Turbulent conic lab vortices scale to wide ranges of violent natural actions

1. LAB GYRE FLOW STRUCTURES DEFINE TORNADO INCEPTION SITES IN HURRICANE IVAN

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SUMMARY

In this first of two papers correlating flows and forces of lab vortices with violent weather from surface to mesosphere, underwater and surface vortices are viscously driven by immersed 30 degree cones to high turbulence. In centrifugal spiral wave planform disks of conic surface gyres, each separate spiral wave above the cone base is driven into a quantified spirally coiled sub-vortex itself, with quasifractal wavelets. If such a spiral disk gyre is deeply submerged, the multiwave centrifugal disk above the cone (in the equivalent surface gyre) coaxially drives measured upper and lower toroidal ring vortices in unequal hemispheres of a sphericly complete conic vortex. Outer shells of toroid flow carry spiral wave eddies into the hemispheres, and converge at each pole in axial inflows to the primary centrifugal flow spiraling out above the cone. Inward spiral waves arise on any surface under the lower toroid. The quantitative lab flow velocity data enable correlation of lab conic gyre structures with those of a tropical cyclone.

In Hurricane Ivan, satellite microwave temperature images of cloud altitudes reveal, between tall, widely separated, convective rain band spirals, another set of low altitude spiral waves, due to viscous sea surface friction, equivalent to the strong centrifugal spiral waves in the lab upper spiral disk, but with lower hemisphere inward flow. These low spiral waves, at the peak wind levels, systematicly overtake the more slowly rotating spiral rain band cells, causing much greater convection pulses to colder heights, correlated to lab flow speed ratios. This pulsed interaction of two coaxial spiral wave sets recurs on Ivan's landfall with 23 outer rain band tornadoes at the Equation 2 limit of scaled turbulent lab gyre diameter, in quantitative correlation of cyclone structure with lab gyre structures.

KEYWORDS: Conic driven vortices   Immersed vortex   Surface vortex   Hurricane anatomy   Tornado initiation   Cyclone tornadoes   Vortex spiral waves   Toroidal gyres   Turbulent vortex interactions   Lab vortex experiments

1. INTRODUCTION

This is the first of two related papers on empirical correlations of previously neglected features of turbulent conic vortices in the lab with some very energetic, but not fully understood,

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cyclonic weather formations from the surface to the mesosphere. These papers originated in experiments with vortices driven in water by central cones to sufficient rotational energy, and turbulence, that both full anatomy of water particle velocities (reported herein) and forces (Howard 2006) resulting from secondary flows in single and dual gyres could be readily observed and measured. The experiments were initially intended as preliminary trials in connection with other on-going research (in submicroscopic electron current vortices) that might lead to a more precise and narrowly focused experiment elsewhere. However, the exploratory data and force equations show quantitative correlations with mechanical interactions of the strongest types of weather vortices, such as tropical cyclones, mid-latitude supercells, and tornadoes, and add at once to the scant empirical data on forces and secondary flows in the highly turbulent lab conic gyres that are most relevant to violent weather. The scarcity of such data contrasts with the large body of literature on vortex experiments that are not as directly relatable to violent weather, such as laminar surface vortices, two dimensional vortices without secondary flows, and isolated cylindric or toroidal gyres.

The immediate stimulus to these experiments arose, during searches for information on secondary flows of vortices, from a citation by Brunt (1942), the distinguished President of the Royal Meteorological Society (Walker 1992), of unexplained experimental evidence (Fujiwhara 1921-3) that pairs of vortices can on occasion attract or repel each other in exact contradiction of the accepted theory. The papers recorded obscurely only that effects reversed with depth of an undescribed impeller. No resolution of such a contradiction of theory was found in the literature.

After the new flow velocity data were reduced (Figs. 1 to 4), an unusual new similarity was noticed in microwave temperature images from satellites (NavSatMet, 2004) of Hurricane Ivan cloud heights (Fig. 5) during a wide opening between rain belts that occurred near Jamaica. The images had been put into video loops (Marti Group, 2004) that aided perception of cloud interactions. These were then studied in the original satellite images. Separate spiral cloud waves in two altitude ranges can be discerned rotating cyclonicly in coaxial planform at quite different velocities. The speeds are similar to typical wind profiles (Henning, 2005) from GPS dropsondes (Fig. 6) in a previous well instrumented hurricane (CAMEX Group, 1998). When an unusual, faster moving, thin wave (like the new lab data), in the pale blue color of low altitude warmth, overtakes a typical cold, yellow-green, higher altitude, heavy rain band cell, an orange, red, or purple-coded surge to a higher, much colder altitude brightens the rain cloud tops.

Such convective surges recurred in two destructive incidents when Hurricane Ivan came ashore into Alabama and Florida from the Gulf of Mexico. At the shoreline, NOAA radar data (Fig. 7) show a damaging downburst of wind and rain at the edge of an opening in the eyewall, which correlates with events in other open eyewall cyclones (Holmes et al. 2005; and Blackwell 2000). Traces of low altitude spiral waves in the open area at the time can again be detected in the satellite microwave and surface radar images (NavSatMet 2004; Marti Group 2004; and Nexrad 2004). More definite indications (Fig. 7) of lower spiral waves are visible in an Ivan outbreak (Fig. 8) of 23 tornadoes (Watson et al, 2005) in one right front, outer rain band spiral.

This paper points out these new tropical cyclone features and correlates them numericly to lab vortices. Some flow measurements of the lab experiments serve to explain in geometricly similar flow patterns and flow ratios (not full heat release models) possible additional causes of the convection surges in the cyclone. The coincident synchronized surges in the early open circulation are apparently rapid and strong enough that they might play a part in tornado initiation. Recurrences of dual spiral waves with known tornadoes are consistent with such synergetic interactions. The tornadic outlying rain band is just within the violent weather diameter limit scaled from Ivan's eye wall data by lab data equation (2). That all the major structures in the cyclone images correlate directly with those of the lab vortices further strengthens these inferences (which may also apply to tornado generation in other temperate zone cyclonic and unstable anti-cyclonic circulations. Further fractal eddy circulations, seen clearly in the lab and marginally in the cyclone images, could influence tornado generation too.)

The lab experiments of this paper are described in section 2, followed in section 3 by the measured vortex flow velocities (Figs. 1, 2, 3, and 4) in flow structures which correlate with the newly described and other typical structures of Hurricane Ivan. Numericly scaled correlations with satellite and radar data on Ivan's convection surges and tornadoes (Figs. 5, 6, 7, 8, and 9) are in section 4, with implications to other unstable circulations. Section 5 lists conclusions.

2. General description of the conic vortex flow experiments

Many natural vortices are conicly tapered along their axes of rotation, short in axial length on a diameter scale, and centrally driven by a viscously coupled heat engine, plus Coriolis momentum effects or other viscous sources of rotation. The gyres often develop spiral waves, with centrifugal flow out from a broad upper end of the conic taper (such as a cirrus cap) and flow into a lower, narrower diameter end (such as an eyewall.) That type of vortex shape with centrifugally accelerated flow was centrally driven to high turbulence in city tap water at 20° C by a spinning, wooden, unpolished, right circular cone of 30 degrees total cone angle and 7.94 cm base diameter, on a 6 mm shaft with an acorn-shaped fastening nut at the slightly truncated tip of the cone. For this paper, the cone was driven only in direct axial base drive, by a typical electric motor of a 10mm (3/8 inch) hand drill, in clockwise base-referenced rotation with the base up in the plan view. Angular rotation rate was optically measured under loads and converted to peripheral (or tangential) velocity of the base of the cone, with less than 4% maximum observed deviation from the average 872.9 cm s^{-1}. Viewing angles and vortex submersion were varied (to full immersion) in different tubs of adequate size for short data periods (typically less than 10 to 30 seconds) without significant interference from tub walls and tub flow distortion. With the wood cone drive, the entire vortex process was viscously (or quasi-frictionally) driven without disturbances (as from paddles on a rotating wheel impeller.) This arrangement provided known angular and peripheral velocities on a known boundary layer surface of viscous rotational flow in the main body of the vortex.

Flow visualization and velocity measurements were obtained through the water surface by stop-motion video (at 30 frames per second, from 2 meters distance) of flow patterns among neutrally buoyant and individually distinctive, irregular particles in the 0.25 to 1 cm size range. The particles exhibited continued fluid suspension with the same apparent density as water. (In available particles, only broken, well soaked and washed, edible meats of thin-shelled, light tan "English" (Persian) walnuts, *Juglans regia*, from California, were suitable. Floaters and sinkers were removed.) In momentum exchange, with drag coefficients of 1.2 to 2, velocities of these particles were estimated as close approximations of the determinable lower limits for water streams with diameters equal to or greater than the particle sizes. The particles were videoed against a 5 cm white grid on a black background 20 to 25 cm behind the center of action, with data taking limited to a measured number of seconds before observable wall interference could develop in each configuration. Fully immersed and surface gyres were viewed in axial plan, in elevation, and obliquely. Multiple particles were tracked in slow motion to define a projected, curved path on a 0.9 m diagonal, high definition display tube. Frame-by-frame, point-to-point, grid-calibrated minimum limit speed measurements were then made on typical particles. This instrumentation measured definite primary, secondary, and tertiary flow velocities in turbulence.

As to the accuracy of the data: In flow velocity measurements, water surface distortion effects were minimized by the calibrating grids. At the higher particle velocities, displacements ranging to 10 cm per video frame at 30 frames per second were large enough to compensate for image blurring. But there was no means of correcting for non-circular out-of-plane trajectories and curved paths. Thus, the measurements are actually minimum limits of speed where rotational flow is involved, especially in the spiral waves. Frame-to-frame, apparent flow velocities in cm sec^{-1} in the projected plane of view (Fig. 1, 2, 3, and 4) are shown at the approximate locations of the median speed of sample bins. Most sample bins are arbitrarily spaced down by factors of two from the maximum repeatedly measured speed. From frequent repetition of measurements at locations, it is estimated that with long continued testing one sigma deviation would resolve at about 10% and 5 degrees. However, since the instantaneous velocities of particles are continuously changing in such turbulent flows, after traveling about 10 cm net through corkscrew tracks, the particle is often rapidly decelerating in a region with an apparent speed about 50% lower due to viscous loss of momentum to the surrounding water. Any peak velocity estimate should be increased further. It is estimated that the true peak velocities of the observed particles must be at least 50% higher than the measured velocities shown. Such effects have less impact in parts of the figures with midrange speeds or less curvature of trajectory. Speed ratios from one part of the flow to another would be more valid than the velocities shown. Within the lowest speed bins, small speed ratios are not clearly distinguishable. The sizes of structures, such as gyre diameter *GD*, are not affected by the velocity uncertainties; repeatedly measured dimensions are estimated at ±5%.

3. Flow Structures of surface & immersed conic gyres correlating to Hurricane Ivan

Figures 1, 2, 3, and 4 (all with the same drive, section 2) summarize, within quantitatively scaled schematic plots of the interacting flow structures, the quantitative components of flow velocities in cm sec^{-1} for particle tracks measured at projected locations in turbulent lab vortices.

(Correlations to such weather effects as tornadic events in Ivan, or elsewhere, arise by scaled similarity in these structures, flow velocities, and sequences of mechanical flow interactions.)

The seven subfigures of Figure 1 introduce the numeric flow velocity data by gradual steps in sequential interactions which drive gyre flow structures, starting with the initial viscous coupling of momentum into water at the surface of the drive cone. Figure 2 shows interacting locations for the combined data (as it appears in the lab) in the planform view of spiral wave cores in the central, highly turbulent disks of both the surface and fully immersed vortices; below that schematic, the figure also shows the cone-base portion of the elevation view of a surface hemispheric vortex. Figure 3 shows the relative locations of the combined data in a matching elevation view for a fully immersed, complete, spheric conic vortex (and the similar surface vortex) standing free of any flow interference. (A few critical angles are marked in condensed degree notation, converted to radians for equations.) Figure 4 is a bottom flow plan and an elevation plot of changes in quasi-frictional flow on a floor inserted under the drive cone (in mean similarity to lower flow structures of various typical weather gyres over earth's surface.)

Within experimental uncertainty (section 2), flows of the conicly driven surface gyres herein are equivalent to those of the immersed vortices when the surface vortex is driven with the cone base up, at one base diameter below the water surface, as shown in the relevant figures and standardized for this paper. Accordingly, only three views (like those of Figs. 2 and 3 taken together) are needed, one above the other, for each subfigure (in Fig. 1) to exhibit the flow development in scaled structures for both the surface and the immersed vortices in one sequence.

In the elevation schematic plots, each right half of a full view of a gyre is an exterior window view (with structural flow core borders behind surfaces of view shown by the usual dashed or broken lines.) Each left half of an elevation view is a partial cross section of the fluid flow structures in the plane of the vertical axis of the cone, but shows the front surface of the cone (not its section), plus flow lines near it. Also, the water within the sectioned spiral wave and toroidal ring cores is not shown with section lines, as if the water in the gradually diffused core circulation structures were scooped out or cut away at unrealistic hard lines in the section plane to emphasize the scaled locations of these large secondary flow structures. Except where they are on effective structural borders (beyond which velocities merge into other flow patterns), measured particle flow directional tracks in the view plane are dotted with arrows, and speed components of velocity in the plane are shown in cm sec^{-1} for the adjacent tracks at the locality.

In Figure 1a, then, in its column of three views, the flow velocity lines display the first stage of viscous (quasi-frictional) coupling of momentum from the drive cone to the adjacent fluid. (Per section 4, the drive cone data correlate to the observed concentration of heat release and Coriolis effect in the Ivan eyewall velocities.) The two primary flow structures driving all subsequent data are plotted by tracks of particle velocities along the two surfaces of the base and the sides of the drive cone, with a boundary line between the two flows and with another above the flow off the base in the two cross sections. With little initial mixing, these two flows spread centrifugally from the base perimeter. In the upper elevation view the flow stream spiraling upward along the cone's sides is comparatively quite thick and gradually accelerated in almost laminar flow to a lower centrifugal velocity $\mathbf{V_S}$ at the base perimeter in the thicker stream from the side flow than those of the thinner, faster sheet of turbulently pulsed flow off the base plane. The base centrifugal flow is more quickly accelerated in about a third as much distance along the cone outline to its 33% greater observed lower limit of projected peak velocity $\mathbf{V_B}$. However, that is only a little more than a third of the more accurately known peripheral velocity $\mathbf{V_P}$ shown for the base of the cone per section 2. In scale speed ratios (section 4) which limit coupling:

$$\frac{|\mathbf{V_B}| \;/\; |\mathbf{V_P}|}{|\mathbf{V_S}| \;/\; |\mathbf{V_P}|} = \frac{0.349}{0.262} = 1.33, \qquad (1a)$$

where also $$|\mathbf{V_S}| = 1.47\,|\mathbf{V_{SU}}|, \qquad (1b)$$

and $\mathbf{V_{SU}}$ is the mean upward velocity along the side at 156 cm s^{-1} (as in Ivan's convection scale.)

The elevation view of the surface vortex (Fig. 1a bottom) at the standard base immersion noted earlier, has the same flow pattern and velocities (where the same structures can exist under water) as the immersed vortex (Fig. 1a top). The plan view between the elevation views shows schematic particle trajectories in the conicly shaped sheet of the base primary flow, neglecting turbulences too small to measure reliably. These turbulences (and larger ones, Fig. 1c) die out, and speeds decline (as they do in scaling Ivan (2), section 4) at a definite gyre diameter (*GD*), shown (Figs.1a--c) as empiricly observed, with a tangential component of water particle velocity.

Within the *GD*, the underside of the base flow sheet (Fig. 1a) loses little momentum to a 25% slower (1a) side flow with its similar flow direction. (The turbulent momentum of the base primary flow sheet couples largely into the spiral waves of Figs. 1b and c above it.) The dividing line between the flow off the base and off the sides of the cone is not in the plane of the cone base, but is at a slope of 1 in 4, or (π/12.82) = 14.04°, above that plane (in the nominal axial up direction from the base reference herein.) Thus, the cone-shaped centrifugal flow off both the base and the sides has an upward flow component (1d) (Fig. 1c). (This is a new quantitative feature of conic vortex structure with numeric consequences in vortex force equations relevant to tornado forces in the next paper (Howard 2006).) Herein, this angle of flow viscously draws the lab lower toroid (Figs. 1f and g) in and up under the *GD* to merge in this primary side upflow (for direct quantitative correlation (2) (3c) (Fig. 9, section 4) to violent features of Ivan.)

Figure 1b exhibits the cores of a typical complete spiral wave and an interstitial partial wave generated secondarily in the central turbulence zone by viscously quasi-frictional coupling from the base primary flow sheet (Fig. 1a). The upper vertical section emphasizes both the centrifugal velocity with which the core of the wave is driven by the primary flow in which it is embedded and the velocity retained after rotation to the top of the wave while losing momentum to the surrounding water. There is also a figurative cross-section at the point of maximum core diameter at the *GD* (with a cut-away view behind the section of a vertical core flow velocity $\mathbf{V_R}$ that is directly relevant to convective surges in the rain bands of Ivan in section 4.) From near the axis to this point the vertical thickness of the wave core has been growing farther above the 14 degree upward slope noted (Fig. 1a). The middle plan view shows that the turbulent spiral waves do not usually appear to arise at the axis, but rather at a small radius with a large angle of movement relative to the radius. This view emphasizes again the rotary component of internal motion $\mathbf{V_R}$ imparted tangentially to the wave near the *GD* by the couple through the base flow sheet from the more rapidly rotating base of the cone at $\mathbf{V_P}$ (as used in scaling Ivan, section 4):

$$|\mathbf{V_R}| \,/\, |\mathbf{V_P}| = 0.262 \qquad (1c)$$

The wave core is a newly described, long, cylindricly tapered and bent vortex itself (re tornado forces, Howard 2006) surrounded with growing outer shells (not shown) of rotating water full of yet smaller turbulent waves to the *GD* limit. At the *GD* the turbulent momentum couples out to the additional entrained water and surroundings more rapidly than it is added from the base flow sheet below, and the turbulence disappears at the *GD* (correlating directly to Ivan.) This occurs where the decelerating core bends increasingly past 45 degrees ($\pi/4$) away from the local radius from the main axis. Beyond the *GD* to 2 *GD* the wave, moving as a wave as shown, changes into a circularly spreading, very smooth wave system with the other waves of the gyre.

In the plan view of Figure 1c a typical number of about six such complete wave cores with an interstitial core (indicative of a variable additional number) are shown as the basis for the outstandingly visible turbulence of the subplanar spiral wave disk within the surface *GD*. The conic inner tips of the waves constantly vibrate vigorously about 0.5 cm amid larger turbulence, and so do smaller wavelets (not shown) over the spiral wave bodies. (These upper spiral wave cores correlate in rotational velocity with the lower spiral waves of Hurricane Ivan in section 4.) One of the waves in the plan view is shown with the repeatedly measured overall corkscrew motion and point-to-point projected typical velocities of particles in the wave cores, for which the separate projected rotary, peak centrifugal, and wave motion components are shown in the various waves. In these cases the particle motion along the top surface of the core is shown with a continuous structural line, and on the bottom surface of the core with a dashed structural line. The typical corkscrew out-of-plane vertical rotational radius for this trajectory is around 1.5 cm. The rotary component of each wave is still significant over most of the less notable outer part of the disk extending to about twice the *GD* turbulent diameter, beyond which point the non-turbulent almost circularly expanding waves appear negligible compared to other flow structures. The entire spiral disk of waves in the plan view is shown rotating at the tangential velocity $\mathbf{V_D}$ near the GD for an angular rate of 2π to 4π s^{-1} typically (also numericly relevant to tornado forces, Howard 2006). In the top and bottom elevations the turbulent portion of the disk within the *GD* is seen growing in a coaxial depression (at an average centrifugal wave velocity $\mathbf{V_W}$ of 267 cm s^{-1}) between the 14 and 30 degree angles (average 22°, π/8.2) above the plane of the drive cone base, from a very small thickness around the axis to a very thick structure at its *GD* peak. This adds to the upward flow (Fig. 1a) momentum component in and under the disk:

$$\mathbf{P_{DU}} \propto M_W \mathbf{V_W} \tan(\pi/8.2) + M_S \mathbf{V_S} \tan(\pi/12.8) + M_B \mathbf{V_B} \tan(\pi/12.8), \qquad (1d)$$

(re tornado forces (Howard 2006)) where the water masses are those in the centrifugal flows above the volume centroid of the cone and between the perimeter of the cone and the *GD*.

At the peripheral velocity $\mathbf{V_P}$ shown (per section 2) of the cone base in 20°C tap water, the turbulent *GD* itself, which is generated by this disk wave structure (Fig. 1c), is about 2.56

times the cone base diameter or 20.3 cm average, with ±1 to 1.25 cm of increase at each spiral wave and decrease between waves. (In numeric (2) herein (section 4), from equation (1) (Fig. 1) of the next paper on data and equations of vortex force effects (Howard 2006), the lab *GD* varies systematicly with functions of the peripheral velocity and surface area of drive cones and ratio of fluid density to viscosity, not with sizes of experimental tubs herein. As noted (Figs. 1a and b), the lab *GD* dimension, as a quantitative scaling limit of turbulence, extends beyond and includes other gyre parts (Fig. 1f) in close correlation (section 4) with violent structures of Ivan.)

Initial numbers of waves (Fig. 1c) in such a surface spiral disk above the cone base may vary with some drive conditions from two to about twelve (including interstitials), but they settle toward six equally spaced spiral waves after drive removal, while the spirals briefly continue advancing in the rotary direction of the primary rotational drive. Then they reverse direction of wave angular advance to rotate against the established angular flow of the main original vortex, since they are now driven by the continuing momentum of the prior quasi-frictionally imparted (Fig. 1b) internal rotation within each wave. In this reversal the waves change from spirals to shorter diametric bars, in two radial sections, with spiral waves trailing from each outer tip, very much like the conventional barred spiral forms so common in astronomic galaxies (p. 9, Longair 1996). This reversal process confirms the high levels of internal tangential momentum per cc $\mathbf{P_{IW}}$ stored in the fluid at the rotation periphery of each spiral wave core near the *GD* (correlating with surging waves of active Hurricane Ivan (section 4), and with dissipating cyclones):

$$\mathbf{P_{IW}} = M_{IW}\mathbf{V_{IW}} \geq 1 \times 229 \text{ gm cm s}^{-1} \qquad (1e)$$

where $\mathbf{V_{IW}} \geq \mathbf{V_R}$ (1c), the observed lower limit of the internal rotational core velocity.

Figure 1d shows inflows to and direct outflows from the primary flows on the surfaces of the drive cone (Fig. 1a), and contains the only observed difference between water flows of the surface gyre of this paper and the fully immersed gyre. Here the upper inflow of water for the centrifugal spiral waves of the surface vortex (Fig. 1d bottom) tumbles in from all sides over the spiral wave disk, viscously acquiring from it some rotational momentum in the process. (This apparently thin base inflow and thick centrifugal outflow below it do balance in volume due to wide peripheral variation of the outflow between waves.) In the immersed gyre (Fig. 1d top), the inflow to the primary base flow and spiral waves is axially downward, and it viscously receives initial rotational momentum from shells of the upper toroid (Fig. 1f). Otherwise, flows in surface and immersed gyres are interchangeable within experimental uncertainties. Both types of gyres recirculate much of the net primary outflow back into the inflow at the point of the cone (Fig. 1d, top), as shown next by eddies (Fig. 1e) in the lower toroidal flows (Figs. 1f and g) (leading on in sequence to correlations with Ivan's violence in section 4.) Immersed gyres (Fig. 1d, top) recirculate similarly in upper hemispheres (correlating to storm supercells (Howard, 2006).)

Figure 1e shows rotational velocities and core sizes of tertiary eddies and typical velocity tracks of carriage in the spiral flows of the toroids (next.) The conic eddies arise at the edges of the secondary spiral wave cores as these bend to more than 45 degrees from the local radius and lose turbulent momentum at the *GD*. Eddy rotational sense depends on its source at the leading or trailing edge of a wave, low or high in the wave disk. Eddies are ejected from the disk into the centrifugal flow of the outer shells of the toroids (Figs. 1f, g, and 4), which bring the eddies around into the main inflows (Fig. 1d), largely in the lower hemisphere. With continuous forming and ingestion of eddies, their numbers appear constant. (In Hurricane Ivan, discernible traces of eddies are consistent indicators of steady inflow from outer toroid flow carrying them.)

In the top elevation view of Figure 1f, separated coaxially by spaces for the prior spiral wave disk (Fig. 1c) and primary side outflow (Fig. 1a) which drive them, core outlines of the two large upper and lower hemisphere toroids summarize the internal rotational velocities of spiral corkscrew particle tracks around parallel circular axes of toroidal rings centered on the main gyre axis. (Flow directions in these rings account for Fujiwhara's (1921-3) contradictions (section 1).) The middle and bottom views show the core of the lower hemisphere toroid (of which central portions within the *GD* (not shown) correlate directly to the violence of Hurricane Ivan, section 4.) The cores and surrounding flow (Figs. 1e, f top, and g) actually occur as multiple, flexible, diffusely spiraling shells of particle and eddy tracks which both merge and peel away to spiral (similarly to Ivan's spiral rain bands) into the strong primary drive flows (Figs. 1a and d). Thus, as noted earlier, each toroid returns some of its circulating momentum and energy, with its fluid and embedded eddies, to the top or bottom input flow of its hemisphere. Each toroid also stores momentum and energy and viscously couples a portion outward (measured in the force paper section 4 (Howard 2006)) to fluid around it beyond the *GD* (as in Ivan's flows (section 4).)

Otherwise the two toroids are quite different. Both toroids are positioned by the prior upward-angled centrifugal flow components (1d) (Figs. 1a and c) which push the upper toroid away from the drive cone, while drawing the lower toroid up around the cone and in under the *GD* (re Ivan (2) (Fig. 9) (section 4).) The upper (more tertiary) toroid is impulsively driven at separate points by the peak flow (Fig. 1c) of each secondary spiral wave as it loses turbulence at the *GD* and by the vibrations of disk wavelets. The impulses spread the upper toroid diffusely at a lower spiral rotating velocity and broaden its inflow return area (with correlations to storm supercells (Howard 2006).) The lower toroid is smoothly and continuously driven viscously over a large portion of its inner and upper surface by the primary spiral flow up the sides of the drive cone and centrifugally out under the spiral wave disk (Fig. 1a). Peak observed velocity tracks $\mathbf{V_T}$ in the lower toroid approximate vector sums of the averaged components on the vertical $\mathbf{V_{TV}}$ and horizontal $\mathbf{V_{TH}}$ axes, with a speed ratio to the cone $\mathbf{V_P}$, as:

$$[\ |(\mathbf{V_{TV}} + \mathbf{V_{TH}})| \ / \ |\mathbf{V_P}\ |] \approx \ (|\mathbf{V_T}\ | \ / \ |\mathbf{V_P}\ |) \ = \ (114 \ / \ 872{,}9) \ = \ 0.13 \qquad (1f)$$

(which applies to the scaling of toroidal flow in Hurricane Ivan (section 4).)

Figures 2 and 3 show the relative locations of the combined flow velocity data from the different flow structures (Figs. 1a through g) in both the immersed vortex (Fig. 3) and the equivalent surface vortex (Fig. 2 bottom) (which are used as scaling references for Ivan.) This completes the sequence of interacting structures in an immersed, conic vortex standing free of boundaries (briefly, in practical experiments.) However, correlation to Ivan's weather over earth also includes lower boundary effects, with any resulting alteration of the prior data.

Figure 4 adds the minimum effects of a floor boundary under the lower hemisphere, in a floor level plan view and an elevation view of the bottom half of the hemisphere. The floor is set at about 6 cm below the tip of the cone, just below or beyond the apparent average return tracks for eddies and their carrier shells in the free gyres. (Selected on this basis, the spacing later correlates to Ivan's toroid core bottom spacing versus its vertical dimensions (Fig. 9) (section 4).) That leaves the figurative opening A_I for the slow inflow of outer shells and eddies around the sides below the toroid core (in the elevation view) with more than twice the area of the central opening A_O for the sequential primary upward flow around the tip of the cone, scaled as:

$$(A_I / A_O) > 2.6 \qquad (1g)$$

Within the experimental uncertainty (section 2), such a floor position does not appreciably change the net inflow rate or the flow velocities within the vortex above the tip of the cone, and the overall vortex flow continues comparably to the prior experimental standard flow structure.

Before and in passing under the toroid core, the structure of eddies and outer toroid flow shells spiraling inward as before (from all horizontal spiral directions in the lower polar plane) is altered by a new frictional spiral wave system (Fig. 4) which is viscously generated on the floor, with mild turbulence at the low flow speeds (Fig. 1f). In net effect, the eddy rotation components, which were previously carried at random locations within the outer toroid spiral shells to merge on the inflow axis with little apparent turbulence, are now swept together by the new centripetal spiral waves beneath the toroid cores and either augment the waves on the floor or are carried by shells spiraling into the vertical inflow between the waves. These typical bottom spiral wave fronts are more nearly radial to the cone axis than those of the upper spiral wave disk; they extend beyond the 20 cm *GD* and the bottom arc of the toroid; and their number is variable. They maintain fluctuations over the lower inflow area, similar to the much faster vibrations above the spiral wave disk (Fig. 1c). (The track structure of the bottom centripetal waves (Fig. 4) correlates directly to the lower spiral waves of the Ivan cyclone on the earth's surface (Fig. 5) (section 4), but, with the available drive power, lab speeds are too low for good ratio data. In contrast, the order-of-magnitude faster, internal rotational speeds $\mathbf{V_R}$ (1c and e) of the turbulent centrifugal waves (Fig 1c) in the upper spiral wave disk demonstrate most clearly the speed ratios applicable to the new observation in Ivan.)

In the planform and cross section views of the centrifugal spiral wave disk (Fig. 1c), the velocities of the rotating cylindric sub-gyres $\mathbf{V_R}$ in the waves $\mathbf{V_W}$ are imparted by the viscously frictional motion of the surface of the cone base relative to the water in the gyres. Those motions may be transposed to axes rotating with the cone, in which case the waves and their fluid move with respect to the base of the cone, and thus the wave velocity direction $\mathbf{V_W}$ and the leading and trailing edges of the wave are reversed. (The primary flow is still centrifugal, but that is not the flow component of present interest.) The internal rotation $\mathbf{V_R}$ of the cores of the spiral waves is not reversed. The trailing edge of the wave is the edge in which the secondary rotary motion within the core of the spiral waves has just been frictionally accelerated in rotation by the coupled movement across the cone surface, so that accelerated tangential velocity of the circular rotation component of the wave particle motion (Fig. 1c) is perpendicular to the cone base and away from it, or nominally upward along a dimension equal to that of the plan view width of the wave core. The velocity of the wave $\mathbf{V_W}$ across the surface at the base periphery is the difference between the base local velocity $\mathbf{V_P}$ and the observed lab wave velocity $\mathbf{V_O}$ and is fractionally indicative of the observed peak tangential, now upward, velocity $\mathbf{V_U}$ and momentum component with which packets of mass would separate centrifugally upward from the base if not contained by surrounding pressures, as:

$$\frac{|\mathbf{V_U}|}{|\mathbf{V_W}|} \geq \frac{|\mathbf{V_U}|}{|\mathbf{V_P}| - |\mathbf{V_O}|} = \frac{229}{872.9 - 76} = 0.29. \qquad (1h)$$

This speed ratio is a correction to (1c). As such, this ratio (1h) to an observed wind velocity would indicate the motion component (in the trailing edge of a low level spiral wave in a continuous wind layer moving over a fixed surface) which might lead to vertical surges in an unstable rain cell with pre-established vertical convection (which would relieve atmospheric pressure that previously contained the rotation from above, as in Ivan's convection surges.)

4. CORRELATION WITH SATELLITE IMAGES OF HURRICANE IVAN

From 8 to 13 September, 2004, Hurricane Ivan passed by Jamaica in the Caribbean Sea with maximum steady winds ranging from 125 to 145 knots, 230 to 270 km h^{-1}, or 64 to 75 m s^{-1} at the central eye wall. There was an unusually wide opening between spiral rain belts in most of the left quadrants and rear areas to the west and south away from the islands. This open area permitted distinct comparative viewing of active cloud heights at different microwave (85-89 GHz) brightness temperatures in false color images from several NOAA satellites using sensors developed by the Naval Research Lab, Monterey, Marine Meteorology Division (NavSatMet, 2004). To see the flow of cloud interactions in sporadicly available satellite still pictures (at one per satellite pass), the images had also been put into video loops (Marti Group 2004) by the University of Wisconsin's Space Science and Engineering Center (working with NRL, Monterey.)

During initial looks at these loops for a quick overview, the similarity of Ivan's cyclone anatomy to the prior lab data was first noticed. The original still images in the "H" color series were downloaded on the internet (NavSatMet, 2004). Several unusual, low altitude spiral waves, rotating cyclonicly across the open area at a radian to a quarter-radian angular separation, and their interactions with the higher, coaxially rotating, spiral rain bands, are vividly distinct in the loops and distinguishable in the still images against a dark blue background. When one of the faster moving, thin waves (like the new lab data), in the pale blue color of low altitude warmth overtakes a typical cold, yellow-green, higher altitude, heavy rain band cell, a yellow, red, or purple surge of convection to a higher, much colder altitude brightens the rain cloud tops (Fig. 5).

The color scales below the images show that brightness temperatures range from about 270 K (pale blue), at the lower spiral cloud altitude, to 190 K and less (shades of purple), in the highest cloud tops of the central eye wall. Surges of the rain band clouds start from about 240 K (deep yellow-green) and go typically to 225 K (bright yellow), 212--200K (vermillion red), or as low as 190--180 K (purple.) (In comparison of altitude indications from these early September temperatures in Ivan's Category 4 to 5 circulation near 18N, 78W, other data near 27N, 73W in late August from four NASA GPS dropsondes (CAMEX Group, 1998), in the four quadrants of a typical (Henning, 2005) Category 3 Hurricane Bonnie (Fig. 6), average 245 K ±2 K at 10 km altitude with an average lapse rate of 6 K km^{-1} from 6 to 10 km. Below this the rate is about 10% less to 300 K at 0 km. Arbitrarily extended, the upper lapse rate extrapolates to 185 K at 20 km. The wind profiles of these dropsondes (Fig. 6) also show typical low to higher altitude wind speed differences like those noted above in Ivan's dual coaxial wave interactions.)

The four original still images (Fig. 5) are a particularly clear short series with time separations of 35 minutes, 103 minutes, and 47 minutes as various satellites passed within a few degrees of Ivan. There are lower cloud waves and convection surges over several days in the two by two degree segment immediately to the south and west of the cyclone's eye (Fig. 5) where correlation with lab data was first recognized at 95--145 km from the eye in larger scale views, but the sequence of original microwave coverage is broken (Fig. 5b) in this part of the images, as in many series. South and east of the eye in this set there is more open coverage in all four images for 11 September 2004 at 1130 UT, 1205 UT, 1348 UT, and 1435 UT.

In the southeast area (Fig. 5) there are two spiral rain bands with separated cells aligned north and south and moving north at about 50 knots or 93 km h^{-1}, just to the east of 76 W and also of 74 W, with a third, more faint NS band at about 72.5 W. The three arrows in the open area between the two more definite rain bands point out three of several traceable lower altitude spiral waves (coaxial with the rain bands at the eye of Ivan) which also move to the north, at about 60 knots or 110 km h^{-1}, crossing the NS rain bands obliquely with NW to SE wave fronts.

The interactions of these overtaking waves with the rain bands create the striking configuration of multiple oblique parallelograms of convection cells in crossing lines to the east of the set of three arrows and the 74 W meridian (Figs. 5a and b). This interference pattern then diminishes (Figs. 5c and d) as these outlying rain cells, at about 300 nautical miles (nmi) or 550 km from the cyclone center, dissipate about two hours later in the cycle.

The longer lasting cells in the two rain bands on each side of the three arrows show a more complete sequence of surge details. The inner rain band of the two is at about 160 nmi or 300 km from the eye, and the outer band is about 100 nmi or 185 km farther out. The low altitude spiral wave just north of the more northerly first arrow in the sequence (Fig 5a) has brightened the rain cell at 16.2N, 75.8W to light green with a small surge, and left it behind.

In the image 35 minutes later (Fig 5b), the first cell is dying back, while the first wave has overtaken the two cells at 17.5N, 75.8W and 16.5N, 74W with the beginnings of surges in the yellow-green. At the same time the lower wave ahead of the second arrow has reached the trailing edge of the first cell, now at 16.5N, 75.8W, has broadened it in deep yellow-green at 15.7N, 75.8W, and has brightened the faint cell at 15.5N, 74W to a lighter green. The main effects of small surges from the low altitude waves at this point are the stepped augmentation of the cells in the NS rain band near the 76W meridian and the filling out of the three wave front parallelograms to the east in company with a wave ahead of the one pointed out by the first arrow. Apparently it is only necessary to have an open area between convective rain cells for these air and cloud spiral waves to build up within the low altitude wind layers of the cyclone. This is consistent with prior studies of the typical coalescence of small vortices into larger ones (e.g., Melander et al., 1988; Riccardi and Piva, 1998; Smyth and Peltier, 1994; etc.).

In Fig. 5c, 103 minutes later, the 75.5--76W rain band has brightened continuously to light green, and the cell at 17.5N, 75.5W behind the first arrow has brightened to yellow.

After 47 more minutes (Fig. 5d), the 75.5--76W cell just behind the first wave (and its arrow) has surged to heights coded purple, ≤ 190 K (≈ 20 km nominal). So have the two cells just behind and just being reached by the wave pointed out by the third arrow. These surges are clearly in synchronization with the waves passing them.

Just behind this group of waves with the three arrows there is another wave which is beginning to create surges (Figs. 5c and d). About a radian farther behind, after an open space in the pale blue lower clouds, another group of low waves is pointed out by two arrows (which drop back one wave between images to indicate the highest nearby surges at the image time. There are also surge-like indications from these waves to the north in the outer parts of the heaviest rain band west of meridian 76W.) Moving apparently in coaxial spirals along the 14N parallel in these pale blue clouds around the arrows, there are several darker blue circles that are consistent with eddies carried in by toroid shells between these waves (as in Fig. 4 of the lab data.) Their darker and bluer, therefore warmer, color could be associated with clearer descending air in anticyclonicly rotating eddies. Cyclonic eddies, on the other hand, would be associated with rising air and weakly convective condensation of moisture at their axial centers along other spiraling shell lines, which would appear very much like the sequential cells of the weaker outer rain bands. The blue, putatively anticyclonic eddy-like, cells are about a quarter to a third of a meridian degree in diameter, or 15 to 20 nmi and 28 to 37 km, very similar to larger rain cells.

Furthermore, near these two arrows in the lower clouds (Fig. 5c) there are fine pale blue wave filaments that are about 6 km wide, at the limit of resolution. These 270 K wave elements at a nominal 5 to 6 km altitude, from the prior NASA dropsonde average temperatures (Fig. 6), can only be the upper parts of rotary air cores of secondary spiral waves derived from boundary layer friction between the vortical wind of the cyclone and the surface of the sea, in direct similarity to the spiral waves of Fig. 1c (with reference axes transposed to the cone base) and Fig. 4. From the ratio equation (1h), with a wave and wind velocity $\mathbf{V_W}$ of 110 km h^{-1} or 31 m s^{-1}, the speed of the estimated upward tangential velocity $\mathbf{V_U}$ at the rear edge of the core is:

$$|\mathbf{V_U}| \geq 0.29\,|\mathbf{V_W}| \approx 9 \text{ m s}^{-1} \times 1.5 = 13.5 \text{ m s}^{-1}, \qquad (1i)$$

where the 1.5 factor is the estimated correction for the known low limit of speed (section 2).

When such a wave with an overtaking velocity encounters the aft side of the base of an advancing convection rain cell, something clearly happens that leads to a surge of increased convection of a noticeable amount. If the 11 September surges of Ivan (Fig. 5) are examined closely, it is further notable that the highest surges (purple pixels) are almost invariably on the edges of a convection cell, not in the center, and are most frequently on the trailing or aft half-perimeter by a predominance of 174 to 95 (by hand count.) If convection surges were only a matter of the advancing cells' encountering humid air packets in the lowest boundary layer of the general cyclonic wind on the sea surface, then the front edges and the centers should have far more of the highest surges, but that is not the case. This is immediately similar to tendencies of tornadoes to be associated with strong convection in storm cells, and to form on rear flanks of moving cells (e.g., Fujita and associates as summarized by Forbes and Bluestein 2001, Rasmussen et. al. 1994, etc.), which leads to the possibility that the low spiral waves and associated surges of convection observed in Ivan (Fig. 5) might play a part in initiation of tornadoes (section 1).

The most intense study of pretornadic conditions is that of Project Vortex by Rasmussen and associates at the University of Oklahoma, the longest lasting study that of Fujita and associates at the University of Chicago, and the broadest that of the Severe Weather Unit and its successors as part of the US National Weather Service (typified herein by Watson et al. 2005). (Some members of these research groups have participated in two or more of the studies.) None of these efforts has been conducted at sea with tropical cyclone conditions like those of Ivan (Fig. 5). The CAMEX Group effort (1998) remedied this lack in part, and the NRL, Monterrey cooperation with NOAA satellites and the University of Wisconsin, plus the NWS and US Air Force Reserve hurricane-penetrating aircraft, gather data from every tropical cyclone world-wide.

The open episode of Ivan in the Caribbean provides a new low level data input (Fig. 5) in widespread secondary spiral waves. These waves are similar to the critical local wind 10 to 25 m s^{-1} and horizontal vorticity wave 1 to 3 km in depth or diameter identified by Project Vortex (e.g., Rasmussen et al. 1994, and Ziegler et al. 2001), but twice as large in depth and diameter at 6 km and thus four times the vorticity wave cross section, with similar wind velocity at about 30 m s^{-1} driving the spiral waves. In addition, the pretornado vertical convection velocities of about 15 m s^{-1} measured in north Texas (Ziegler et al. 2001) are similar to those scaled from lab equations (1i) for the trailing edge of spiral waves in contact with rain cells in the outer rain bands of Ivan.

When the leading edge of such a spiral wave enters under a rain cell, the edge downward velocity would oppose the prior upward convection, providing a downwash like that about 3 km ahead of the Texas tornado initiation (Fig. 5d discussion in Ziegler et al. 2001). Aside from other vorticity tilting considerations at the side edges of the cell therein, this action at the mid-rear of the cell would also disrupt the horizontal spiral wave, create a small pressure drop above it by reduction of prior cell convection, and release the momentum of the effective vertical velocity component in the trailing edge of the wave (1i) to surge through the low pressure into the aft part of the cell. The volume per unit length of this sea level wave momentum packet is four times that in Ziegler and reaches twice as high into any rain cell. It could have much more effect in tornado initiation (including vorticity tilting) with increased vertical velocity effects at the larger scale.

At other times in the course of Hurricane Ivan, the same kind of dual wave interaction cycles as those seen off Jamaica are visible at the lower level and in the cloud tops for short periods. Two distinctive incidents occurred during the 15 to 16 September 2004 landfall of Ivan on the Gulf of Mexico shores of Alabama and Florida near NOAA weather radars. Each case has a small, open, non-convective area in which the low altitude, frictional spiral waves can develop briefly before overtaking the rearward edge of a convective rain cell. The intervals between rain cell bands are short, and the low level waves are fragmentary in the satellite images and in NOAA radar views. The second of these two incidents to occur, as the eye came ashore with winds reduced from 110 knots or 57 m s^{-1} to 100 knots or 51 m s^{-1}, is more brief herein. It has been under study at the University of South Alabama in Mobile, where, following prior investigations (Blackwell 2000), Holmes, Blackwell, and Wade (Holmes et al. 2005), continue an analysis of two decades of data on collapsing cores of rain cells with exceptionally severe downbursts of wind in the eye walls of hurricanes, but only in hurricanes with open eye walls at landfall, not usually in hurricanes with complete eyes. They explain excellent local NOAA Nexrad weather radar data on a destructive incident at Gulf Shores beach near Mobile Bay where intense rain cells on the east side of the Ivan eye came ashore on the edge of an opening to the south for about half the eye circumference (Fig. 7d) (Nexrad, 2004). In a long row of houses that were damaged, but left in place, two houses that were under a narrow collapsing core (just ahead of the white arrow) completely disappeared. The collected 20 year data show that such collapsing rain cores in open eyes typically start at 3 to 6 km altitude before descending to ground level at a shallow angle with very intense surface downbursts of wind. Holmes et al. (2005) hypothesize mini-vortex spin-ups for these cases. This now appears consistent with partially developed, low level spiral wave activity, shown just ahead of the white arrows in the original microwave satellite image (Fig. 7c) that is closest in time before the incident (NavSatMet, 2004) #20040916.0515 "H", though two hours earlier than the KMOB radar view (Fig. 7d) at 0702 UT 09/16/2004 (Nexrad, 2004)**.** (The arrow in the radar view also indicates a trace of low level spiral wave cloud.) This is consistent with scaling from lab data (1i) of the altitude and downward velocity $\mathbf{V_D}$ (equal to the upward velocity) of internal rotations of low level spiral waves such as would accelerate collapsing rain cores to the surface in the measured steady winds $\mathbf{V_W}$ at the time of 100 knots or 51 m s^{-1}, as:

$$|\mathbf{V_D}| \geq \; 0.29\,|\mathbf{V_W}| \;\approx\; 15 \text{ m s}^{-1} \times 1.5 \;=\; 22.5 \text{ m s}^{-1}, \qquad (1j)$$

giving a vector sum of 56 m s^{-1}. This wind level does not appear capable of such severe damage as to make two houses vanish, but if it were added to a typical downfall velocity for such a heavy rain and associated with a "minivortex spin-up" at that velocity sum, aided by the vertical surge (and any vorticity tilting) as before, it could be heavily damaging as a brief pretornado. In any event, spiral wave traces appeared, and special damage was done immediately under a rain cell that, from the cited study, is not inconsistent with a surge in the eye wall of Ivan at the shoreline.

Another significant Ivan landfall event was an outbreak of 23 documented tornadoes (Watson et al. 2005) centered between Cape San Blas and Marianna, Florida, at about 200 nmi or 370 km northeast of the eye, which was still at sea with 115 knot winds falling to 110 knots or 204 km hr^{-1} and 56.6 m s^{-1}. This outbreak occurred along a rain band beyond an open space across which partially developed frictional spiral waves at low altitude could rotate to overtake the trailing edges of rain cells. These waves can be observed in a satellite microwave image (Fig. 7a) # 20040915.233l "H" (NavSatMet 2004), 2 1/2 hr before NOAA radar reflectivity image (Fig. 7b) at 0210 UT 09/16/2004 on WSR-88D radar KEVX (Nexrad, 2004), as indicated by white arrows.

The outbreak began at 2030 UT on 9/15 when the rain band lay along the coast through Panama City, FL, and continued to about 1400 UT on 9/16 (Watson et al., 2005), when the band had advanced (with the advance of the eye) beyond Tallahassee, FL, and well into southwest Georgia (Fig. 8, after Watson et al.). The most distinctive item about these 23 tornadoes is where they occurred in the last significant outlying rain band of Ivan in its right front quadrant. Though most of the area is rural woodland and swamp, there were at least 6 deaths, and a number of homes and business buildings were destroyed. These images (Figs. 7a and b) are from the middle of the period. The brightest orange reflectivity spot near the center of the radar image (Fig. 7b) is just moving to the NNW from Blountstown, FL, toward Marianna, from which towns the tornado beneath the cell takes its usual name (though it was actually two separate tornadoes from the cell (Watson et al. 2005).) The cell previously spawned two weaker tornadoes in a straight line to the SSE near the coast (Figs. 7a and 8). At the 0210 UT time of the radar image (Fig. 7b), the position of the rain band which carried this outbreak of 23 tornadoes across NW Florida, is quantitatively scalable from the lab data, equations, and lab figures (Figs. 1 to 4) of this paper.

For scaling, the dimensions of the eye wall are taken (Fig. 7a) in nautical miles at the usual 120 nmi for two degrees latitude. The outer diameter (OD) is 46.5 nmi or 86.1 km, and the inner diameter (ID) is 18.5 nmi or 34 km. These dimensions will later determine the base diameter of the equivalent drive cone d_c in the general scaling equation for *GD* separately lab-derived (and applied to tornadoes) (Equ. 1, Figs. 1a and b, section 3, Howard 2006) as:

$$GD \;=\; d_c \left[\, 1 \;+\; e \left(\frac{\rho}{\eta}\right)^{0.6667} V^{A\sqrt{V}} \,\right] , \tag{2}$$

where the units for diameter are chosen such that the number for d_c is between 1 and 10, the same units (which may be unusual) are used to calculate areas $A \;=\; (2\,A_b \;+\; A_s) \times 100^{-1}$, A_b is the area of the base of the drive cone (in the unusual square units), A_s is the wetted driving area of the sides of the cone (in the same units), $V = \; V_P \times 1000^{-1}$, V_P is the peripheral velocity of the driving cone in cm s^{-1}, e is the base of natural logarithms, ρ is the density of the fluid in gm cc^{-1}, and η is the viscosity of the fluid in centipoise. Here, the unit for base diameter is 10 km.

The mean between the ID and OD of the Ivan eye wall (Fig. 7a) is 60 km ± 1% estimated. A 30 degree cone (as previously tested) whose sides have this diameter at mid-height of the eye wall of 10 km (as indicated by the prior nominal 185 K conversion to 20 km altitude of purple cloud tops in Figs. 5a--d and now in Fig. 7a) has a base diameter of 65.36 km at 20 km and a diameter of 54.64 km at sea level. The scaled Hurricane Ivan drive cone then is a 20 km high frustum of a cone (that fully immersed would be about six times as high.) Converting the dimensions to 10 km units, the base area is 33.552 square units. Using a typical mensuration formula based on diameters, the wetted side area of the frustum is 38.265 square units. Then A in the general scaling equation (2) is 1.0536. For V, assuming that the stated 56.59 m s^{-1} sea level wind at the sea level diameter of the figurative conic frustum conserves angular momentum in rising to the 20 km altitude with 47.31 m s^{-1}, then V becomes 4.731. Since both density and viscosity are continuously changing over the altitude range, it is a suitable estimate for weighted effects over this wide range to use a mean of various handbook values at the nearest altitude (7 km) to the scale height for half the sea level density, with a density to viscosity ratio of 0.036.

This scaling process yields an estimate (2) of the *GD* limit for highly turbulent (i.e., violent) weather in Hurricane Ivan at the stated point in time (Fig. 7b.) of 747.26 km with a radius of 373.63 km. The Blountstown-Marianna tornado in the center of its rain band at that time is at about 357 km from the center of the eye, 17 km within the limit. No potentially violent portion of that rain band is more than 10% farther from the eye at 393 km. Then, the outer parts of this rain band might be 5.1% beyond scaling (2) over six and a half orders of magnitude from the *GD* lab data (Figs. 1a--c and 2), which itself includes a ±5 to 7% variation with the passage of spiral waves on the lab *GD* (section 3, Fig. 1c). (Equivalent intermediate scaling of single tornadoes is demonstrated in the force data paper (section 6a, Howard, 2006).)

To scale the destructive diameter of Ivan from the lab data it was necessary to have the satellite or aircraft data inputs of the maximum steady low altitude wind in the eye wall, the temperature height of the wall, and its ID and OD. This scaling is further supported by (and also supports) other distinctive scale factors inherent in the lab geometric vortical structures that correlate with other features of Hurricane Ivan in its vertically compressed and horizontally expanded structures under the constraints of the earth's very thin layer of atmosphere within which weather occurs. Compared to the lab lower hemispheres (Figs. 3 and 4), the hurricane is a very compressed ellipsoid half with a lower semi-minor dimension of 20 km and a semi-major dimension over the outer toroid core at 1 *GD* of about 750 km. The violent activity is within the coaxial *GD* at a half *GD* radius and ratio to base height of about 18.75:1 versus the lab 0.5:1. This atmosphericly limited ratio affects geometric horizontal scaling from Figs. 3 and 4 approximately proportionately. (The structures within the cyclone *GD* may be adjusted for proportionate distance from the surface of the drive cone at the height level rather than from the axis. This arises because the ratio of the lab cone base diameter to the *GD* is 0.39, while the figurative ratio in Ivan is 0.0946.) While they vary in the indicated directions, the horizontal velocities do not scale directly since the frictional losses, the density changes with altitude, and the latent heat of water involved are not linear, and the gyre drive is not in the same part of the drive cycle sequence (Fig. 1). The lower level wind velocities driving the spiral waves near the surface are driven by external atmospheric pressures to feed the convective pressure drops over the entire *GD* area into the eye wall, and these flows have a long scaled distance to cross. The low level winds from the outer edge of the toroid to the eye wall in Ivan scale toward but are less than the 18.75:1 ratio to typical vertical convection flows noted above (Ziegler et al. 2001) compared to the very low ratio of 0.24:1 for lab flow speeds on the floor (Fig. 4) versus the mean vertical speed (1b). The circulation velocity in the Ivan toroid core is thus coupled viscously to low level flow directly into Ivan's low-medium level heat engine (as in Fig. 3, van Delden 2003).

In a vertical scaling sense, the earth floor of the cyclone is only about a sixth of its nominal cone height from its base (20 km versus 121 km for the equivalent 30 degree cone.) Therefore, low and high altitude cyclonic velocities should scale in quantitative numbers in geometricly similar structures much more closely to lab base area velocities (and other conditions) than to lab floor area data, without marked decline from the cyclone top to the earth. In spiral wave scaling, in particular, the lab floor spirals at about 38 cm s^{-1} are almost exactly a sixth of the 229 cm s^{-1} equivalent speeds of the turbulent disk spiral waves, which would be closely corrected in applying the disk spiral wave data to scaling the low altitude spiral wave surge interactions in the hurricane rain band cells. (This scaling approach also sustains application of the eye wall top as an effective drive cone base with winds within 10% of the maximum steady hurricane winds in estimates of force effects in the second paper in this series (Howard 2006).)

To further clarify the correlative geometric ratios, the upper part of Fig. 9 has the right half of the lower lab hemigyre and the turbulent disk (Figs. 3 and 4) compressed vertically (in proportion to *GD*) by a factor of 0.54:1. The lower half (Fig 9) has a vertical half section of the radial cloud temperature heights of Ivan through the tornado cell before it reached Blountstown

(Fig. 7a) compressed horizontally by 18.75:1, so that the driving cone base heights in the upper and lower scaled schematics are the same, the central axes and the *GD* limits are directly aligned vertically, and the figurative toroid core cross sections are scaled together identically (as 60 degree ellipses. Consequently, the half *GD* dimension and the base height in each make identical approximately square rectangles.) The almost vertical line in the eye wall cloud of Ivan represents the side wall of the estimated (2) drive cone frustum of its 30 degree cone. The ellipses in the lowest part of each schematic represent the apparent spiral wave dimensions at the radii, when present.

In net effect (Fig. 9), the cirrus cap spreading out of the top of the hurricane correlates with the top of the lab side flow outward over the lower toroid, but at an estimated arc tan (0.25/18.75). The core of the toroid extends to 1 *GD* from the center, so that at least to that 750 km radius (when at sea) the cyclone is gathering with inflowing surface winds both solar and sea heat energy, while it is only gathering sea heat and heavily expending the energy within the *GD* itself, as effective heat source and release areas:

$$A_{Sol} \geq A_{GD}\,(4\,-1) \qquad (3a)$$

$$A_{Sea} \geq 4\,A_{GD}, \qquad (3b)$$

where the cyclone *GD* correlates directly with the lab *GD*, as quantitatively demonstrated (2).

The centers (Fig. 9) of the lower toroid core cross sections (Figs. 1f and 3, drawn from lab data) are at about 1/6 of *GD* beyond the *GD*, and the sections are about 2/3 of *GD* in major diameter. The toroid extends under the *GD* to about 1/3 of this toroid diameter or close to 1/4 of *GD*. In Ivan this scaled 1/4 of *GD* is zone A (Fig. 9) of the tornado rain band (and other possible tornado rain bands), which correlates to a toroid shell peeling inward to spiral into the eye with the greatest initial upward velocity component in its rain cells from the toroid circulation itself, but at a low enough height to engage with 6 km high spiral waves for an additional surge through the lower part of the second latent heat release from freezing at about 5 km and above (due to supercooling.) Here, as with the previous vertical scaling ratios, it again becomes clear that the estimated toroid circulation velocity $|\mathbf{V_T}|$ in the cyclone is as much driven by the input flow into the immediately adjacent (though distributed) convective heat engine at the lower altitude level of the storm as by the more sequentially removed peripheral velocity of the eye wall's figurative cone at the top level, as in the lab. This scaling approach, too, effectively inverts the driving relations from the top to the bottom of the figure for the hurricane toroid and transposes to the storm's lower spiral waves the relative strength of the upper spiral wave rotation $\mathbf{V_R}$ noted previously (Fig. 1c, section 3) as correlating with the lower spiral waves in Ivan. $\mathbf{V_S}$ in equation (1a) then becomes $\mathbf{V_W}$ (1h) and $|\mathbf{V_T}|$ from the relations (1a) and (1f) is:

$$|\mathbf{V_T}| = 0.5\,|\mathbf{V_W}|, \qquad (3c)$$

where $\mathbf{V_W}$ scales with $\mathbf{V_P}$, which is now taken as the maximum eye wall velocity at the lower altitude, and was 30 m s^{-1} (Fig. 5a and b) when $\mathbf{V_P}$ was 64 to 75 m s^{-1} near Jamaica with a mean of 70 m s^{-1}. With $\mathbf{V_P}$ now at 57 m s^{-1}, $|\mathbf{V_W}|$ is reduced to 24.4 m s^{-1}, and $|\mathbf{V_T}| = 12$ m s^{-1}. However, the four NASA GPS dropsondes (Fig. 6), taken as typical dropsondes (with good data runs) out in the quadrants of a late summer tropical cyclone in the vicinity of Florida (Henning 2005), indicate that 0.5 (3c) is an excessively low ratio to lower altitude $|\mathbf{V_W}|$ for the toroid velocity near 6 km, and that 0.85 would be more appropriate. This would correct $|\mathbf{V_T}|$ to 20.4 m s^{-1} for estimates of components of initial toroid circulation velocity feeding into rain band convection cells in zone A, in its correlation with the lab toroid core extension under the *GD*.

When rotated toward vertical flow by the figurative scaled toroid (Fig. 9) and associated with the (fragmentarily) observed spiral waves at a rotating velocity in wind speed under prior storm convection found sufficient for tornado initiation inland (Ziegler et al. 2001) and apparently four times that rotating wave cross section, either of those $|\mathbf{V_T}|$ speed values could provide the initial vertical velocity before wave interaction for tornado initiation in suitably unstable conditions. In the presence of sufficient wind to generate the low altitude rotating wave component as in Ziegler et al., and in the presence of actual tornadoes at the location predicted by the lab turbulence limit equation (2), at a location in a cyclone known to provide local wind circulation similar to that part of a possible toroid (e.g., Fig. 3 of van Delden 2003, and Fig. 10 of Hoskins, et al. 1985), the correlation with the lab *GD* equation for the location of the tornado rain band appears to be clearly supported by further correlation of rain bands with the lab data on toroids and toroid shell movements. All of this further coordinates with the lab spiral wave correlation with interactive convection surges as a distinctly possible contributor to tornado initiation. This association of the entire configuration with tornadoes is testable with available airborne doppler radar (Ziegler et al. 2001) (and stock remote control guidance modules adapted to dropsondes with delayed speed brakes to put the dropsondes in the centers of interest.)

Rain bands in Ivan within the zone B (Fig. 9) inner 1/2 of *GD* (Figs. 7a and b), but outside the eye, correlate (Figs. 1f, 1g, 3, and 4) with toroid shells which peel off the toroid at lower altitudes and half the flow speeds (Fig. 4), between surface spiral waves, and with eddies embedded. These rain band shells would receive a lower vertical impulse from the toroids at a larger angle from the spiral wave impulse before disrupting those waves with heavy rain convection. This overall flow pattern also is consistent with the overall mass flow between zones of cyclones (e.g., van Delden 2003, and Hoskins et al., 1985). This zone (B) correlates with the primary flow up the side wall of the lab cone (Fig. 1a). While the main circulations of eddies (ellipses Fig. 1e) are carried by outer toroid shells into this zone, the lab eddies are really spherical gyres (Fig. 1e discussion), and their three dimensional effects may reach zones A or B.

Wherever there is a rain band of heavy convection from about 1 km to 8--10 km or more, the strong vertical convection disrupts the toroid flow above it and the spiral waves within it. Also, although the vertical convective columns in each rain band create their own downgusts to the surface (Ziegler et al. 2001) to give high apparent low level winds, as column structures they are coupled to the lower wind velocities at higher altitudes (Fig. 6) as measured typically (Henning, 2005) in the cited NASA CAMEX dropsondes from Hurricane Bonnie (CAMEX Group, 1998). Thus, rain band cells are overtaken by lower level spiral waves wherever there is an opening for the waves to develop, with consequent interactions, even in zone B, as indicated by the smaller surge (Fig. 9). By similarity of the general circulation that sets up the lower spiral waves, there is an implication that some of these quantitative relations may be present in other cyclonic (or anticyclonic) flows that are sufficiently unstable to exhibit tornadoes.

Rain bands in zone C, 1/6 of *GD* outside the *GD* but within the ring axis of the toroid ring sections (Fig. 3), correlate as minor rain squalls on the periphery of the tropical cyclone whose toroid air parcels peel off in shells too far into the toroid core and too high in altitude to have gathered significant moisture farther out over the sea or to interact significantly with the lower spiral waves. There are very few scattered showers (Figs. 7a and b) farther out in zone D (Fig. 9) to the northeast (or elsewhere) in Ivan than the figurative centers of the toroid sections as scaled from lab data by ratios to the *GD* limit of violent turbulence.

7. Conclusions

As is well known, atmospheric processes are far too complex with too many different types of effects other than flow structures, such as Coriolis forces and altitude lapse rates or precipitation (for instance), to be fully modeled in a single lab experiment. The latent heat engine in the eyewall and rain band moisture condensation and freezing drive the tropical cyclone in a much more diffuse and complex way than a motor-driven cone could possibly model. Only some observable similarities of geometric, mechanical flow patterns can be involved here. Within those restrictions, the GD limit of violent turbulence is scaled from a lab-derived equation to a tropical cyclone, and is reasonably proven as far as that can be done by the single first case of application. The remainder of the lab quantified flow structures that are associated with the formation of the GD, such as the toroid circulation of shells and the spiral waves, are also substantiated in the cyclone to the same extent. Their association with tornado generation in rain bands is clear enough, and their causative influences in both phenomena appear sufficiently possible, that students of weather may find the experimental data and its empirical interpretations at this scale interesting, or even directly informative.

An empirical correlation between flow structures in lab vortex experiments and the location of a localized outbreak of 23 tornadoes at landfall in a large tropical cyclone (Hurricane Ivan) is scaled up over six and a half orders of magnitude. A technique for forecasting radius of major wind damage in tropical cyclones is derived for further investigation. New vortical flow elements are proposed for consideration in the initiation of tornadoes in cyclonic circulations. An initial empirical basis is laid for more detailed observations by hurricane hunter aircraft. Exploratory empirical quantitative data are presented on organized secondary and tertiary flow structures in a single size of highly turbulent conic vortices of both the surface and fully immersed types. A flow structural basis is laid for presentation, and quantitative scaling to violent weather applications, of empirical force data generated within and between such vortices, over wider ranges of size, viscosity, and other parameters, in an immediate follow-on paper.

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REFERENCES

Blackwell, K.G 2000 The evolution of Hurricane Danny (1997). *MWR (Am. Met. Soc.)* **128**, 4002-4016

Brunt, D. 1942 Meteorology. *Encyc. Brit.* **15,** 343--356

CAMEX Group 1998 CAMEX III dropsonde excel data files, D199808242330 & -2347 UT, D199808232136 & -1845 UT . *nasa.gov/camex/bonnie*

Forbes, G. S., and Bluestein, H. B. 2001 Tornadoes: Contributions by T. T. Fujita. *Bul. Am. Met. Soc*., **82**, 73-9

Fujiwhara, S. 1921 The natural tendency towards symmetry of motion and its application as a principle in meteorology. *Q. J. R.. Meteorol. Soc*., **47**, 287--293

1923 On the growth and decay of vortical systems. *Q. J. R.. Meteorol Soc*., **49**, 75--104

1923 On the mechanism of extratropical cyclones. *Q. J. R. Meteorol. Soc.* **49**, 105--118

Henning, R. G. 2005 Private communication with selected typical dropsonde data.

Holmes, J., Blackwell, K.G., and Wade, R. 2005 Collapsing precipitation cores in open-eyewall hurricanes at landfall. *Pre-print, SE Coastal Atmospheric Processes Symposium (SECAPS),* Univ. So. Ala., Mobile, AL, US

Hoskins, B. J., McIntyre, M. E., Robertson, A. W. 1985 On the use and significance of isentropic potential vorticity and maps. *Q. J. R. Meteorol. Soc*. **111**, 877-946

Howard, F. E., Jr. 2006 Turbulent conic lab vortices scale to wide ranges of violent natural actions: 2. 3D gyre forces control tornadoes, supercell mesospheres, & cyclone eyewalls (Being condensed for publication.)

Longair, M. S. 1996 *Our evolving universe*. Cambridge Univ. Press, Cambridge UK

Marti Group 2004 Ivan, MIMI, latest 24 hours, 2004-09-12 00:00 and 2004-09-16-00 00:00 animations. *cimss.ssec.wisc.edu/tropic/real-time/marti*

Melander, M. V., Zabusky, N.J., and McWilliams, J. C. 1988 Symmetric vortex merger in two dimensions. *J. Fluid Mech.* **195**, 303-340

NavSatMet 2004 NRL, Monterey, Marine Meteorology Division. Tropical Cyclone Pages. (A public record.) *nrlmry.navy.mil/tc_pages/tc*

Nexrad 2004 NOAA, NWS Hurricane Ivan landfall WSR-88D radar images *noaa.nws.archive.hurricane.2004.Ivan.KEVX/KMOB*

Rassmussen, E. N., and Straka, J.N. 1994 Tornadoes Experiment: VORTEX. *Bul. Am. Met. Soc.*, **75**, 995-1005.

Riccardi, G., and Piva, R. 1998 Motion of an elliptical vortex under rotating strain; conditions for asymmetric merging. *Fluid Dyn. Res.* **23**, 63-88

Smyth, W. D., and Peltier, W. R. 1994 Three dimensionalization of barotropic vortices on the *f*-plane. *J. Fluid Mech.* **265**, 25-64

van Delden, A. 2003 Adjustment to heating, potential vorticity and cyclogenesis. *Q. J. R. Meteorol. Soc.*, **129**, 3305-3322

Walker, J. M. 1992 Pen portraits of presidents--Professor Sir David Brunt, KBE, MA, ScD, FRS. *Weather*, **47**, 342--343

Watson, A. I., Jamski, M. A Turnage, T. J., Bowen, J. R. and Kelley, J. C. 2005 The tornado outbreak across the north Florida panhandle in association with Hurricane Ivan. *Am. Met. Soc. Radar Conf., Paper 10R.3.*

Ziegler, C. L., Rasmussen, E. N., Watson, A. I., Straka, J. M. and Shepherd, T. R. 2001 The evolution of low-level rotation in the 29 May 1994 Newcastle-Graham, Texas, storm complex. *Mon. Wea. Rev.*, **129**, 1339-1368

Turbulent conic lab vortices scale to wide ranges of violent natural actions

1. Lab gyre flow structures define tornado inception sites in Hurricane Ivan

Fred E. Howard, Jr.

FIGURE CAPTIONS

Figure 1. A step-by-step sequence of the viscous coupling of vortical drive momentum from a 30° wood cone (with a constant rotational rate) to the various schematicly scaled, geometricly quantitative flow structures of fully immersed and standardized surface equivalent, turbulent vortices in lab water. (All of these flow structures scale quantitatively over six orders of magnitude to the cyclonic vortex structures of Hurricane Ivan in various ways, two of which will be emphasized.) All elevation views of the left sides of vortices are in partial cross-section. Plan views are as seen in surface vortices and also as measured in immersed vortices. The incomplete bottom elevation views of surface vortices duplicate the flows of immersed vortices (above) where the flows are present. Solid lines show edges of flow structures in view; dashed lines are structure edges behind the surface of view. Dotted lines and arrows plot continuous fluid particle flow tracks. Numbers quantify local flow velocity vectors on those tracks in the plane of view in cm sec^{-1}. Rotation is clockwise on the upward base of the drive cone. See details in section 3.

Figure 1a. The initial viscous coupling of drive momentum from the base (up) and side surfaces of the drive cone. The side primary flow is thick and laminar. The base primary flow is a thin, turbulent, conic sheet with the highest velocity measured. The two separate flows mix very little out to the visually turbulent gyre diameter (GD) limit, where visible turbulence is abruptly damped out by coupling of its vibratory momentum to the surrounding water.

Figure 1b. The first secondary flow structure is the central core of one complete turbulent, centrifugal spiral wave (of many) and a partial interstitial wave core. Within the GD the wave core (inside its outer shell of less organized turbulence) builds rapidly to a maximum internally rotating diameter at the GD, as a small secondary conic vortex embedded on its side in the primary base flow sheet which drives it. Its turbulence too stops at the visual GD limit, as the wave is retarded (by viscous coupling of centrifugal momentum to surrounding water) and bends, and its internal rotation within the wave continues as a smoothly dwindling cylindric vortex out to about 2GD. Beyond that the waves are negligible circularly spreading ripples.

Figure 1c. A typical, nominal set of about 6 full spiral wave cores making a secondary full and thick, subplanar (actually conic) spiral wave disk of strong centrifugal turbulence (within the GD limit). Note the corkscrew actual water particle track from the two component centrifugal and internally rotating vectors. Within the experimental accuracy, this turbulent disk and all flows below it are the same for fully immersed vortices and for these particular surface vortices, which are standardized with the drive cone base at one diameter depth.

Figure 1d. To maintain the primary base and side flows, each of these must have an axial secondary inflow of fluid and a peripheral centrifugal outflow, each of which participates in the general vortical rotation; the inflows do so to a limited degree by outer viscous coupling. There is also a disk outflow. For the surface vortex in the bottom view, the upper inflow tumbles in from the surrounding water above the outflows and the irregular turbulence of the centrifugal waves in the standard spiral wave disk of Fig. 1c. This is the one appreciable difference between fully immersed vortex flow structures and those flows that are present in the standardized surface vortex.

Figure 1e. By tertiary couplings from the secondary spiral waves, numerous smooth eddies of water particle flow are set up, apparently at about the GD where the spiral waves bend from largely radial to largely circumferential wave fronts. Most eddies are ejected from the spiral wave disk into the side outflow, from which they drift around into the input near the cone point and merge with that inflow. Though shown as ellipses (like the spiral wave disks) of greatest rotating flow velocity, the eddies are actually three dimensional spherical structures like the main vortex.

Figure 1f. Toroidal ring vortex cores complete the upper hemispheres of spheric, immersed conic vortices and the lower hemispheres of immersed and surface conic vortices. The lower toroid core circulation, in measured corkscrew fluid particle tracks, is secondarily pulled in around the cone and smoothly driven by the side primary flow to much higher spiral velocities than the upper toroid. The upper toroid is driven (actually tertiarily) in spurts of dying turbulence from the rotating spiral waves, which push it up and out away from the cone base. Both toroid core rings diffusely shed particle flow tracks in figurative shells into the primary inflows and viscously acquire particle tracks in shells from the outflows (Figs. 1c and d).

Figure 1g. These horizontal upper and lower cross sections of a lower toroid core emphasize the ways in which toroidal particle tracks are figuratively shed and acquired in diffuse shells by the core circulations, including eddies in outer shells.

Figures 2 and 3. These figures compile the flow velocity data from the different flow structures (Figs. 1a through g), in both the immersed vortex (Fig. 3) and the equivalent surface vortex (Fig. 2 bottom), in their relative locations as they appear interlinked together in the lab. This completes the sequence of interacting structures in vortices standing free of boundaries. Within the experimental accuracy, the floor added in Fig. 4 does not change these measured data above the bottom of the lower toroid core.

Figure 4. For closer correlation to tropical cyclones, a floor is added (in the lower elevation view) under the lower toroid core and just below the mean eddy return track in outer shells of the toroid. This criterion does not limit the lower inflow or the vortical flows of Figs. 1 to 3 appreciably, and their structured measurements are unchanged. (The floor level also scales surprisingly closely with the Hurricane Ivan flow in Fig. 9.) In the upper floor plan view, and below the toroid core in the elevation view, the previous axial inward drift structure is replaced by a viscously frictional set of spiral waves on the floor surface (like the turbulent spiral wave disk above the cone), but at too low velocities for good detailed data measurements. (Ratio data of the upper spiral waves in Fig. 1c scale suitably. See section 4.)

Figure 5. A sequence over three hours of false color images of substantial cloud heights from their microwave brightness temperatures measured through the cirrus cap by Naval Research Lab (Monterey) sensors from various NOAA satellites (with one image per nearby orbit) as Hurricane Ivan passed Jamaica in September 2004. Calibrations range from 270 K in pale blue to 190 K and less in purple peaks above the greens, yellows, and reds. See text section 4 for details on convection surges.

Figure 6. Altitude profiles of hurricane winds (w) and temperatures (t) at 125 to 240 km from the eye in the two right and the left rear quadrants of Category 3 Hurricane Bonnie when it was passing the Bahamas, as measured by four GPS dropsondes from NASA Project Camex Group III research aircraft in 23 and 24 August 1998. The drop with least variation of wind with altitude was through lower level 100% humidity. (These drops were selected for representative hurricane winds well away from the eye over water near or south of Florida, and for data continuity throughout the drops.)

Figure 7. Closest prior microwave brightness temperature images two hours before, and NWS weather radar reflectivity images during, two destructive incidents at Hurricane Ivan landfall in the US. 7a and b show conditions for the Blountstown, Florida, tornado, directly under the brightest rain cell at the center of the radar image in 7b. The brightest nearby cell in that outlying rain band in 7a is too early and is evidently for the more diffuse bright radar cell (which did not produce a tornado) to the northwest of the Blountstown tornado cell in 7b. This same cell later produced the separate Marianna tornado to the northwest in a separate cell surge with high rotational velocity (Watson et al. 2005), and had previously produced two weaker tornadoes in a single cell surge as it passed the current location of the radar reflective cell behind it in the band to the south east. Arrows point out indications (among others) of lower level spiral waves that appear to interact with rain band cells at about the times of convection surges to higher cloud heights. The turbulent gyre diameter (GD) limit of violence quantitatively scaled from lab Equation (2) would lie very close to the sequence of three arrows in 7b and well inside the two NE arrows in 7a. 7c and d show similar conditions for the Gulf Shores, Alabama, downsurge of wind and rain that made two houses disappear directly under the orange spot with a trace of lower spiral wave just ahead of the arrow in the edge of the open eye wall in 7d (Holmes et al. 2005).

Figure 8. Plots of the 23 documented tornadoes (after Watson et al. 2005) from cells in the outlying rain band of Hurricane Ivan noted in Figs. 7a and b. This outbreak, and the rain band carrying it, came ashore from the southwest about 2030 UT 15 September 2004 and spread to the northeast ahead of the eye movement over the next half day with numerous additional threats that did not materialize. The series of four tornadoes out of the single convection cell for the two Blountstown-Marianna tornadoes (Fig. 7a and b) are emphasized since the Blountstown incident is at the time of the scaled GD limit of hurricane violence from lab experimental equation (2) at 17 km beyond this cell's center. (The Gulf coast, state lines, and initials of larger towns are indicated.)

Figure 9. Scaling a lab water vortex turbulence limit at the GD to Hurricane Ivan's vortex violence limit with a tornado outbreak just inside its GD at landfall. Laboratory experimental data Figs. 2 and 4 combined, scaled down in vertical proportion by 0.54:l, and set over the structure of Hurricane Ivan scaled down in horizontal proportion by 18.75:1. The central axes and the GD limits of turbulence and violence (quantitatively scaled together over six and a half orders of magnitude by lab empirical equation (2)) coincide, and the toroidal circulation cores match with

identical 60 degree ellipses. Ivan's cloud heights are sketched in along the radius through the rain cell surge in Fig. 7a that is apparently the one which shortly afterward produced the first of its four tornadoes, of which the third is the Blountstown tornado for which the GD limit scaled from lab empirical equation (2) is discussed under Fig. 7. The vertical ellipses schematicly indicate spiral waves. Small horizontal ellipses indicate measured eddy tracks. Observed inner and outer rain band shells are indicated by arrows peeling off the toroid circulation cores at various scaled heights. See text section 4 for details.