

New Hurricane Wind Structures and Wind Speed Measurements

by

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ABSTRACT

A major source of difficulty in past efforts to predict TC intensity, wind fields, and storm surge at landfall has been the inability to measure the surface wind field directly and the inability to predict how it changes in response to external and internal forcing. A synthesis of past observations of gust factors in hurricanes, in addition to new GPS dropsonde observations, have made it possible to estimate peak gust, 1-min and 10-min sustained mean windfields at the 10-M level. Significant departures from the traditional log law have been found. Recently, multiple low-level wind maxima were observed in eyewall observations from GPS dropsondes.

Recent Observations of eyewall mesovortices have made it possible to observe the structure and characteristics of these features as they make landfall. They have been found to be associated with strong convection in the eyewall at a time when rapid strengthening is occurring. This can produce short periods of intense winds at considerably larger distances inland than is normally expected for landfalling hurricanes.

KEYWORDS:

boundary layer; eyewall; gust factor; hurricane; mesocyclone; mesovortex; satellite; radar; tropical cyclone; typhoon.

1. INTRODUCTION

It is an important international priority to improve the forecasts of surface wind field,

intensity, structure and storm surge in landfalling tropical cyclones (TC) in order to successfully mitigate the detrimental physical impacts associated with these storms. Coastal population growth in the U.S. of 4-5% yr⁻¹, is outpacing the historic 1-2% yr⁻¹ rate of improvement in official hurricane track predictions. While specific track prediction models have indicated a 15-20% improvement over the past 2-3 years, very little skill has been shown in the prediction of intensity change or wind field distribution (Neumann et al 1997). For this reason, the average length of coastline warned per storm, about 570 km, has not changed much over the past decade, nor has the average overwarning percentage, about 75%. However, the average preparation costs have increased eight-fold in the past 7 years from \$50M storm⁻¹ in 1989 (Sheets 1990) to an estimated \$300M storm⁻¹ in 1996, or about \$1M nm⁻¹ of coastline warned (Jarrell et al 1992; Neumann et al 1997). The increasing potential for severe loss of life as coastal populations soar, and potential monetary losses of tens of billions of dollars requires that greater effort be directed to understanding all physical processes which play an important role in modulating TC wind fields and storm surge at landfall.

A major source of difficulty in past predictions of TC intensity, wind fields, and storm surge at landfall has been the inability to measure the surface wind field directly and the inability to predict how it changes in response to external and internal forcing. The surface wind field must presently be estimated from a synthesis of scattered surface ship and/or buoy observations and aircraft measurements at 1.5 km to 3.0 km altitude (Powell 1980; Powell et al 1996; Powell and Houston 1996). This task is complicated by variations with height of the storm's structure, such as the change with height of storm-relative flow due to environmental wind shear and to the variable outward tilt of the wind maximum with height.

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Numerous studies of TC structure have been made previously using various combinations of remote sensing and *in situ* data. Numerous studies of TCs have been made concentrating on NOAA aircraft data, ground based radar and surface damage reports, e.g., Willoughby and Black (1996) and Black and Marks (1991).

Based on NOAA aircraft observations, eyewall mesovortices and attendant supercell convection were associated with intense turbulence, vertical air motions in excess of 20 m s^{-1} at cloud base and momentary loss of aircraft control during low-level penetrations in rapidly developing Hurricanes Gladys (1975) and Hugo (1989). Vorticity perturbations were deduced with magnitudes on the order of Midwest thunderstorm mesocyclones. Land based radar observations and damage surveys after Hurricane Andrew (1992) suggested that enhanced swirling motion associated with convectively initiated eyewall mesovortices may have been responsible for the intense inland wind damage associated with landfall in South Florida (Wakimoto and Black 1994; Willoughby and Black 1996). Convective perturbations along the inner edge of the outer eyewall of Typhoon Paka (1997) led to three distinct destructive wind surges over the northern half of Guam.

An in-depth examination of 3-5 s gust factors at 10-m level derived from a number of sources suggest that separate populations of gust factors are associated with mid-latitude storms, over-water and over-land TC conditions. The mean over-water gust factors for 1-min, 10-min and 30-min measurement duration in TC's were found to be 1.23, 1.40 and 1.48, respectively.

The ratio of average maximum wind estimates in West Pacific TCs from the post-1970 data set over those from the pre-1970 data set, is found to be about the same as the ratio between flight-level (cloud base) winds and surface winds, an average of 0.8 (Powell, 1980). Recent Global Positioning System (GPS) dropsonde (GPS sonde) data in the eyewalls of Hurricanes Guillermo (1997) and Erika (1997) in 1997 suggest that different ratios may apply in the TC outer region beyond the eyewall than in the eyewall itself. The difference in wind estimates between the two time periods in the western Pacific may be due to the failure to take into account the decrease of the wind with height in the boundary layer of the TC for the pre-1970 era observations.

Black (1993) suggested that the TC gust factor increased with height at the same rate that the mean wind decreases with height in the TC atmospheric boundary layer (ABL), implying that convection conserves momentum in the ABL, maintaining a nearly constant peak gust wind speed with height. The recent Guillermo and Erika GPS sonde data have shown that the vertical structure in the ABL is much more complex than previously thought containing multiple wind maxima. Multiple wind maxima in the ABL was first observed by Wilson (1979) with instrumented tower observations.

2. EYEWALL MESOVORTEX STRUCTURE

In Hurricane Andrew (1992), an eyewall replacement cycle developed as the storm moved across the Gulf Stream. The Miami WSR-57 radar was able to observe the dissipation of the old eyewall over the Bahamas simultaneously with its replacement by a larger eyewall. A slow contraction of the new eyewall followed and two centers of convective activity formed in the eyewall and rotated around the eye. As the storm approached Miami, two distinct cyclonic mesovortices could be seen adjacent to the convective centers of action on opposite sides of the eyewall, which rotated about a common center in the middle of the eye. The presence of two meso-vortices indicated a predominance of wave number-2 asymmetric structure. However, as the eyewall approached the coast and came into view of the Tampa WSR-57 radar, as well as the Melbourne WSR-88D radar, a transition was observed from a rotating wave number-2 asymmetric flow to a fixed wave number-1 asymmetric flow relative to the translating center, even as the intense winds destroyed the Miami WSR-57 radar.

The Tampa WSR-57 radar, which was being recorded digitally by a team from the Hurricane Research Division, scanned the eyewall at 30-s intervals, covering an altitude band of 3-8 km. The WSR-57 revealed that a series of 7 intense raincells developed in the north portion of the eyewall as it made contact with the coast, moved across south Dade County and dissipated in the south portion of the eyewall, south of Homestead, FL, during the 45 min required for the eyewall to move ashore. Development of the intense raincells, which began as the eyewall made contact with the coast, continued at intervals of 3- to 7-min, and ended once the eyewall was completely over land. Each had a

life cycle of 8-15 min growing in intensity from 30 dBZ ($\sim 10 \text{ mm h}^{-1}$) to 50 dBZ (150 mm h^{-1}). The rapid growth in cell intensity implied intense updrafts within the cells. These updrafts, imbedded within the background TC-scale vorticity, enhances the vorticity locally on the scale of the updraft by means of vortex tube stretching and tilting of horizontal vorticity into the vertical. Thus, meso-vortices, similar to that associated with the tornado cyclone in rotating severe thunderstorm cells, were probably produced in Andrew's eyewall in association with each intense raincell.

Through the process of geostrophic adjustment, the pressure field adjusts rapidly to perturbations in the wind field on the mesoscale which are larger than the Rossby radius of deformation (on the order of 10 km for TC eyewalls). Hence, as the perturbation vortex grows with the raincell, an accompanying pressure perturbation develops near the inner edge of the eyewall, where the updraft is located. Anecdotal evidence for the existence of this pressure perturbation was obtained from two sources. First, by pure serendipity, the NOAA-11 polar-orbiting spacecraft passed over South Florida at a time exactly midway through the raincell production process as the eyewall was moving onshore. The 1-km resolution infrared image (not shown) revealed a "hot spot" in the image, not in the center of the eye, as normally expected, but offset from the center immediately adjacent to the eyewall convection. The second serendipitous observation was made by a private citizen, who observed their minimum pressure reading for the storm from a home barometer, later calibrated, which was situated exactly within the warmest pixel of the image and within 3 min of the satellite image time. Four additional private pressure observations in the nearby area confirmed the existence of a pressure perturbation along the edge of the eyewall that was 9 hPa lower than the minimum pressure in the center of the eye observed by Air Force reconnaissance aircraft at nearly the same time.

Such a mesovortex was actually penetrated by research aircraft at low altitude (300 m) in Hurricane Hugo (1989), obtaining detailed flight-level measurements. The Hugo aircraft flight revealed a classic meso-vortex signature with a wind speed perturbation of 30 m s^{-1} and a pressure perturbation of 13 hPa and was tracked for 5 revolutions about the eye center during a 1.5 h period as 5 separate cells developed and decayed, an almost identical scenario to Andrew.

An eyewall mesovortex was first photographed from above by a U-2 aircraft in Typhoon Ida (1958) (Fletcher et al 1961). The eyewall actually folds into the eye as it attempts to partially wrap around the meso vortex in Ida. Both Ida and Hugo shared a common characteristic with Andrew in that they were both very intense and deepening rapidly. One might conclude that meso-vortices and their attendant enhanced and streaky surface winds are a characteristic of intense, deepening storms, and that, should this occur as landfall approaches, then intense inland wind damage is to be expected.

2.1 Hurricane Hugo

On 15 September 1989, a NOAA WP-3D made the first aircraft penetration into Hurricane Hugo at an altitude of 450 m when it was $\sim 500 \text{ km}$ northeast of Barbados. The aircraft encountered intense turbulence and suffered the loss of an engine. Data from this aircraft showed that it penetrated a mesoscale vortex imbedded in the inner edge of the eyewall adjacent to intense convection.

The mesovortex had a diameter of 1 km at 500 m altitude which is a factor of 10 smaller than the eye diameter. This is about the same ratio as suction vortex size to its parent tornado (Fujita, 1971). The 1 km is also 10 times smaller than a tornado's parent mesocyclone and about 5 times larger than a tornado. The wind and pressure perturbations about a linear pressure and wind speed profile are 30 m s^{-1} and 12 hPa, respectively. The former is about a factor of 3 smaller than the eyewall maximum winds. In contrast, suction vortex winds are about a factor of 2 greater than tornado rotational winds (Fujita 1971). The perturbation vorticity is $\sim 10^{-1} \text{ s}^{-1}$, an order of magnitude greater than eyewall or mesocyclone vorticity and about the same as tornado vorticity.

During 14 subsequent orbits of the eye the aircraft penetrated the vortex on nine different occasions with diameters of 1-2 km. The vortex penetrations, at gradually increasing altitude, showed that the vortex's maximum strength and smallest diameter appeared to be at cloud base and broadened with height. The vortex rotated around the center of circulation with a period of 19 min, implying a translation speed of 30 m s^{-1} . This was the first time that an aircraft had penetrated such a phenomena in a TC, although vortices of this type have been observed, and are probably more common than previously

believed (e.g., Fletcher et al 1961; Marks and Houze 1984; Muramatsu 1986; Bluestein and Marks 1987).

2.2 Hurricane Luis

During the daylight hours of 6 September 1995, 1-km resolution GOES-9 1-min interval images and GOES-8/9 15-min stereo images were obtained over Hurricane Luis. These data were concurrent with NOAA WP-3D one-min horizontal and vertical airborne radar scans. These observations revealed a series of 8 cycloidal loops. The low-level center is indicated by the primary low-cloud swirl, while the upper-level center is indicated by the center of the cirrus cloud rim and the infrared maximum temperature. Secondary low-cloud swirls appeared to rotate around the primary swirl. The cycloidal loops had an average period of 90 min and an average diameter of 20 km. The upper eye diameter averaged 60 km, while the low-level diameter averaged 40 km. The upper-level center was displaced to the east-southeast of the primary low-cloud swirl by an average of 25 km. Overshooting convective turret clusters were observed in the eyewall with similar 90-min periods and duration averaging 20 min.

One event, corresponding to the first WP-3D eye penetration, was analyzed in detail using the radar and one-min GOES-9 data. Several minutes after rapid increase in radar reflectivity occurred in the northeast eyewall sector, a cluster of overshooting turrets was observed emerging above the cirrus shield in the north eyewall sector. The cluster continued to bubble as the turret and reflectivity maximum rotated around to the west eyewall sector. Strong evidence of cyclonic rotation of the turret elements was observed during the peak overshoot period. Simultaneously, the GOES-8/9 stereo imagery revealed that thin cirrus elements at the upper edge of the eyewall were being entrained into the eye as they descended toward the primary low-level center adjacent to the overshooting turret cluster. During this period, the low-level center was migrating toward the eyewall sector where the turret cluster was observed.

2.3 Synopsis

Features observed here are very similar to those encountered during a NOAA WP-3D flight into Hurricane Hugo (1989) (Black and Marks 1991). The storm structure was somewhat different in that case with a smaller eye than Luis, but the intense convection was clearly

associated with a mesovortex which was separable from the intense background vortex circulation. The mesovortex had perturbation pressure on order of 15 hPa and wind perturbation on order 30 m s^{-1} . Vertical reflectivity structure was similar to that in Luis with intense cores sloping outward and upstream.

The mesovortex in Luis never penetrated to low levels, and did not appear to be as strong. However, the 6 revolutions about the eyewall in Hugo were very similar to the 8 loops observed for Luis. Only the revolution period was longer for Luis (90 min) compared to Hugo's (20 min) due to the larger eye diameter (60 km vs. 14 km respectively). A schematic composite of the flow fields, depicted in Fig. 1, illustrates how the mesovortex flow is superimposed upon the TC-scale flow.

3. RECENT ABL OBSERVATIONS IN HURRICANES GUILLERMO AND ERIKA (1997)

The successful deployment of the new GPS sondes with reliable wind, temperature, humidity and pressure measurements every 0.5 s to within less than 10 m of the surface were made for the first time from the NOAA WP-3D and Gulfstream IV (G-IV) aircraft in the inner core of eastern Pacific Hurricane Guillermo (1997). Additional drops were made on three days in Atlantic Hurricane Erika (1997).

Preliminary analysis of a few of the eyewall soundings have revealed several new and unusual ABL structures. Figure 2 shows three normalized eyewall ABL soundings of potential temperature (θ), specific humidity (q) and wind speed (WS) from Hurricanes Guillermo and Erika. The vertical coordinate is normalized by the depth of the ABL, defined as the depth of the constant θ layer ($\sim 300 \text{ m}$). These eyewall soundings indicate three consistent low-level wind maxima at approximately 0.7 normalized height units ($\sim 200 \text{ m}$), at 1.4 units ($\sim 400 \text{ m}$), and at 2.5 units ($\sim 750 \text{ m}$). The lowest wind maximum appears just above the top of a constant- q layer, whose depth is shallower than the constant- θ layer. The other two wind maxima occur at and just above the constant- θ layer. These soundings are typical of other eyewall soundings that show multiple wind maxima in the ABL and exhibit a shallow constant- q layer. The latter corresponds with a layer of nearly

constant wind direction (not shown), and may be representative of the surface layer. These wind observations are consistent with Australian tower observations in the inner, high-wind core of TC first reported by Wilson (1979) and recently discussed by Kepert and Holland (1997). These data showed a low level wind maximum consistently at the 60-m level, as well as a wind maximum near the top of the 400-m tower.

The observation of a thin layer of elevated specific humidity in the high wind region beneath the eyewall is very suggestive of a spray layer which may enhance evaporation in the >90% relative humidity air. The existence of a wind maximum above this layer indicates that upward vapor fluxes in the ABL may be controlled more by shear-induced turbulence at the top of the high specific humidity layer than by direct flux from the sea. Sea spray processes such as discussed by Fairall et al (1994) may become important. Additional analysis of this revolutionary new data source should lead to profound new insights into the workings of the TC eyewall ABL.

4. CONCLUSIONS

A unique combination of 1-min interval super-rapid-scan GOES-9 images and NOAA aircraft data provides unprecedented insights into the dynamics of eyewall convective outbreaks, eye motion, and low-level cloud motion in the eye. The mesovortices observed in concurrent GOES/Aircraft 1-min animations appear to be similar to features of eyewall mesovortices observed by the flights into Gladys (1975) and Hugo (1989) and to observations in Andrew (1992). It is hypothesized that the mesoscale vortices are advected by the TC-scale vortex causing significantly higher winds in regions where the wind velocities of the two vortices are near their maxima and in the same direction. The insights gained from this work have potentially far reaching implications as to an improved understanding of the track and intensity fluctuations associated with these features and to strategies for mitigating attendant damages at landfall.

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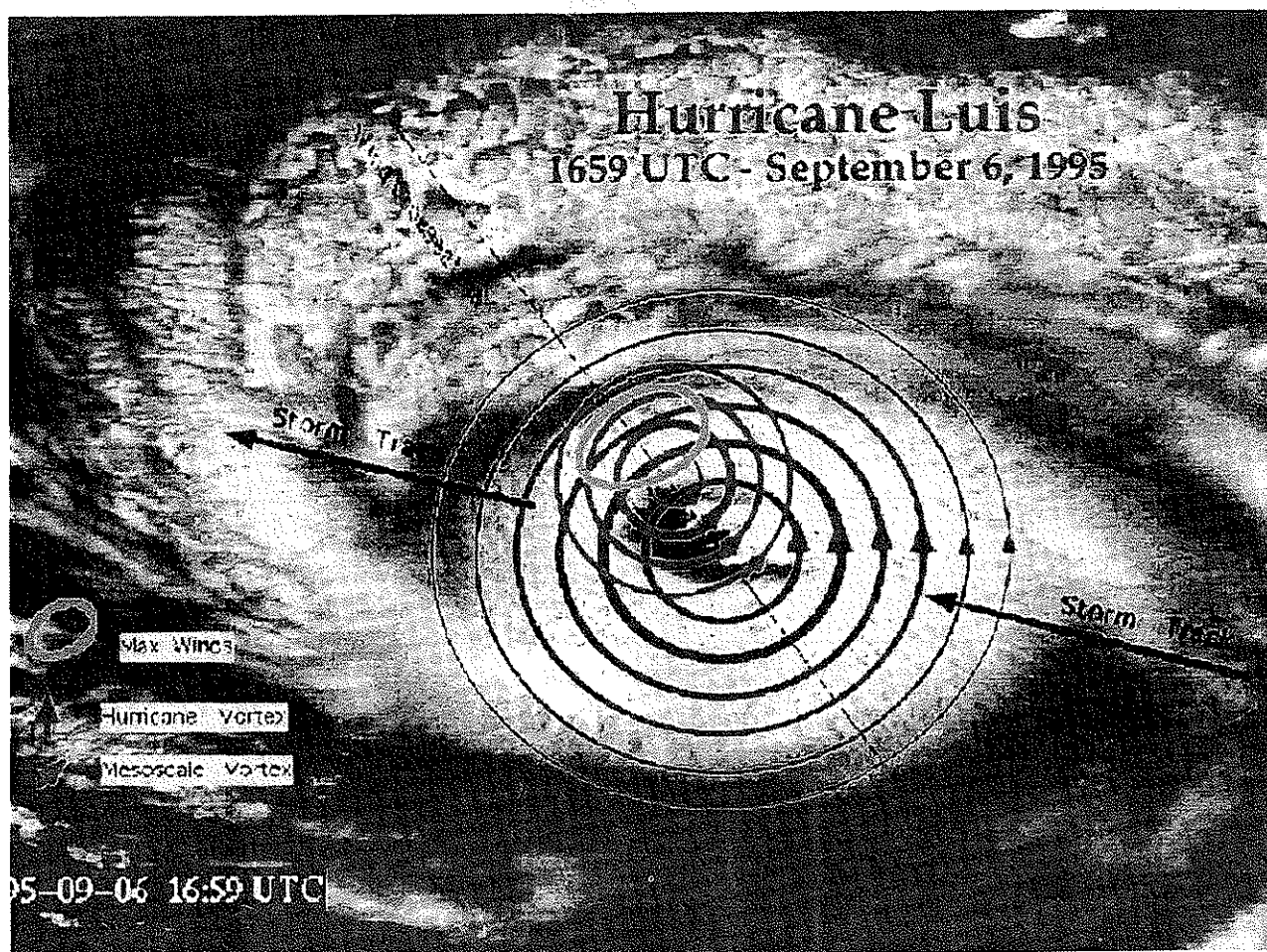


Fig. 1 Schematic representation of the flow field in a eyewall mesovortex superimposed upon the hurricane scale circulation. Both circulations are superimposed on a visible image of Hurricane Luis, September 6, 1995.

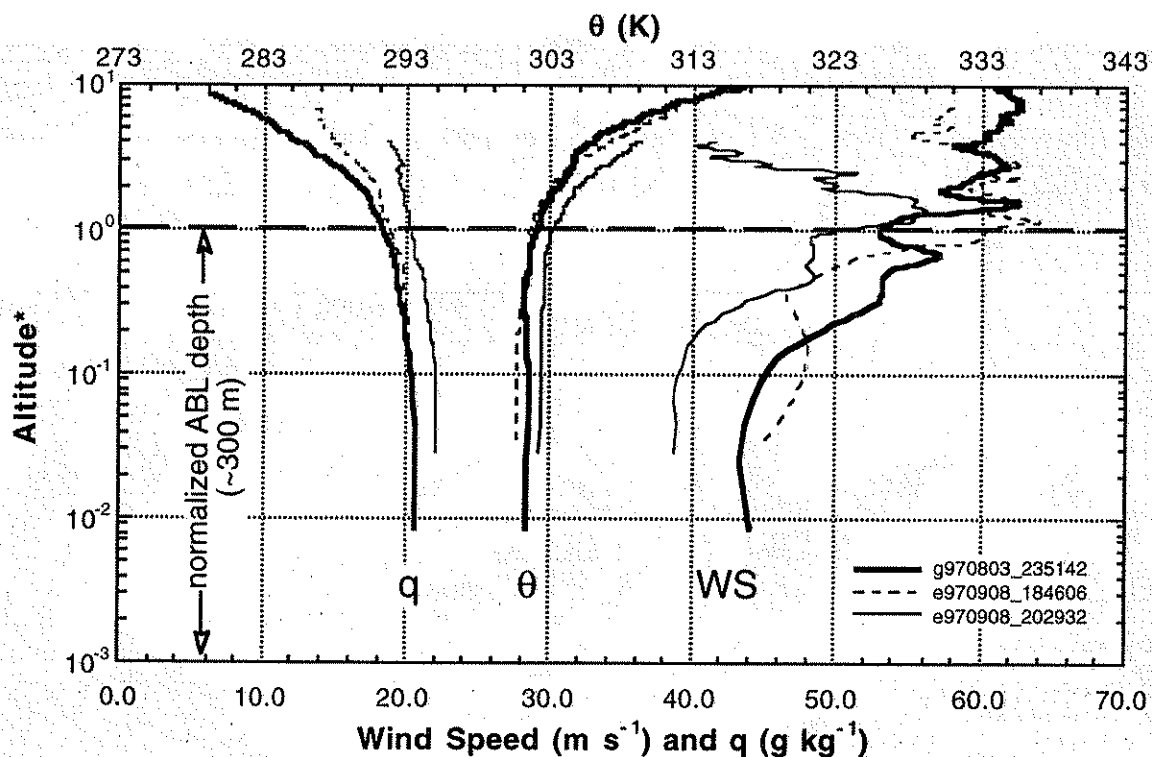


Fig. 2. GPS dropsonde profiles of specific humidity (q g kg^{-1}), potential temperature (θ $^{\circ}\text{C}$) and wind speed (WS m s^{-1}) for three typical profiles in the eyewall of Hurricanes Guillermo (thick solid lines) and Erika (thin dashed lines). Vertical coordinate is normalized by the depth of the ABL defined as the depth of the constant q layer (~ 300 m).