Analysis and Visualization of High-Resolution WRF Hurricane Simulation using VAPOR

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Introduction:

Recent high-resolution hurricane simulation, using the WRF-ARW model [1], has provided improved understanding of hurricane dynamics, and has identified turbulent eddies, not previously noted, near the eyewall [2]. We report here on a visual exploration and analysis of these simulation results, using the VAPOR visualization tool. By combining steady and unsteady flow integration with various interactive rendering techniques, we are able to provide large-scale overview of the hurricane dynamics. Closer examination of the turbulence in the eyewall reveals the presence of numerous vortex tubes in the lower 500 m. These tubes are moving in the dominant rotating vortex of the hurricane but were isolated and examined by subtracting the 1-minute time-averaged wind velocity. The evolution of the vortex tubes is tracked over time using a field line advection capability of VAPOR applied to the wind difference field.

Hurricane Simulation:

The WRF-ARW model employs up to 6 telescopic nested grids with horizontal resolutions from 15 km to 62 m centered on an idealized hurricane over the sea with constant sea surface temperature on an f-plane. Comparison of volume renderings of velocity (of 5-level nesting on a 185 m grid versus 6-level nesting, on a 62 m grid) identified energetic turbulent eddies in the boundary layer under the eyewall that do not appear in 5-level nesting.

VAPOR capabilities:

VAPOR (Visualization and Analysis Platform for atmospheric, Oceanic and solar Research, http://www.vapor.ucar.edu) was developed at NCAR to enable scientists to interactively visualize and analyze the results of turbulence simulation. VAPOR uses a multi-resolution data representation to enable interactive exploration of large and small scale details. Useful features of VAPOR include Image-Based Flow Visualization (IBFV) [3], providing an animated view of a flow, by advecting random spot noise along a planar slice of the flow. VAPOR's Planar Probe tool enables visual seeding of streamlines and path lines based on field strength or by visual features in IBFV images. VAPOR's Field Line Advection (FLA) [4] capability enables tracking of the motion of field lines in a velocity field.

Overview of the hurricane structure:

The eyewall of the hurricane can be identified as the cone-shaped region where the vertical velocity (*W*) is largest. This can be illustrated by combining a planar contour cross section of *W* with unsteady flow integration. To understand the origin of the wind flow in the eyewall, unsteady flow seed points are positioned along the cone at maximal values of *W*. The wind flow is integrated backwards in time to determine the path lines that pass through the flow seed points. It is seen that the particle traces spiral inward, near the earth's surface, then rise abruptly as they approach the eyewall. To see that these particles acquire entropy as they rise in the eyewall, the particle traces are colored by the value of the equivalent potential temperature, becoming red at highest entropy. The hurricane structure and the cone-shaped eyewall are seen in the planar cross-section that is colored according to the value of *W*.

An animation showing the motion of these particles in the hurricane is available at http://vis.ucar.edu/~alan/ams09/unsteadyFlow.mov. The unsteady flow calculation exploits VAPOR's multi-resolution data access by enabling interactive integration through 60 time steps at lowered resolution. A volume rendering of *QCLOUD* (cloud ratio) in the animation sequence shows the background rotation.

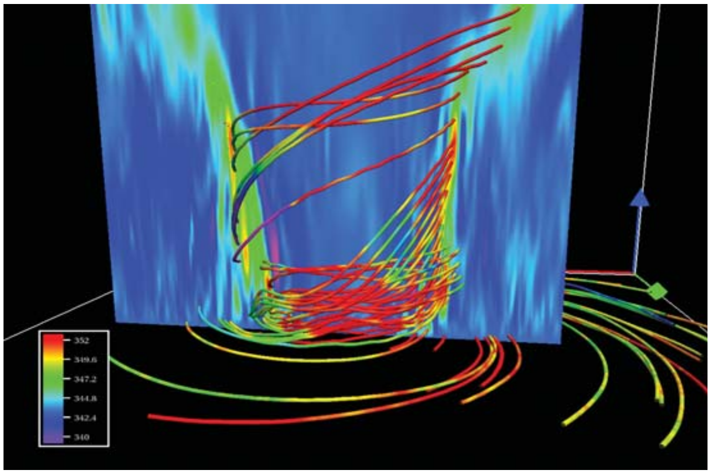

Figure 1: Overview of hurricane structure, indicating path lines that approach the eyewall at points of increased vertical velocity. The planar cross-section is approximately 75 km wide, 10 km high. Color scale indicates color mapping of path lines based on equivalent potential temperature.

Increased turbulent eddies resulting from higher resolution simulation:

Turbulent eddies at the boundary layer under the eyewall were found to result from high resolution simulation, but not at lower resolution. These eddies are easily identified by comparing volume rendering of vorticity magnitude:

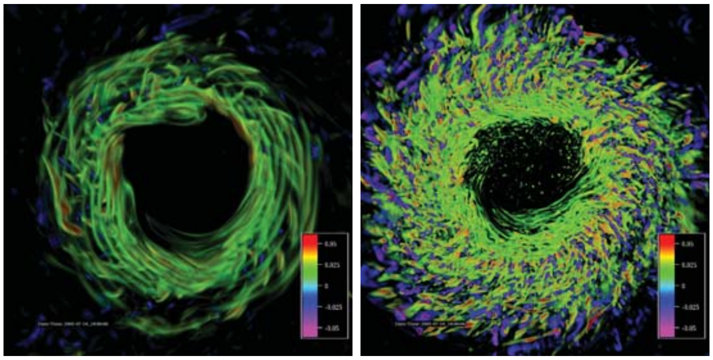

Figure 2: Comparison of volume rendering of vertical vorticity resulting from lower- and higher-resolution WRF simulations, using same color mapping. The left image is a view from above of a volume rendering of the z-component of vorticity calculated on a 185 m grid, the right image is on a 62 m grid. Region shown (in both) is approximately 35 km in diameter. Note that the internal structure of the higher-resolution simulation could not be anticipated from the lower resolution results.

Vortex tubes near the surface eyewall:

In order to better understand the turbulent eddies near the eyewall, we used direct volume rendering [5] of vorticity magnitude near the sea surface. The increased vorticity sometimes appears in tubular structures that suggested vortex tubes rotating about the hurricane. To isolate these tubes from the background wind velocity, we subtracted the 1-minute averages of **Wind** = (*U*, *V*, *W*), resulting in a velocity field, **Wind_Diff**, thereby subtracting out the dominant counter-clockwise hurricane rotation. We can then apply flow integration to **Wind_Diff** for understanding of small-scale structure of the flow. Streamlines were constructed using flow seeds inserted along planes orthogonal to the tubular shapes, revealing spiraling motion in **Wind_Diff.**

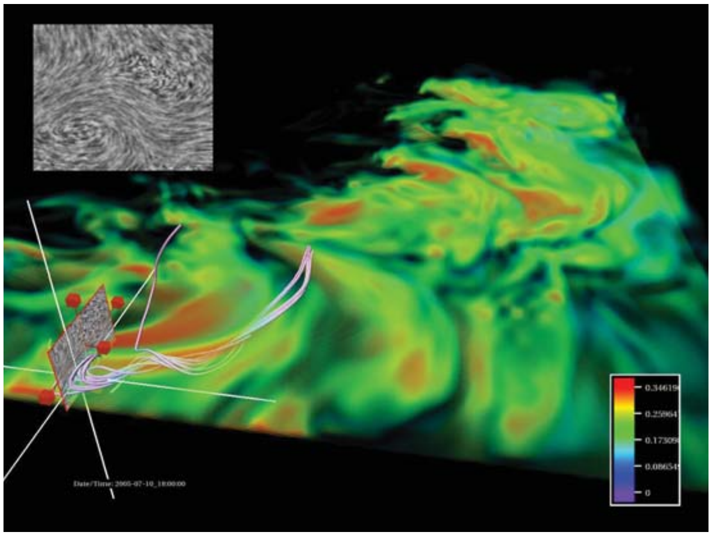

*Figure 3: Streamlines of **Wind_Diff** placed using image-based flow visualization intersecting a vortex tube. Inset is one frame of the IBVF animation image indicating vortex location.*

In the above figure 3, a number of tubular structures can be seen in the vicinity of the eyewall. One of these (at about 250 m elevation) is examined more closely. It is probed using image-based flow visualization (IBFV), indicating rotation of **Wind_Diff** with axis along the length of the tube. Streamlines of **Wind_Diff** are inserted near the axis of rotation, resulting in lines that twist about the vortex tube. This animating IBFV sequence can be seen at:
http://vis.ucar.edu/~alan/ams09/Ibfv.mov.
The probe IBFV image is about 1 km wide and 750 m high.

Larger vortices at increased elevation:

At higher elevation the vorticity magnitude is decreased; however vortex tubes can still be observed. These tubular shapes have larger radius, and coincide with vertical extensions of increased vorticity. Figure 4 shows streamlines of **Wind_Diff** with a volume rendering of vorticity magnitude, with a vortex core at elevation 600 m. The IBFV planar slice shown is about 3 km wide.

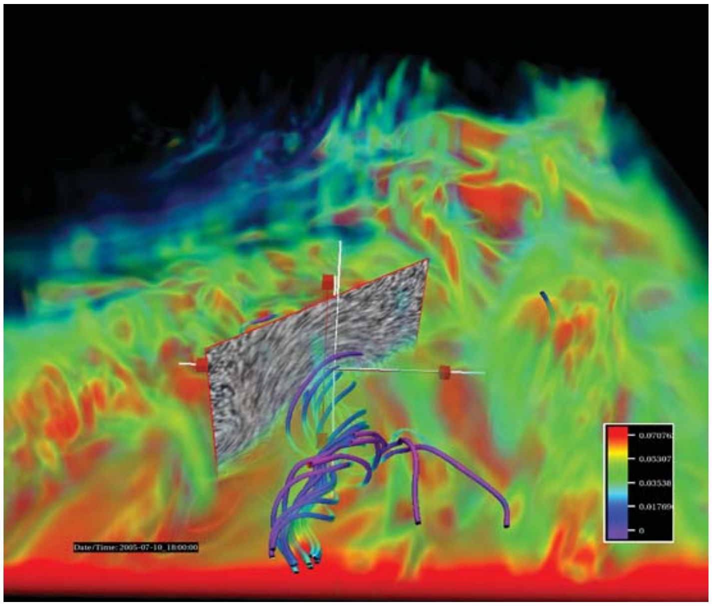

*Figure 4: At higher elevation (600 m), a wider vortex tube is identified with streamlines of **Wind_Diff** and also with an IBFV planar probe.*

Tracking vortex motion:

The vortex observed in figure 4 is one among a series of such vortices that rotate with the dominant wind field about the hurricane. We can combine the IBFV capability with field line advection to visualize the motion of these vortex tubes. VAPOR's field line advection is used to advect seed points for the **Wind_Diff** streamlines in the **Wind** velocity field. With the advance of time, a number of vortex tubes can be observed to rotate around the hurricane. When tracked over time, these tubes are seen to form and dissipate after 30-60 seconds. In figure 5, using data at 5-second intervals, the vortex motions are tracked forwards and backwards in time from the seeding time. Figure 5 below (left and right) illustrates **Wind_Diff** streamlines in one vortex and associated IBFV images, 10 seconds before and after the time the streamline was seeded. Note that several vortices (including the vortex identified with colored streamlines) have moved with the **Wind** field.
See http://vis.ucar.edu/~alan/ams09/flaAnimation.mov for an animation tracking these 12 streamlines in the vortex backward (25 seconds) and forward (50 seconds) from the original seeded time.

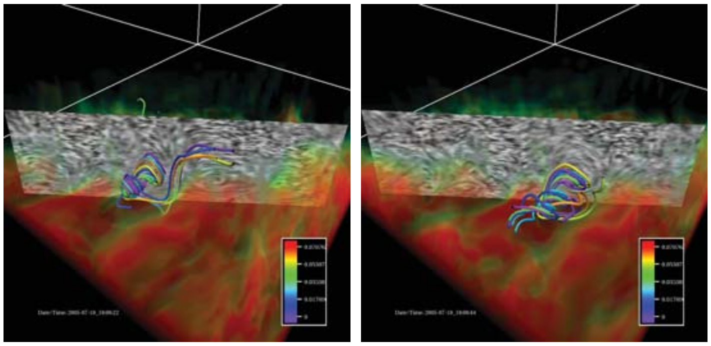

Figure 5: Several vortices in the eyewall are followed in an IBVF cross-section, while one vortex is tracked with moving streamlines as they are advected using in the wind field.

Summary:

Increased resolution WRF simulation of hurricane has revealed a complex structure of turbulent eddies occurring near the base of the eyewall. Exploration of these eddies, using the VAPOR visualization and analysis package, was used to identify a pattern of transient vortices that rotate about the hurricane center. To better understand the complex dynamics of the turbulent eddies, they were visualized and animated in VAPOR using image-based flow visualization, steady and unsteady flow integration, and field line advection.

Acknowledgements:
The WRF simulation was performed in CISL/NCAR's super-computer facility. The visualization and flow analysis capabilities of VAPOR that were used in this report were developed at NCAR with contributions from Liya Li, Han-Wei Shen, Victor Snyder, Kenny Gruchalla and Aake Nordlund.

References:

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