PICTURE OF THE MONTH

Kelvin–Helmholtz Billows in the Eyewall of Hurricane Erin

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ABSTRACT

A photograph of vertically aligned Kelvin–Helmholtz billows in the eastern eyewall of Hurricane Erin on 10 September 2001 is presented. The vertical shear instability in the horizontal winds necessary to produce the billows is confirmed with a high-altitude dropwindsonde observation. This shear instability is not known to be common in tropical cyclone eyewalls and is likely only in cases with a very large eyewall tilt. However, research and reconnaissance aircraft pilots need to be aware of the possibility of their existence, along with other types of hazardous conditions, in such rare circumstances.

Penetration of hurricane eyewalls by aircraft has become commonplace over the past half century. During such events, aircraft frequently encounter mild turbulence due to up- and downdrafts in the eyewall convection. In tropical cyclones, vertical motion is only infrequently strong (Black et al. 1996), so eyewall penetrations are generally completed without heavy turbulence. However, in instances in which the eyewall is highly tilted, the relatively calm eye may be situated above the fast-moving eyewall. The vertical shear of the horizontal wind may then be large enough to cause Kelvin–Helmholtz instability. Resulting vortices may have large local up- and downdrafts, and should be avoided by aircraft. Kelvin–Helmholtz billows were photographed on 10 September 2001 during a penetration of Hurricane Erin by the National Oceanic and Atmospheric Administration (NOAA) WP-3D aircraft located at an altitude of approximately 4500 m (Fig. 1). The photograph was taken inside the eye looking horizontally and eastward. Vertically aligned wavelike features are seen in the eyewall at an elevation of approximately 6000 m, well below the highest clouds in the eyewall (approximately 13000 m) seen behind. The eastern eyewall is seen in radar reflectivity cross sections from the P-3 tail radar (not shown) to have a slope of about 60°. The cyclonic circulation means that the wind was moving across the photograph from right to left, so the waves are breaking into the wind.

A dropwindsonde from the National Aeronautics and Space Administration (NASA) ER2 aircraft (Hal-
verson et al. 2006) was released from an altitude of about 19,000 m at about the time of the photograph (Fig. 2). The dropwindsonde drifted into the eyewall just below 6000 m as seen by the rapid increase of relative humidity and wind. At this altitude, the wind speed \( V \) increased from less than 15 m s\(^{-1}\) to about 45 m s\(^{-1}\), with the highest shear in the region of saturation: the wind speed at 6264 m is 22.7 m s\(^{-1}\), and at 5579 m is 34.1 m s\(^{-1}\). In this narrow region, \( \theta \) is nearly constant at 335 K. The Richardson number

\[
\text{Ri} = \frac{g \frac{\partial \theta}{\partial z}}{\frac{\partial V^2}{\partial z}}
\]

is less than 0.01, accounting for a very unstable environment for the growth of shear instability.

Though the wavelike features appear to be vertically aligned, any tilt from the vertical could allow instability of rotational flow to be important. The billows have a wavelength of approximately 0.5 km, and the eye was about 85 km wide at 600-m altitude. Assuming the eye to be circular, the circumference was about 267 km. Thus, each feature extends over an arc of about 2/3°, and any curvature over such a small arc is likely to be negligible.

Additionally, vertical motion may contribute to the instability (Leibovitch and Stewartson 1983). For instability, either the angular velocity must decrease with radius, or

\[
\frac{d\Omega}{dr} \frac{d\Gamma}{dr} + \left( \frac{dw}{dr} \right)^2 < 0,
\]

where \( \Omega \) is the angular velocity, \( \Gamma \) is the angular momentum, \( r \) is the radius from the center, and \( w \) is the vertical wind speed. Since the billows are seen on the inner edge of the eyewall, the angular velocity and angular momentum are both increasing with radius, so these stability criteria are not met.

Since the billows appear in the highly convective eyewall, convective instability may be important. Emanuel (1983) provides a stability criterion that can be tested with a single sounding, all that is available in this case, by adding to the sounding temperature the value

\[
\frac{1}{2} T_{\text{co}} \frac{f}{g} \frac{d}{\eta(z)} \frac{d}{dz} (v - u_0)^2,
\]

where \( T_{\text{co}} \) is the temperature of a reversibly lifted parcel, \( f \) and \( g \) are the Coriolis parameter and gravitational acceleration, respectively, \( v \) is the wind speed of the
parcel, $v_w$ is the wind speed of the environment, and $\gamma$ is the absolute vorticity. An approximation of the absolute vorticity can be obtained from flight-level wind measured by the P-3 as it penetrated the eyewall below the feature. A value of 0.012 is obtained for the above term, assuming little rotation. Therefore, the values added to the temperature in the region of the features are very small, reaching a maximum of only about 0.1 K, suggesting that this criterion is also not met. The failure of these stability criteria thus suggests that the billows are the result of Kelvin–Helmholtz instability.

Aircraft encounters with rapidly changing wind velocity within vertically aligned Kelvin–Helmholtz billows are likely to be high-impact events. The vertical wind shear required to produce such features in the eyewall only occurs in the rare instance in which the eyewall is highly tilted so that the relatively calm eye overlays the rapidly moving eyewall air. It is unknown whether such billows have been encountered previously in a tropical cyclone eyewall; this is the first known photograph of such features. None of this analysis precludes other types of instability in the eyewall region that might be hazardous to aircraft. The possibility exists that vertically aligned Kelvin–Helmholtz waves may occur in certain circumstances; planning for eyewall penetrations should take this into account.

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**REFERENCES**


