

Vortical Swirls in Hurricane Eye Clouds

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ABSTRACT

A collection of images depicting various swirling patterns within low-level cloud decks in hurricane eyes is presented and described. A possible causal mechanism for the presence of these cloud patterns is suggested by comparison of the observed cloud patterns with the evolution of passive tracers in a simple 2D barotropic model. The model is initialized with a barotropically unstable flow field that imitates the observed flows in hurricanes, and numerical integration of this field simulates vigorous mixing between eye and eyewall. During the mixing process, passive tracers initially embedded in the flow form swirling patterns in the eye that are strikingly similar to cloud patterns often observed in the eyes of hurricanes.

1. Observations of vortical swirls in hurricane eye clouds

Mature hurricanes often have low-level stratus or stratocumulus cloud decks below the inversion level in their eyes, and it is not uncommon to find various vortical, or “swirling,” shapes embedded in these cloud decks. An example of this phenomenon in Atlantic Hurricane Erin at 1515 UTC 11 September 2001 is shown in Fig. 1. At that time, the low clouds in the eye of Erin appeared as convoluted cloud streets that form an “ox-bow” northeast of the storm center and an elliptical swirl west of center. Regions between the cloud streets were relatively devoid of clouds. Also visible at that time [1115 eastern daylight time (EDT)] was a smoke and dust plume being advected southward from the collapsed World Trade Center buildings near the southern tip of Manhattan, New York. The south tower of the World Trade Center collapsed at 1405 UTC (1005 EDT), and the north tower collapsed at 1428 UTC (1028 EDT), 47 min before the time of Fig. 1. In this case, the presence of Hurricane Erin may have been beneficial, because Erin’s surface flow contributed to the northerly winds that carried smoke and dust away from a highly populated area.

The swirling patterns in hurricane eye clouds can take on a variety of shapes, ranging from circles centered in

the eye to convoluted patterns containing multiple swirls at varying positions in the eye. Figure 2 displays eye-cloud patterns in western Pacific Supertyphoon Ida (1958), western Pacific Supertyphoon Yuri (1991), eastern Pacific Hurricane Emilia (1994), Atlantic Hurricane Alberto (2000), western Pacific Typhoon Man-Yi (2001), Atlantic Hurricane Erin (2001), western Pacific Typhoon Nari (2001), and western Pacific Supertyphoon Podul (2001). The dominant pattern in the eye clouds of Man-Yi (Fig. 2f), Erin (Fig. 2g), and Podul (Fig. 2i) was approximately circular with its center nearly collocated with the eye center, suggesting that the vorticity structures in the eyes of these storms were approximately axisymmetric.

The patterns evident in the eye clouds of Ida, Yuri, Emilia, Alberto (Figs. 2a–e), and Nari (Fig. 2h) are not well described by circles centered in the eyes, and they are more complicated and variable from storm to storm. The various shapes seen in these storms suggest that coherent regions of vorticity were present in their eyes and that the spatial scales of the coherent regions of vorticity were smaller than the parent vortex (i.e., the hurricane inner core) in which they were embedded. Such small-scale regions of vorticity are known as mesovortices, and their presence in hurricane eyes and eyewalls has been widely documented (Fletcher et al. 1961; Marks and Houze 1984; Muramatsu 1986; Bluestein and Marks 1987; Marks and Black 1990; Black and Marks 1991; Willoughby and Black 1996; Hasler et al. 1997).

The cloud patterns in Ida (Fig. 2b) suggest that a mesovortex was located in the lower-right part of the

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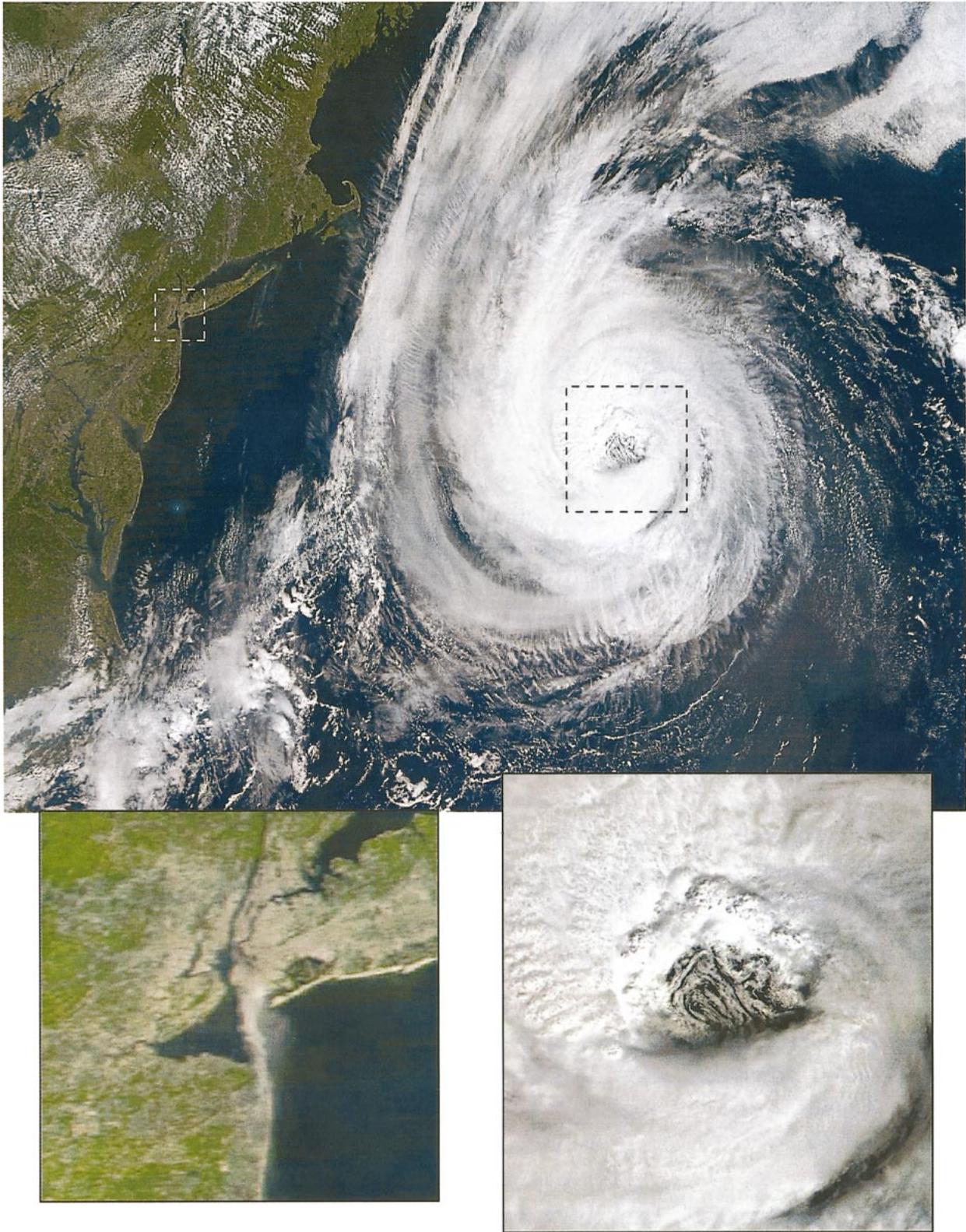


FIG. 1. Moderate-Resolution Imaging Spectroradiometer (MODIS) satellite image of Atlantic Hurricane Erin at 1515 UTC 11 Sep 2001. The right inset shows a magnified image of convoluted clouds in the eye. The left inset shows a smoke and dust plume being carried southward from the collapsed World Trade Center buildings, away from the populated island of Manhattan, in part by Erin's surface flow.

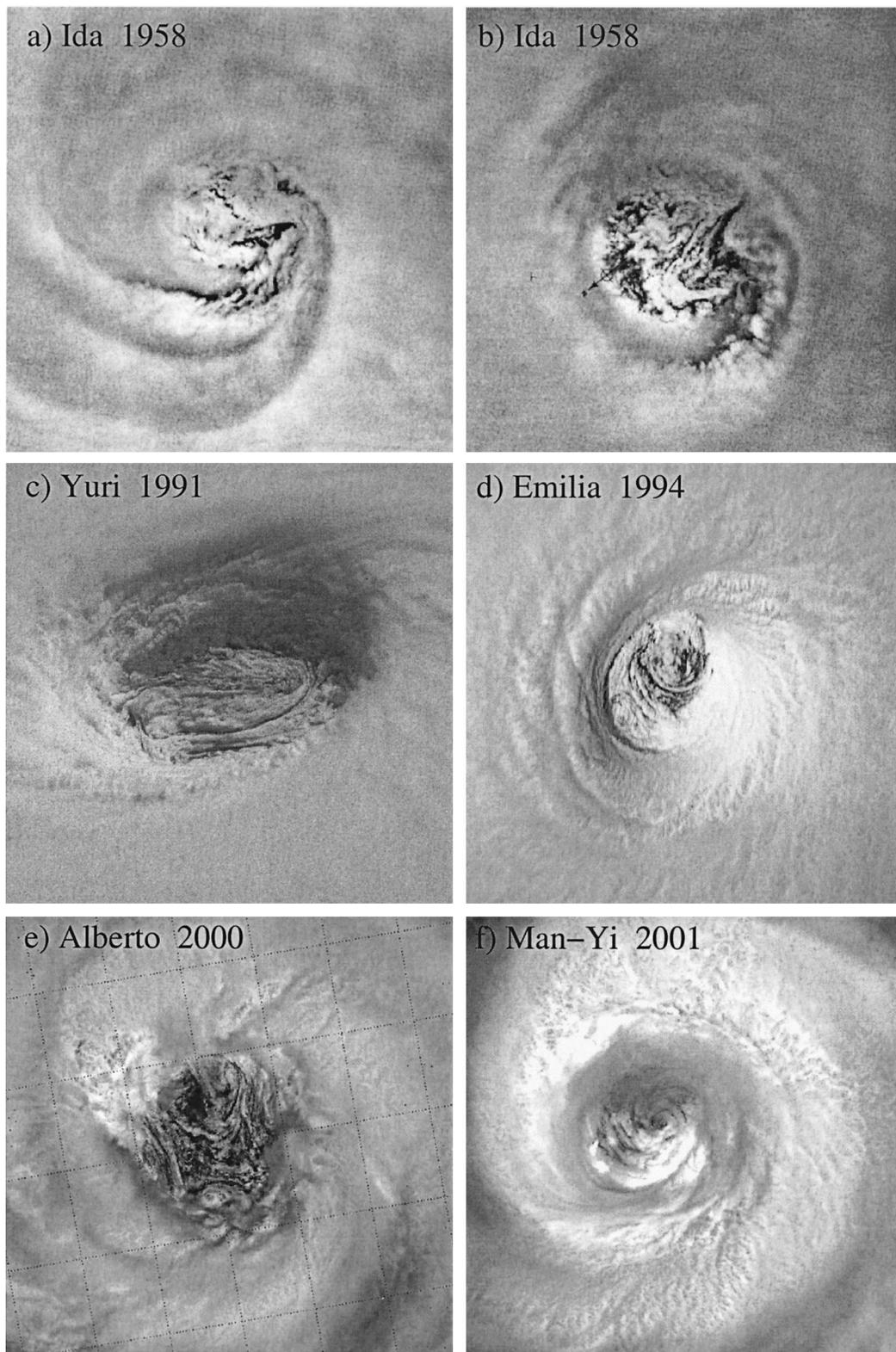


FIG. 2. Montage of images showing a variety of swirling patterns in hurricane eye clouds: (a),(b) high-altitude U-2 aircraft photographic reconnaissance (from Fletcher et al. 1961), (c),(d) photographs taken from the space shuttle, and (e)–(i) MODIS images.

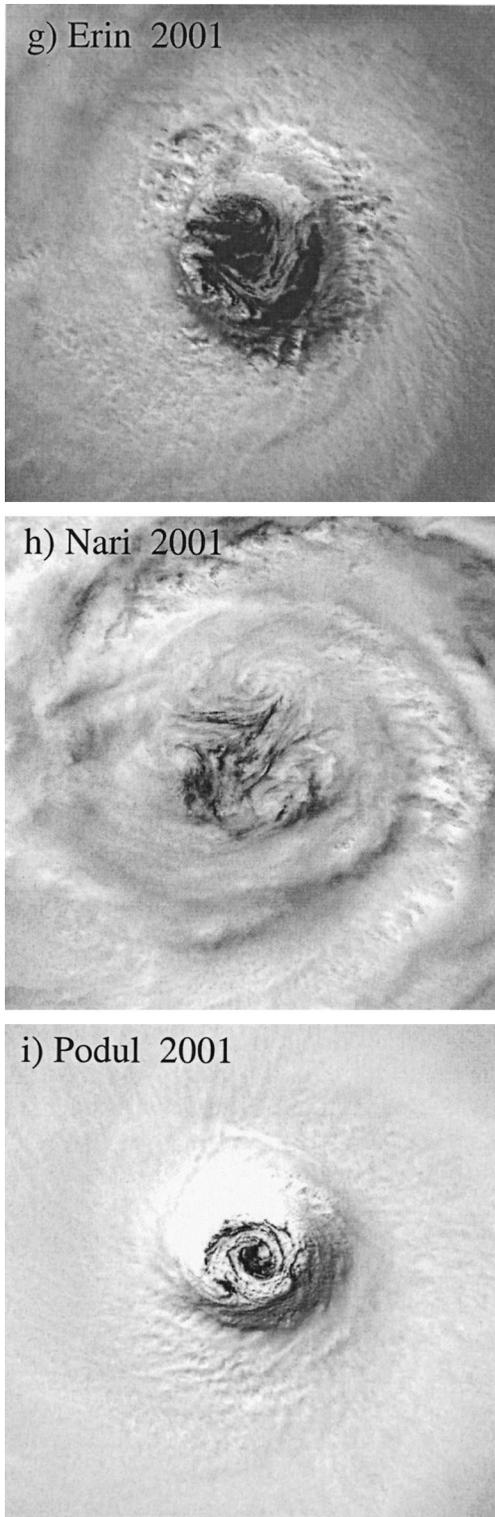


FIG. 2. (Continued)

eye and another mesovortex was located adjacent (above and left) to the first mesovortex. A similar mesovortex configuration was evident in Emilia (Fig. 2d), but the two mesovortices were located in the lower-left and upper-right parts of the eye. In Emilia, the mesovortex at the upper right appears to be larger than its neighbor to the lower left. The pattern in Alberto (Fig. 2e) suggests that a relatively large mesovortex was located in the upper part of the eye and at least three smaller mesovortices were located in the left, bottom, and right regions of the eye. The clouds in the eye of Nari (Fig. 2h) exhibited complexity similar to that of those in Alberto. Three distinct mesovortices appear; one in the upper part of the eye, one in the left part, and one in the lower-right part. The areas surrounding the mesovortices were relatively cloud free. It is not clear whether the cloud-free regions are a result of horizontal advective processes or of local updraft–downdraft couplets associated with the mesovortices.

Our interpretation of the relationship between flow patterns and stratiform cloud patterns assumes that the cloud lines are approximately parallel to local streamlines. Although there are situations in which stratiform cloud lines over general oceanic regions are aligned so as to be nearly perpendicular to local streamlines, this is not likely to be true here. Wind patterns in the neighborhood of hurricane mesovortices can be inferred to be coincident with cloud patterns by using a combination of photographs (Bluestein and Marks 1987), radar (Willoughby and Black 1996), and flight-level data (Black and Marks 1991). The relationship between cloud lines and streamlines in the hurricane eye is most likely that they are parallel in a manner analogous to the swirling features of von Kármán vortices that are sometimes evident in low-level marine stratiform clouds downwind of islands.

2. Dynamical interpretation

In this section we suggest a dynamic mechanism, based on barotropic stability arguments, to explain the presence of mesovortices in the hurricane eye. The barotropic dynamics are presented using a simple nondivergent barotropic numerical model, and they show that numerical integration of barotropically unstable initial conditions leads to a breakdown of the eyewall and formation of mesovortices that migrate from the eyewall into the eye. Passive tracers, initially inserted into the flow to represent cloud particles, are convoluted by the mesovortices and form swirling patterns that are very similar to the swirling patterns observed in the eye clouds of the storms shown in Figs. 1 and 2.

When a hurricane eye forms, inner-core deep convection is generally confined to the annular region of the eyewall. Such an annular convective structure confines the diabatic production of potential vorticity (PV) to the annulus and will, over time, produce a PV structure described by relatively high PV in the eyewall

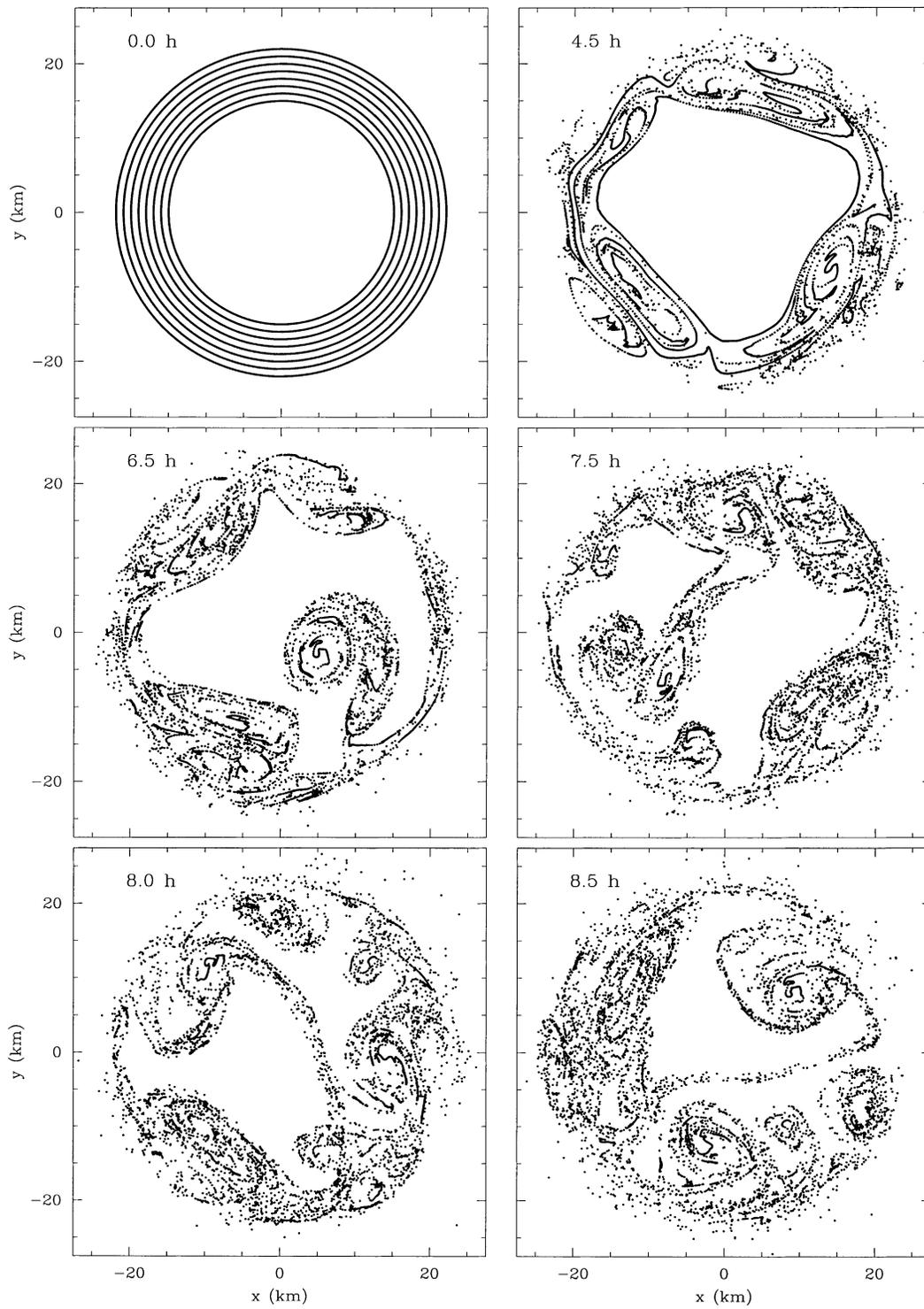


FIG. 3. Two-dimensional maps showing the evolving distribution of passive eyewall tracers placed in the initially unstable model flow.

flanked on both sides by relatively low PV. Such a PV structure is called a “hollow tower” PV structure (Möller and Smith 1994), and the reversal of the radial PV gradient sets the stage for barotropic instability. Evidence that such PV structures are typically present in developing and mature hurricanes was shown by Kossin and Eastin (2001).

To demonstrate the nonlinear evolution of hollow-tower, or annular, PV structures, we consider the simplified framework of a nondivergent barotropic model and employ the same pseudospectral numerical model described by Schubert et al. (1999). This model isolates the dynamics in the absence of any baroclinic effects and thus might seem inappropriate for modeling mature hurricanes, which typically have large vertical wind shear in the near core. However, recent work by Nolan and Montgomery (2002) shows that instabilities in three-dimensional hurricane-like vortices are fundamentally two-dimensional in nature and are modeled well in a nondivergent barotropic framework.

Our axisymmetric initial condition, consisting of an annular vorticity structure, and all model parameters (domain size, grid spacing, time step, and kinematic viscosity) are the same as those used by Kossin and Eastin (2001). The initial profile of vorticity describes a hurricane-like vortex with maximum tangential wind of 60 m s⁻¹ at radius $r = 20$ km. To describe the evolution of cloud particles, concentric rings of passive tracers are placed initially into the annulus of high vorticity (i.e., the “eyewall”). The tracers are initially contained along eight concentric rings with $r = 15, 16, \dots, 22$ km. The number of tracers along a concentric ring increases with increasing radius so that the number concentration of the tracers is the same along each ring.

The tracer evolution is shown in Fig. 3 in the form of two-dimensional maps. At time $t = 4.5$ h, barotropic instability of the flow around the eyewall has resulted in wave breaking and distortion of the tracers. At $t = 6.5$ h, most of the tracers are embedded in coherent mesovortices, with the remaining tracers smeared out within “filaments” of vorticity that connect the mesovortices. A distinct mesovortex in the eastern quadrant of the vortex has migrated into the eye. During the subsequent 2 h, interaction of the mesovortices and convection of the filaments result in a variety of swirling shapes within the tracer field, and at $t = 8.5$ h the tracer field is remarkably similar to the low-level cloud fields observed in the eyes of Hurricane Alberto (Fig. 2e) and Typhoon Nari (Fig. 2h). By $t = 24$ h (not shown), the tracers (and the vorticity field) have nearly achieved their axisymmetric end state. At this time, the vorticity is approximately monotonic and the eyewall tracers form circles centered in the eye (see Kossin and Eastin 2001; their Fig. 11).

3. Concluding remarks

The observed presence of swirling shapes in the low cloud decks in hurricane eyes was first formally doc-

umented by Fletcher et al. (1961) using high-altitude U-2 aircraft photographic reconnaissance. Nowadays, the appearance of swirling eye clouds, usually noted in satellite imagery, often inspires a flurry of informal scientific communication that is generally in the form of electronic mail containing remarkable images of hurricane eyes. This article has documented a number of these images and has offered a physical mechanism, based on simple 2D barotropic dynamics, to explain the source of flow patterns that may be responsible for the presence of vortical swirls in hurricane low-level eye clouds.

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