A possible mechanism for the eye rotation of Typhoon Herb

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Abstract

An elliptical eye that rotated cyclonically with a period of approximately 144 minutes in Typhoon Herb 1996 was documented. The elliptical region had a semimajor axis of 30 km and a semiminor axis of 20 km.

Full Text

Headnote
ABSTRACT

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An elliptical eye that rotated cyclonically with a period of approximately 144 minutes in Typhoon Herb 1996 was documented. The elliptical region had a semimajor axis of 30 km and a semiminor axis of 20 km. Two complete periods of approximately 144 min were observed in the Doppler radar data. The rotation of the elliptical eye in the context of barotropic dynamics at three levels were explored: linear waves on a Rankin vortex, a nonlinear Kirchhoff vortex, and with a nonlinear spectral model. The linear wave theory involves the existence of both the high (potential) vorticity gradient near the eye edge and the cyclonic mean tangential flow in the typhoon. The propagation of (potential) vorticity waves in the cyclonic mean flow makes the elliptical eye rotate cyclonically. The rotation period is longer than the period of a parcel trajectory moving in the cyclonic mean flow around the circumference, because the vorticity wave propagates upwind. The nonlinear theory stems from the rotation of Kirchhoff's vortex. Estimates of the eye rotation period from both linear and nonlinear theories agree with observations of the eye rotation period when the observed maximum wind from Herb is used. Nonlinear numerical computations suggest the importance of the interaction of neutral vorticity waves. which determine the shape and the rotation period of the eye. The calculations also support the rotation of the eye in approximately 144 min in the presence of axisymmetrization, vorticity redistribution, wave breaking, and vortex merging processes.

1. Introduction

The eyewall of a typhoon is often circular in shape. However, using photographic records of storms observed with both land-based and airborne radars, Lewis and Hawkins (1982) documented cyclonically rotating polygonal eyewalls. A wide variety of shapes was observed, including triangles, squares, pentagons, hexagons, and incomplete versions of many polygons. Circular and elliptical shapes were also noted in their review, but such smooth shapes were often quickly replaced by polygonal features. Because they found polygonal eyewalls using airborne 5-cm radars far offshore, Lewis and Hawkins concluded that proximity to land is not a requirement for the generation of polygonal features. Lewis and Hawkins concluded that polygonal eyewalls could be attributed to the partial reflection of inward propagating gravity waves with different wavenumber and periods, an idea whose origin is in the theoretical work of Kurihara (1976) and Willoughby (1978). Unfortunately, the period of rotation of the polygonal features was not examined in the Lewis and Hawkins study.

Using a remarkable 15-h record from land-based radar, Muramatsu (1986) also observed polygonal eyewalls in Typhoon Wynne 1980. The polygonal features consisted of cyclonically rotating squares, pentagons, and hexagons. The pentagons and hexagons had rotational periods of approximately 42 min, and the squares had periods of approximately 48 min. This decrease in the rotational period with increasing tangential wavenumber will be discussed further in the theoretical argument presented here.

Typhoon Herb in 1996 was the strongest typhoon to hit Taiwan in the last decade. Based on wind observations 700 m above mean sea level on Wu-Feng Mountain, the maximum wind in Herb was estimated to be 60 m s^sup -1^ or higher [see also Lee (1997) for Doppler winds analysis]. It destroyed the newly installed Central Weather Bureau WSR-88D Doppler radar on Wu-Feng Mountain. Before the destruction of the radar, the radar pictures revealed that Herb had an elliptical eye that rotated cyclonically with a period of approximately 144 min. Two complete periods were observed. The objective of this paper is to document the elliptical eye rotation and to explore possible mechanisms for the eye rotation. Section 2 gives the radar observations and theories for the eye rotation. Numerical results are presented in section 3, and concluding remarks are in section 4.

2. Observations and theories

Figures 1 and 2 are the radar pictures of Typhoon Herb from the Central Weather Bureau WSR-88D Doppler radar. The sequence of the pictures in each figure is from left to right and from top to bottom, and the time interval between each image is approximately 18 min. Each of the two sets of images in Figs. I and 2 illustrate one complete cyclonic eye rotation with a period of 144 min. Thus, there are two complete periods of approximately 144 min in the elliptical eye rotation that have been observed with the radar. Since the radar pictures in Figs. 1 and 2 represent the maximum reflectivity in each vertical column, the elliptical eye is a deep tropospheric phenomenon. Other PPI images (not shown here) indicate that the elliptical eye is the most dominate feature at each vertical level. Significant polygonal features were not observed on any individual level, although some irregular eyes in the images were noticed in the second rotation period. In this observation period, Typhoon Herb is closer to Taiwan. The elliptical region observed in the figures has a semimajor axis of 30 km and a semiminor axis of 20 km, approximately. It is interesting to note that there was often deep convection (strong reflectivity regions) near the tips of the major axis in the elliptical eye.

The timescale for a parcel circulating around the circumference of the eye region, based on the observed maximum wind of 60 m s^sup -1^ and on the size of the major axis and minor axis, was approximately 50 min. The elliptical eye rotation period of 144 min is much longer than the parcel circuit time. The existence of an elliptical eye with a long period of rotation (144 min) in Typhoon Herb seems to be a unique feature that has not been found in previous studies.1 An important question is, what mechanism caused the elliptical eye to rotate more slowly than the period related to the maximum wind speed?

We consider the elliptical eye shape as a wavenumber 2 asymmetry of a circular eye. The eye is viewed as a region of nearly constant and high (potential) vorticity with a large (potential) vorticity gradient at its edge. Under the conservation of (potential) vorticity, the gradient of (potential) vorticity provides a state on which (potential) vorticity waves (the generalization of Rossby waves) can propagate. Thus, the wavenumber 2 asymmetries near the eye edge should propagate to the left of the vorticity gradient, which means that the asymmetries should move upstream with respect to the mean flow. This effect would cause the elliptical eye to rotate anticyclonically with respect to the mean wind. However, with the strong cyclonic tangential mean flow in the typhoon, the wave asymmetries should propagate downstream, but with a propagation speed slower than the advective speed. This wavenumber 2 asymmetry propagation corresponds to a cyclonic elliptical eye rotation. The linear analysis of the (potential) vorticity wave on a Rankine vortex was done by Sir William Thomson (Lord Kelvin) in 1880 (Thomson 1880) and was summarized by Lamb (1932) and by Guinn and Schubert (1993). His analysis indicates that the speed of the wave is given by

semimajor axis vorticity profile can also be seen in Fig. 3a. The design of the experiment does not imply that the vorticity distribution in the eye region resembles the Gaussian function, but rather it is designed to show that the maintenance of the elliptical eye is crucially dependent on the vorticity distribution in the eye region. The vorticity distribution sets the dynamic background for the presence of neutral waves and/or asymmetry-damping processes. With the Gaussian structure as in (3.5), d(omega)/(d)r is not zero, so a disturbance can either grow or decay depending on the tilt of the waves. Figure 5 gives the initial vortex and the numerical results in 48-min intervals up to 144 min. It is clear from Fig. 5 that axisymmetrization or vortex stablization processes (Melander et al. 1987; Carr and Williams 1989) have produced a nearly circular vortex with surrounding filaments of vorticity. Details of the axisymmetrization as they relate to hurricane dynamics were discussed by Carr and Williams (1989), Guinn and Schubert (1993), Smith and Montgomery (1995), Montgomery and Kallenbach (1997), and Montgomery and Enagonio (1998). Due to the asymmetry damping, it is difficult to identify any distinct rotation period in this experiment. These two experiments suggest that the maintenance of an elliptical vortex is dependent on the vortex structure. This is consistent with the finding of Dritschel (1998) that the steepness of the vortex edge controls the vortex axisymmetrization.

coming from some random convection outside the eye. Figure 9 gives the vorticity field for experiment 6 at 0, 48, 96, and 144 min. A region 150 x 150 km in the computational domain is shown. Figure 9 indicates that the neighboring vorticity is quickly elongated and wrapped around the elliptical eye. There are also wavebreaking and vorticity redistribution processes (e.g., Schubert et al. 1997; Schubert et al. 1999) associated with the elliptical vortex. The center of the elliptical eye translates a distance of 30 km toward the northwest. The eye continues to be an ellipse throughout the integration. The elliptical eye also rotates with a period of 144 min in the presence of vorticity redistribution, vortex translation, vortex merging, and wave-breaking processes. Figure 10 gives the vorticity field for experiment 7 at 96 and 144 min. We observe the vortex has been distorted significantly from the elliptical shape and the rotation period is very difficult to determine.

Some of our model integrations reproduce the cyclonic rotation of the elliptical eye with a period of approximately 144 min. The maintenance of an elliptical-shaped vortex requires a vortcity structure that resembles the Rankine vortex. The rotation period is sensitive to the peak vorticity value. When a minimum vorticity in the center of the eye is considered, the rotation period as well as the maintenance of elliptical shape are crucially dependent on the spatial structure of the minimum vorticity region. The interaction of neutral vorticity waves plays an important role in determining the shape and the rotation period of the eye. A minimum vorticity region inside the eye with the structure given by (3.la) often distorts the shape and changes the rotation period of the elliptical eye. This is in agreement with the analysis in section 2 and in the appendix.

4. Summary and concluding remarks

We have documented an elliptical eye that rotated cyclonically with a period of approximately 144 min in Typhoon Herb. The elliptical region had a major axis radius of 30 km and a minor axis radius of 20 km. Two complete periods of approximately 144 min each were observed with the Doppler radar. We propose two theories to explain the eye rotation. The linear wave theory requires a uniform high (potential) vorticity within the eye and zero vorticity outside. Vorticity waves propagate to the left of the vorticity gradient with respect to the mean cyclonic flow. Since the mean flow is strong the waves still move cyclonically, but with a much longer period. The predicted period is very close to the observed period. The fact that the linear theory predicts a smaller rotation period for the polygonal eyes also agrees qualitatively with the observations (Muramatsu 1986). The nonlinear theory stems from the rotation of the Kirchhoff vortex. With the observed ellipse radii, the Kirchhoff solution reduces to the linear wave period. The Rankine vortex structure is assumed in the theories and is shown to be important in the numerical experiments. The key point is that the basic flow in a Rankine vortex does support neutral wave solutions, which makes the elliptical eye rotation possible. On the other hand, a Rankine vortex structure for the minimum region in the center of the eye can distort the shape of the eye and change the rotation period due to the interaction of neutral vorticity waves. A fairly smooth (such as the Gaussian function) minimum vorticity region in the eye center does not distort the eye shape significantly. Estimations of eye rotation period from both linear and nonlinear theories seem to agree with the observation that an elliptical eye in a typhoon can rotate cyclonically with a period of approximately 144 min.

Our argument, however, does not answer the question of what causes the formation of an elliptical eye in Typhoon Herb. The role of diabatic heating due to moist convection has yet to be included in the theory. Moreover, the detailed potential vorticity structure in Typhoon Herb is needed, but this is not possible with the very limited observations. The potential vorticity field in a typhoon is determined by the complex interaction of diabatic, frictional, and advective processes. The frictional convergence and moist convection continually act to concentrate high potential vorticity in the eyewall region. Due to the nature of convection, the potential vorticity generated should be highly asymmetric. This process is opposed by the asymmetry-damping mechanism (Carr and Williams 1989). Furthermore, there is no latent heat release in the central region of the eye. Large values of potential vorticity within the eye then would not tend to occur unless they were transported in from the eyewall region. The process of potential vorticity inward mixing might then be related to the asymmetric eye contraction mechanism proposed by Schubert et al. (1997) and Schubert et al. (1999). To conserve angular momentum and/or kinetic energy during the redistribution process, the inward potential vorticity mixing must be accompanied also by some outward potential vorticity mixing. The outward mixing can be seen in the form of filaments that orbit the vortex core. Before we can fully understand the dynamics of eye rotation we need to know the timescale of the potential vorticity modification by moist physics, the timescale of potential vorticity axisymmetrization and redistribution, and the final resultant (potential) vorticity spatial structure. Because of the term zeta (raised dot) (inverted Delta)theta in the potential vorticity equation, the potential vorticity modifications by diabatic heating are related to the relative spatial distribution of cumulus convection and vorticity within the tropical cyclone. In addition, the potential vorticity redistribution without an azimuthal wavenumber-one component can result in a very different macroscopic potential vorticity structure (Schubert et al. 1999). It is very likely that the adjustment timescales of potential vorticity by the redistribution and moist physics modification are initial condition dependent.

With simple dynamical model calculations, our intent is not to undermine the importance of the moist physics, but rather to isolate the fundamental dynamics believed responsible for the rotation of the elliptical eye in Typhoon Herb. There remains the question of how the (potential) vorticity is organized into the "right" structure and the "right" magnitude for our theory to be valid in a moist convective environment and in the presence of potential vorticity axisymmetrization and redistribution in a typhoon. This may be related to the important but unanswered question of eye dynamics. Without detailed observations of the potential vorticity distribution inside the eye region in Typhoon Herb, and without a thorough understanding of the eye dynamics, the question is difficult to answer. Simulations of Typhoon Herb by high-resolution "full-physics models" with a good physical initialization scheme and accurate cumulus parameterization may partially answer the question.

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Footnote

1 Kurihara and Bender (1982) found in their 5-km resolution modeling study of tropical cyclones that asymmetry in the vortex structure is evident in various fields. Regions of anomalous rainfall intensity, temperature anomaly, and ascending motion are simulated at a few locations within the eyewall. The asymmetric features within the eyewall moved cyclonically at a much smaller rotation rate than the cyclonic wind within the eyewall. Attention in the paper is given to the balance between the wind and pressure fields and to the budgets of angular momentum, heat, and water vapor.

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