. There are no observations of a triangular or heptagonal shapes.

The deformation of the polygon is restricted within the narrow, limited portion with several kilometers width inside of inner eyewall of concentric double eye. The phenomenon coincides with the largest shear of tangential velocity. As the result of tracking small convective cells in the eye, the cells rotate in a Rankine vortex field; moreover, polygonal features have a higher rotational velocity than the cells inside the eye. The straight-sided portion of polygon becomes wavy as if instability exists at the inside boundary of eyewall. The phenomenon took place in the concentric double eye of well-developed tropical cyclones with approximately 920–950 mb central pressure and 30–50 km of eye diameter.

1. Introduction

Lewis and Hawkins (1982, referred to as L.H.) first investigated the occurrence of polygonal and partial polygons in the wall clouds and rain-bands of strong typhoons. A possible kinematic explanation based on interference patterns of internal gravity wave is also shown in their paper.

In the present paper, polygonal eyes of the mature typhoon in the northwestern Pacific Ocean are studied in detail by using successive PPI radar images taken at 6 minutes intervals at Miyakojima radar. Fortunately, the distinct radar eye of the typhoon 8019 WYNNE was observed for 36 hrs, during which period polygonal eye occurred for 15 hrs within the radar range of 300 km radius.

The kinematical explanation for the polygonal eye formation will be discussed in analysis of observations on the well-defined its shape and structure change. Moreover, by comparison with other cases, common conditions forming the polygon are investigated. Trochoidal motion of the eye in this typhoon was already studied (Muramatsu, 1986).

2. Data

Observational data used in this study comprise, 1) time-lapse 35 mm film photograph of Plain Position Indicator (PPI) radar and Range Height Indicator (RHI), 2) geostationary meteorological satellite (GMS) cloud imagery, 3) reconnaissance aircraft data.

The Miyakojima radar is located on a small, isolated island. No other large island exists in the range of 300 km radius. Thus we can obtain good echo images which are not influenced by environmental orography.

3. Polygonal eye of the typhoon 8019

Fig. 1 illustrates the best track fixed by JMA (left part) and original track of radar eye center observed by Miyakojima radar cite (right part)
Fig. 1. Best track fixed by JMA (left part) and the original track of radar eye by observed by Miyako-jima radar (right part) for the typhoon 8019 WYNNE.

Typical features of mature typhoon are seen, in which black and white brightness represent the radar reflection and no echo, respectively. The distinct eye surrounding with well-defined eyewall of 20–30 km width is seen northeast of the radar cite. Simultaneous RHI image directed across the center of eye is shown in Fig. 3 in which the black and white colours are reversed to those in Fig. 2. The echo top reaches to near the tropopause, and the diameter of eye, which has a vertical axis increases vertically. On the other hand, the developed convective ring-shaped cloudiness on the visible GMS image at 04100 GMT corresponds to eyewall of radar reflection. Its cloud top temperature is below minus 75°C corresponding to that of the tropopause.

In Fig. 2, it is most interesting that the eye of the typhoon becomes a polygonal feature. The inner side of eyewall is deformed into an equilateral hexagonal feature characterized by six straight sides. The radius of the eye, defined as a circle inscribed within the apexes of the polygon, is 30 km at 0400 GMT. The deformed portion was restricted within narrow ring of approximate 3 km width.

Moreover, the well-defined hexagon changes to a equilateral pentagon after 41 minutes, shown in Fig. 4. The lower part of the figure represents a echo reflectivity corresponding to

For the typhoon 8019 WYNNE. WYNNE attained to typhoon intensity at 0600 GMT on October 6. It reached minimum central pressure of 890 mb at 1600 GMT on 8th after rapid intensification. Within 300 km of the radar, the typhoon maintained strong typhoon intensity with 920 to 935 mb central pressure and a distinct radar eye for 36 hrs.

In Fig. 2, in the PPI images at 0400 GMT, a
rainfall intensity of more than 1 mm/hr. Each side of the polygon is line echo (b–c) or a chain of small echo cell (a–b) at the inside of eyewall.

The polygonal deformation does not extend to the whole eyewall itself but is restricted within narrow limited ring innermost part of eyewall of several kilometers width in this case.

Miyakojima radar is settled a small island in the Ryukyu islands lie between the East China Sea and the Pacific Ocean. No large islands exists within of 300 km radius. Thus the deformation of eye is one of the proper phenomena for eye structure of typhoon not the result of orographic effects.

4. Rotation of the polygonal eye

1) Rotation of the polygonal eye

To discuss the kinematic structure for the polygonal eye more clearly, successive PPI images at 6 minutes intervals between 0441 and 0551 GMT are presented in Fig. 5. It is clearly found by tracking the characteristic echo indicated by “U” that the polygonal shape rotates counterclockwise. Similarly, the straight-sided portion marked by an asterisk (V) at 0452 GMT and features marked by (V) at 0503 GMT and (X) at 0551 GMT can be tracked till 0551 GMT, 0515 GMT and 0533 GMT, respectively. As a result of tracking each marks, the pentagonal shaped eye rotates counterclockwise though one and three-quarters cycle in 70 minutes, giving a period of about 40 minutes.

Fig. 6 illustrates the consecutive shapes of the eye approximated by polygon between 0340 to 0440 GMT and 0441 to 0533 GMT. It can clearly be found that the arbitrary major axis (j–k) of hexagon rotates around the center of the eye. The mean angular velocity of rotation for each of the five peaks is 167 degrees for 18 minutes, corresponding to a rotation period of 41 minutes. Between 0441 GMT to 0452 GMT and 0515 GMT to 0533 GMT, the periods of the rotation for the major axis (n–m) equal to 41 and 43 minutes, respectively. The relation between the period of rotation and number of the sides of polygon is summarized in the Table 1. There is significant difference between the period of 47 to 50 minutes for the square shape and the smaller period of 41 to 43 minutes for the pentagon or hexagon. Namely, the period of the rotation decreases (tangential velocity increases) as the number of corners of the polygon increases.

Several investigators have studied the rotation of elliptical eye (Imakado, 1966; Black et al., 1972; and Mitsuta and Yoshimizu, 1973) and
found rotation periods for 1 to 5 hrs. The rotation of polygonal eye is studied first in the present paper.

Furthermore, the remarkable pentagonal eye shown in Fig. 5 has maintained its shape for the 70 minutes though rapidly rotating with approximate 37 m/s tangential velocity. This observation suggests that the portion of deformation rotates with uniform angular velocity around the center of the eye; because the polygonal shape can not hold its shape for a long time if the narrow ring has different angular velocity in the large wind shear inside of the eyewall.

2) Rotation of small convective cells in the eye

In Fig. 4, small convective echo cells are recognized in the radar eye. The heights of echo tops have 2–5 km altitude in the RHI image. The comparison of the original image with an attenuated one suggests that these echo cells are relatively weak convective echoes. The reconnaissance aircraft that penetrated the eye at 0349 GMT reported small cumulus clouds with low altitudes of echo top in the well-defined eye.

Fig. 7 shows enlarged PPI images. A question mark-shaped echo configuration is seen in the eye, and the shape rotates counterclockwise. In an effort to make the analysis more quantitative, we discuss the displacement of the small cell, denoted by A through H. The movements of the echo cells are represented in the lower part of the figure, and shows that the echo cells are rotating counterclockwise concentrically around the eye center. Based on Fig. 7, the relation between displacement speed and the distance from center is shown in the Fig. 8.

We can sum up the features of the rotation cells in the eye as follows: 1) All echo cells in the eye rotate concentrically counterclockwise around the center of the eye. 2) The angular velocities of cells have almost same values ($2 \times 10^{-3}$ rad. sec$^{-1}$); namely, it suggests the Rankine vortex field in the eye. 3) The characteristic
features of the cells are maintained for about 1 hr; nevertheless each cell rotates around the eye center which move on the trochoidal trajectory (Muramatsu, 1986).

The result of analysis suggests that the polygonal features have a higher rotational velocity than the small convective cells with constant velocity in the eye, they seem to indicate the presence of shear in the rotational velocity. Moreover the deformation is restricted to a narrow ring at inner edge of the eyewall, approximately 3 km in width.

5. Discussion

As previously mentioned, the distinct structure of polygonal eye of the typhoon is studied first in this paper. To investigate the common features of the polygonal eye formation in the tropical cyclone, other cases presented in L. H. (1982)'s paper are also examined.

The typical polygonal eye of the hurricane DONNA (1960) is seen in the PPI image shown in Fig. 9, which is copied from the Jordan and Schatzle (1961) though the interest echo feature referred to as “double eye” is reported firstly in his paper. The diameters of inner and outer eyewall were 23 km and 90 km, respectively; the eye deformed into a distinguishable pentagonal shape. A pentagonal and square eye are also observed in the double eye of the second Muroto typhoon (T6118) at Tanegashima radar, shown in Fig. 10. The size of eye diameter is about 25 to 35 kilometers.

Factors of tropical cyclone and features of polygon are listed in Table 2 when the polygonal eyes are recognized in papers showing radar analyses. Common of these characteristics typhoon (hurricane) with pentagonal eye may be summarized from Table 2 as follows: 1) concentric eye (Willoughby et al., 1982) structure in developed typhoon (hurricane) stage, 2) range from 920 to 950 mb at central pressure, and
3) square to hexagonal shapes of eye and pentagonal shape occurred highest frequency.

On the other hand, the polygonal eyes also are observed in the Southern hemisphere cyclones (Barkly, 1972) and in the GMS image shown in Fig. 11. For the typhoon 8520, the square eye with 110 km diameter occurred at 0840 GMT as well as a pentagonal one with 119 km diameter at 1310 GMT. In another case distinct hexagonal eye is depicted in the image taken by DMPS with 0.9 km resolution on the Typhoon Gloria (Holliday, 1977). Thus, polygonal eye formation appears to be one of the property in mature typhoon stage.

In kinematical consideration for polygonal eye formation, L. H. (1982) suggest that interference patterns produced by a spectrum of horizontally propagating internal gravity waves is a one possible explanation. As previously mentioned in chapter 4, however, the present observations revealed that the portion changed to polygonal shape is restricted within the narrow ring of about 3 km width located in the eyewall. The whole eyewall or rainband are not changed the shape. Our result is different from the result of L. H. (1982), in this respect.

Moreover, in the image at 0441 GMT (Fig. 5) five sides were composed of a thin line echo or a chain of small convective cells. The sides of polygon becomes wavy with characteristic features indicated by g and f at 0509 GMT. Amplitude of wave becomes maximum at 0522 to 0533 GMT and returns to straight line structure again. The observations suggest that the phenomenon occurs near the boundary between the clear area (downdraft) in the eye and the eyewall (updraft) where the largest horizontal azimuthal wind shear exists.
Though the scale of phenomenon is different from that of the polygonal formation, multiple vortex phenomena in tornado meso-cyclone (Fujita et al., 1972; Agee et al., 1976) are similar to that of polygonal eye structure. Agee et al. (1976) pointed out that there must have been multiple tornadoes rotating around each other in a parent meso-system to produce the actual damage track of tornadoes. In the Snow (1978)'s paper, actual tornado with subsidiary vortices embedded within the parent circulation are depicted photographically. Both phenomena have similar features as follows: (1) Multiple vortices rotating counterclockwise around each other at the outer edge of the core zone of parent meso-system (meso-cyclone). (2) There exists inside of boundary of uniform updraft surrounding the central downdraft and a combined Rankines vortex field in the eye and parent meso-cyclone.

Several investigators have studied in laboratory experiments (Monji, 1985) and in theoretical experiments (Snow, 1978; Staley and Gall, 1979). Snow (1978) investigated the "inertial" stability of vortex with an "internal shear layer"; the other hand, Staley and Gall (1979) also studied the barotropic instability and found the wave number of the order of 1 to 5 are significantly unstable. Thus, observations reveal that polygonal eye formation is related to an instability in the large shears of azimuthal velocity near the inner edge of inner eyewall.

6. Remarks

In the eyewall with vorticity concentration over $10^{-3}$ sec$^{-1}$ of and tangential velocity over 50 m/s, a distinguishable polygonal eye is observed in PPI images from the Miyakojima radar of typhoon 8019 WYNNE, which had 920–935 mb central pressure.

In the present paper, features of rotation and change of shapes are investigated firstly in detail and is compared with result of the L. H. (1982)'s paper. Result of analysis shows that the narrow ring of inner eyewall of the concentric double eye is deformed to polygonal shape. The shape changes among square, pentagon and hexagon, and rotates counterclockwise with a period of 41–50 minutes. The periods of rotation are 41–43 minutes for pentagon and hexagon, against that of 49–50 minutes for the square. Thus, the period of rotation decreases (the rotational angular velocity decreases) as the num-

<table>
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<th>Cyclone names</th>
<th>Feature</th>
<th>Eye diameter</th>
<th>Concentric double eye</th>
<th>Central pressure</th>
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<tr>
<td>DONNA 1960</td>
<td>5</td>
<td>23 km</td>
<td>90 km</td>
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<td>6</td>
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<td>120</td>
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<td></td>
</tr>
<tr>
<td>5</td>
<td>33</td>
<td>67</td>
<td>yes</td>
<td>926</td>
<td></td>
</tr>
<tr>
<td>FREDERIC 1979</td>
<td>4</td>
<td>30</td>
<td>100</td>
<td>yes</td>
<td>950</td>
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<td>Typhoon 8019 WYNNE</td>
<td>4–6</td>
<td>30</td>
<td>260</td>
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<td>26–35</td>
<td>150</td>
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<td>920</td>
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</table>
umber of corners becomes larger. There are no observations of triangle or heptagon shapes.

The equilateral hexagonal eye at 0400 GMT changes drastically to equilateral pentagonal one through a transitional stage of irregular polygonal shape. Pentagonal shape occurs most frequently and lasts for the time. For example, 111 minutes from 0441–0632 GMT; conversely, square has the lowest frequency and the shortest persistence, less than 18 min.

The polygonal deformation does not extend to a whole eyewall but is restricted to a narrow ring inside of eyewall of several kilometers width in this case. Thus, the result of our analysis is different from the result of L. H. (1982).

On the other hand, it is revealed that there exists rotational flow in the eye by tracking the displacement of small convective cells. The rotational velocity of polygonal portion is different according to Fig. 8. The polygonal features have a higher rotational velocity than the small convective cells with constant velocity in the eye.

Moreover, the observations show that five sided-portions composed of thin line echo or chain of small convective cells become wave-like and subside to line structure again. The phenomenon occurs in the boundary between the clear area (downdraft) in the eye and the eyewall (updraft due to severe convection). Its phenomenon is similar to multivortex phenomena in the tornado mesocyclone though large difference exists in the scales as described in chapter 5.

As polygonal eyes are also depicted on satellite images these deformations extend vertically to the cloud top. As shown in Table 2, we found the polygonal eye formation occurred occasionally when concentric double eye structure appears in the mature stage of developed typhoon (hurricane) with 920–950 mb at the central pressure.

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References


台風の多角形眼の構造

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要 約
明瞭な多角形眼が台風8019の PPI エコー上で観測された。直径30kmの眼は4角形から6角形までその形を変え、台風眼中心に対して半時計回りに回転していた。回転周期は5—6角形で41—43分。4角形で47—50分と回転速度が速い（周期が短い）ほど多角形の角数が増加した。多角形眼は形状を変えながら約15時間観測され、5角形が最も頻度が高く、111分という長寿命であった。逆に、4角形は不安定で寿命は12分前後で、頻度も最も高く、3角形や7角形は観測されなかった。

多角化は眼の壁雲の最も内側の数km幅の狭い領域で起こっていた。眼の中の小気囲セルの追跡の結果、小気囲セル（眼の中の気塊）は等角速度運動をしており、多角形に変形した部分はそれよりやや速い速度で回転していた。多角形眼の現象は水平シーザーの大きい、眼の内の下降流と眼の壁雲の上昇流領域の境界で起こり、境界面の不安定を示唆する多角形の各辺の波打ち現象がしばしば見られた。この現象は発達した台風（ハリケーン）で明瞭な二重眼構造をもつ、中心気圧940 mb 前後、眼径が30—50kmの場合で多く見られた。