# Case Study on Visualizing Hurricanes Using Illustration-Inspired Techniques

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**Abstract**—The devastating power of hurricanes was evident during the 2005 hurricane season, the most active season on record. This has prompted increased efforts by researchers to understand the physical processes that underlie the genesis, intensification, and tracks of hurricanes. This research aims at facilitating an improved understanding into the structure of hurricanes with the aid of visualization techniques. Our approach was developed by a mixed team of visualization and domain experts. To better understand these systems, and to explore their representation in NWP models, we use a variety of illustration-inspired techniques to visualize their structure and time evolution. Illustration-inspired techniques aid in the identification of the amount of vertical wind shear in a hurricane, which can help meteorologists predict dissipation. Illustration-style visualization, in combination with standard visualization techniques, helped explore the vortex rollup phenomena and the mesovortices contained within. We evaluated the effectiveness of our visualization with the help of six hurricane experts. The expert evaluation showed that the illustration-inspired techniques were preferred over existing tools. Visualization of the evolution of structural features is a prelude to a deeper visual analysis of the underlying dynamics.

**Index Terms**—Hurricane visualization, illustration-inspired visualization, visualization in physics, expert evaluation.

## 1 Introduction

Accurate forecasts of the tracks and intensification of hurricanes are crucial in order to minimize loss of life and to plan evacuation strategies. The *category* of a hurricane is an important measure of the potential damage and coastal flooding. The category of a hurricane, as defined by the Saffir-Simpson scale, is predominantly determined by the sustained wind speeds and the minimum central pressure of the hurricane.

Certain structural features of hurricanes, and their evolution in time, give information about the dynamical processes involved in the intensification or dissipation of a hurricane. Common representations are 2D visualizations that allow the user to visualize the data only at a particular height/level in the data [2]. This may prevent the user from being able to correlate features on that level with surrounding spatial features or features in adjacent time steps. This significantly limits the user's ability to explore the data for further investigation and discovery. Three-dimensional visualization systems can provide an overview of the spatial structure of a phenomenon such as a hurricane [9], [10]. Such systems are great for visualizing the overall structure using standard visualization techniques such as isosurfacing and volume rendering. All these techniques are limited by the fact that they may occlude internal structural details and are not able to provide temporal context to experts investigating hurricanes.

The process of understanding spatial relationships between hurricane features in a single time step and temporal relationships within the time-varying data is one of the main challenges in this application domain. Specific challenges deal with the identification and visualization of the vertical wind shear and visualization of the formation and evolution of mesovortices in the hurricane. *Vertical wind shear* is when the magnitude and direction of the winds surrounding the hurricane vary across the height of the hurricane. This causes the storm to lose vertical coherence. A sufficiently strong vertical wind shear will lead to the weakening of a storm. The region surrounding the eye of the hurricane, called the *eyewall*, is crucial and visualization of attributes in that region immensely helps in the process of understanding and correlating the scientific models to the observed structure in the hurricane.

The use of illustration-inspired techniques, such as volume illustration techniques [22], stippling techniques [16], importance-driven volume visualization [29], and flow illustration techniques [13], [27], have resulted in informative visualizations that facilitate the effective visualization of structural data and the ability to more effectively convey the temporal nature of time-varying data. We use techniques from this field of research to visually investigate and understand the structural and temporal changes in a hurricane.

Drawing from our respective expertise in visualization and atmospheric physics, we approached the application domain based on the questions we were attempting to

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answer. To answer questions related to a single time step such as identification and quantification of the vertical wind shear, we used techniques to accentuate hurricane features in a single time step. In order to answer questions regarding the time evolution process of the hurricane, we used illustration-inspired techniques to display the change in attribute values when the hurricane changes its category. The visualization of temporal information in a single image provides useful semantic information about the rate of intensification of the hurricane.

To evaluate the value of the visualizations that we have generated, we invited experts and practitioners in the field of hurricane research to give us critical feedback. We presented them with a set of images that contained 2D and 3D images generated by tools that they were more familiar with, as well as visualizations generated using our illustration-inspired techniques. Experts mostly preferred our visualizations over those generated from their standard tools to visualize the hurricanes.

## 2 Application Domain

A *hurricane* is another name for a tropical cyclone, a vertically coherent vortex of rapidly swirling air with a low pressure core that forms in the tropical Atlantic and Eastern Pacific oceans. Warm moist air over the tropical oceans spirals inward at the sea surface and ascends in the *eyewall*, the cloudy region of maximum winds surrounding the cloud-free *eye* where the air is descending on average. The airflow is outward at the top of the hurricane, and the cloudy spiral arms are the *rainbands*. While forecasts of the track of a hurricane have improved in recent years, accurate prediction of hurricane intensity change has proved elusive. Increases in the spatial and temporal resolution of both satellite observations and NWP models have revealed numerous small-scale, turbulent flow features that may play an important role in determining hurricane intensity, although the exact mechanisms are not known [20]. Among these are *mesovortices*, small scale and intense vortices in the eye and eyewall.

Mesovortices in the eyewall are thought to be associated with strong vertical motion in so-called *hot towers*, and the rising motion in the eyewall may in fact be largely concentrated in these regions [1]. Other effects of eyewall instabilities include radial transport of warm, buoyant air from the eye to the eyewall, or transport of angular momentum from the eyewall to the eye which is thought to be important in intensification [20]. In addition to their possible role in intensity change, mesovortices may lead to significant increases in damage to coastal areas, due to their high tornado-like winds.

Vertical wind shear has been known to cause dissipation in a hurricane and is closely observed by meteorologists during the evolution of a hurricane. Current methods used by meteorologists to observe wind shear consist of looking at satellite data showing the movement of cloud features. A recent analysis of the hurricane Bonnie simulation used here [1] suggests that wind shear, convection, and mesovortex formation are linked, and one of our objectives is to develop methods that allow this connection to be seen clearly in three dimensions.

Identifying basic structural features such as the eye, the eyewall, the rainbands, and mesovortices is crucial to the domain. In addition to that, studying the evolutionary process of the hurricane as it starts from a disorganized cluster of clouds and intensifies to a category 5 hurricane is crucial to the overall understanding of the phenomenon.

The hurricane visualizations presented here are based on model simulations of hurricane Bonnie (August 1998), hurricane Isabel (September 2003), and hurricane Katrina (August 2005). The data for hurricane Bonnie was obtained from a MM5 model simulation, with 2-km spatial resolution and 3-minutes temporal resolution for 6 hours [1]. The data for hurricane Isabel was produced by the Weather Research and Forecast (WRF) model, courtesy of NCAR, and the US National Science Foundation (NSF) and was the same data used for the IEEE Visualization 2004 contest [15]. The hurricane Katrina simulation was obtained by running the National Center for Environmental Prediction's Eta numerical weather prediction model, run at 10-km horizontal resolution and a 1-hour temporal resolution for 72 hours, with 60 vertical levels. The variables contained in our data set are Cloud water [kg/kg], Geopotential height [gpm], Mean sea level pressure (Eta model) [Pa], Relative humidity [percent], Temperature [K], u wind [m/s], v wind [m/s], and Pressure vertical velocity [Pa/s].

The current tools that we use are time-tested and effective but limited due to their 2D nature [2]. Two-dimensional visualization is effective in visualizing contour plots of a single level, but exploring the 3D structure of the hurricane is not possible.

## 3 Related Work

Researchers have used compression [24], optimized data structures and algorithms [26], [30], and graphics hardware [17] to effectively visualize time-varying data from domains as diverse as medicine, computational fluid dynamics and molecular dynamics. Woodring et al. [31] presented a novel technique to visualize time-varying data by treating it as 4D data and innovatively used hyperplanes to effectively visualize the data.

Hurricane visualization has been a topic of interest for the last few years because of the immense destruction that has been caused by hurricanes. At the IEEE Visualization 2004 contest, hurricane Isabel data was made available as part of the contest [15]. Researchers adopted approaches based on immersive visualization [6], multithreaded OpenGL-based glyph visualization [12], interactive brushing in data views [3], anisotropic diffusion for visualizing vector fields [8], variants of volume rendering techniques [11], and texture advection techniques for flow visualization [23]. These techniques, though effective in visualizing certain aspects of the hurricane, were limited in their ability to show internal structural details of a particular time step as well as to convey the temporal nature of the hurricane.

Weather and climate researchers use a combination of tools that produce 1D and 2D visualizations of their data. The Grids Analysis and Display System (GrADS) [2] developed at the Center for Ocean, Land and Atmosphere Studies (COLA) is one such 2D visualization tool widely

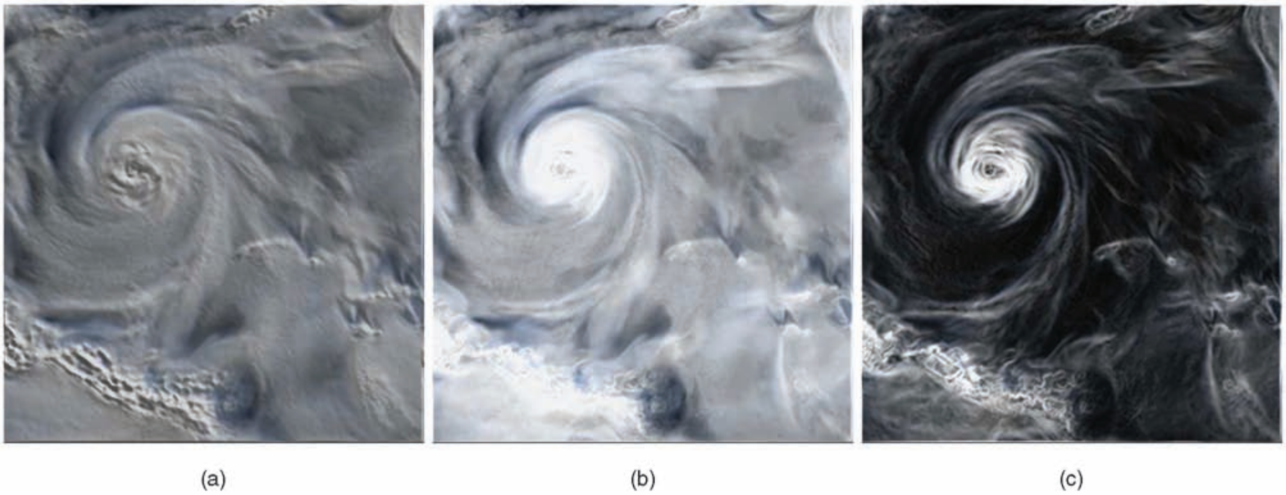

Fig. 1. (a) The image depicts a standard volume-rendered image of humidity for time step 53 of hurricane Katrina. (b) The image depicts the boundary-enhanced version of the same image with the eye, eyewall, and the rainbands being seen. (c) The image depicts the silhouette-enhanced version with the features being preserved while the unimportant regions are removed.

used by atmospheric physics and weather researchers to explore and study their data.

Illustration-based styles have shown considerable promise in effectively conveying information. Researchers in the field of computer graphics and visualization have applied techniques from the fields of illustration, abstraction, and art to produce effective and expressive visualizations. These techniques have been used to generate insightful visualizations of medical and scientific data [7], [16], [22], [29]. Stompel et al. [25] introduced novel visualization techniques such as strokes based, temporal domain enhancement, and so on to enhance time-varying data obtained from the field of computation fluid dynamics (CFD).

## 4 Approach

Visualizing hurricanes in an illustrative style provides crucial morphological and temporal information that is not always apparent from standard visualization techniques. We apply illustration-based techniques such as boundary enhancement and silhouette enhancement to accentuate internal features in the underlying data. We found that the silhouette enhancement algorithm also helps in the identification of vertical wind shear in a hurricane. Illustrative visualization was useful in investigating vortex rollup and mesovortex formations. Such phenomena are believed to cause dissipation in a hurricane and so their investigation proves crucial. We convey temporal change in the data by applying illustration-inspired techniques such as speedlines and opacity-based techniques introduced by Joshi and Rheingans [13] to convey the temporal nature of the storm.

## 5 Understanding Spatial Distributions

Visualizing the morphology of a single time step is critical to the overall understanding of the phenomenon. A visual representation of each time step can be obtained by visualizing the various scalar quantities such as cloud water, humidity, and temperature. We generated a volume-rendered representation of the hurricane to provide a 3D representation of the hurricane.

Traditional raycasting-based visualization tends to limit the visualization of internal structures of the hurricane due to the obscuration of voxels farther from the eye by voxels closer to the eye. Volume illustration techniques were inspired by illustrations that capture and accentuate key features de-emphasizing uninteresting regions [22]. These techniques generate expressive visualizations of scientific data by using data-dependent characteristics such as the gradient magnitude and direction. *Boundary enhancement* is one such technique that identifies and accentuates boundaries between features in the data. *Silhouette enhancement* is a technique in which the silhouettes of the structural features in the data are accentuated. These techniques highlight internal features such as the eyewall, surrounding rainbands, and other features that are significant for exploratory and investigative purposes. The silhouette computation considers voxels whose gradient is perpendicular to the view vector and accentuates the opacity of those voxels.

The humidity attribute is particularly useful for domain experts to visualize the evolution and transformation of the storm. Fig. 1 shows a set of examples where our techniques generated more insightful images than standard visualization techniques. Fig. 1a depicts a standard volume-rendered image of the humidity attribute with lighting. The eye is located toward the top left of the image. Fig. 1b shows a visualization where the boundary enhancement technique has been applied to enhance feature boundaries. The boundary enhancement technique enhances the boundaries of the rainbands and the eyewall. Fig. 1c shows a visualization generated using the silhouette enhancement technique where the eyewall and the rainbands are accentuated while the unimportant detail is removed. The width of the eyewall as well as the structure of the rainbands can be most clearly seen in this visualization.

### 5.1 Investigating Vertical Wind Shear

Visualizing the hurricane using knowledge about the intensification and dissipation of hurricanes produces more effective and informative visualizations. It is known that the presence of *vertical wind shear* leads to hurricane weakening

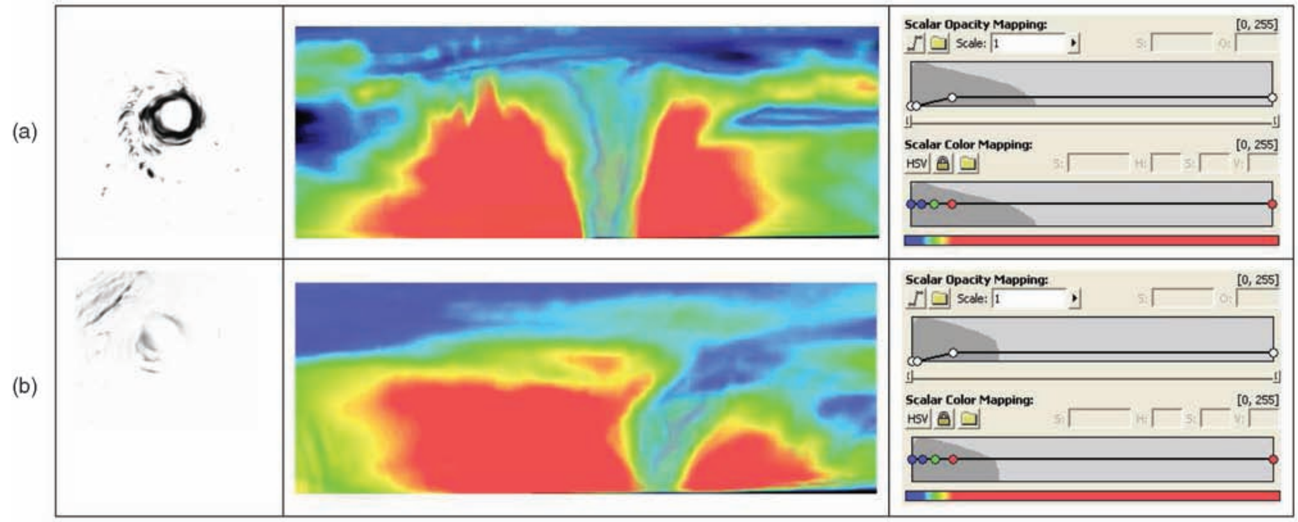


Fig. 2. This image depicts the silhouette of the wind speeds and a cross-sectional view of the same time step. (a) The row shows a completely formed circular silhouette that indicates no vertical wind shear as can be verified from the right cross-sectional view. (b) The row shows a light, barely visible silhouette that indicates high vertical wind shear. The cross-sectional view confirms the presence of high vertical wind shear in the hurricane at that time step. The parameters used to obtain the silhouette-enhanced visualization are $k_{sc} = 0.0$, $k_{ss} = 0.7843$, and $k_{se} = 0.9$.

and dissipation. Vertical wind shear is the difference in the wind speed and direction between the upper and lower atmosphere due to surrounding winds. If there is large vertical shear, the hurricane cannot form and hold itself vertically which eventually leads to its dissipation.

We found that the silhouette computation algorithm, when used in a top-down view to generate a visualization, identifies vertical wind shear. In a silhouette-enhanced visualization, a strong, crisp, well-defined silhouette implies less vertical wind shear and a blurred, diffused silhouette indicates the presence of a large vertical wind shear. The equation to produce the silhouette-enhanced visualization for the investigation of vertical wind shear is given by

$$o_s = o_v\Big(k_{sc} + k_{ss}(1 - abs(\nabla f_n \cdot V))^{k_{se}}\Big),$$

where $o_v$ is the original opacity of the voxel, $\nabla f_n$ is the gradient of the current volume sample, $V$ is the view vector, $o_s$ is final silhouette-enhanced opacity of the voxel, $k_{sc}$ controls the scaling of the non-silhouette regions, $k_{ss}$ controls the amount of silhouette enhancement, and $k_{se}$ controls the sharpness of the silhouette curve.

In order to validate our vertical wind shear identification, we generated visualizations to investigate the shear in a particular time step based on its silhouette-enhanced image. Fig. 2 shows some results. The left column depicts the silhouette-enhanced image for time step 7 and time step 46 of hurricane Isabel. The top image in the left column shows a strong, well-defined silhouette that correlates with the strong vertical coherence of the hurricane which can be seen in the second image from the left in Fig. 2a which is a cross-sectional view of the hurricane eyewall. As can be seen in the cross-sectional view, the eyewall of the hurricane shows a well-formed vertically coherent funnel. On the other hand, the first image in Fig. 2b shows a silhouette image in which the silhouette is blurred and can barely be seen. This correlates with the large amount of vertical wind shear that can be seen in the second image in Fig. 2b that shows the cross-sectional view of that time step. The cross-sectional view shows a rightward curving hurricane eyewall with much less vertical coherence. The right column contains the transfer functions used for the cross-sectional visualizations.

### 5.2 Investigating the Structure of Mesovortices

Theoretical studies have shown that a rapidly spinning column of fluid becomes unstable, and wavelike perturbations will grow. In Fig. 3, which is an illustrative visualization of cloud water in hurricane Katrina, we can see this type of instability showing a nearly vertically aligned wave having an altitude-dependent amplitude in the cloud water field. Due to this instability, some cloud water can break off from the main eyewall. This image shows a depiction of the hurricane eyewall just before the hook-shaped cloud breaks off from the hurricane. These instabilities in the eye of the hurricane are clearly associated

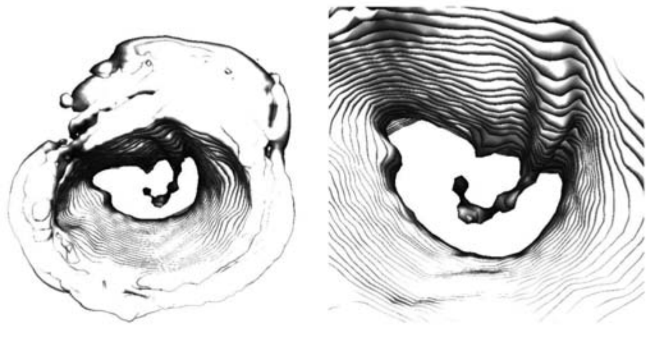

Fig. 3. Illustrative visualization of the cloud liquid water attribute of the 53rd time step of hurricane Katrina. (a) and (b) These images were generated by enhancing the volume rendering process by using a gradient-based boundary enhancement technique. The grayscale colormap used provides an illustrative feel to the visualizations. (b) The image shows a closer look at the hook in an illustrative style.

(a)

(b)

Fig. 4. (a) The image is a volume-rendered image of the vorticity, rendered in green, and vertical velocity, rendered in red, of the first time step of hurricane Bonnie. Dark red regions depict regions of strong positive vertical velocity and bright green regions depict high positive vorticity. (b) The image depicts an illustration-style rendered image of the same positive vorticity.

with regions of strong upward motion (upwelling). Rapidly rising air stretches in the vertical direction and vorticity is spun up by vortex tube stretching. The basic principle is conservation of angular momentum, an example being a spinning skater who draws in her arms and spins up. To investigate this instability further, we visualized the vorticity attribute in conjunction with the upward (vertical) velocity.

Fig. 4a is a volume-rendered image of the vorticity and vertical velocity fields of the first time step of hurricane Bonnie. In this image, the vertical wind velocity is rendered in red and the positive vorticity is rendered in green. Dark red regions are regions of strong positive vertical velocity and green represents regions where the positive (counter-clockwise) vorticity is large. The technique emphasizes regions that are vertically aligned. The outer band of green

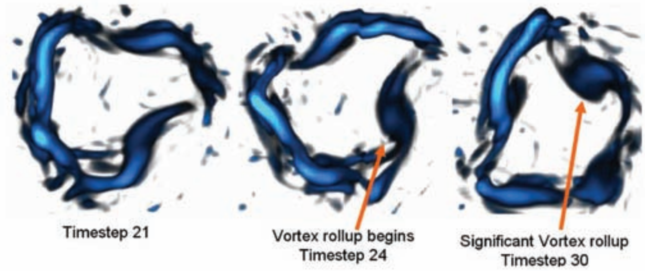


Fig. 5. These images show snapshots from three different time steps of vorticity in hurricane Bonnie. They show the vortex rollup phenomenon clearly.

in the northern part of the eyewall coincides with strong upwelling. Fig. 4b is an illustration-style rendering of the same positive vorticity. The illustrative visualization shows that the two green vorticity rings in Fig. 4a are actually observed at different levels and a connection between them can be seen as a ledge.

Fig. 4a also shows mesovortices which can seen as localized patches of high vorticity (green) around the outer vorticity ring. Those vorticity regions are colocated with high vertical velocity regions, which confirms the theory regarding strong upward convection (upwelling) in regions of high vorticity. Rapidly rising air (signified by high vertical velocity) stretches in the vertical direction and vorticity is spun up by vortex tube stretching. This process is similar to the flowing of water from a bathtub into the drain.

The illustration-inspired image provides depth cues that a volume-rendered image with lighting cannot provide. The illustration-stylized image facilitates the visualization of mesovortices and allows the viewer to visualize the varied depths at which these vortex structures occur. Such illustrative images help us investigate and understand the interactions between the vorticity at different levels.

A spinning ring of fluid is known to become unstable when the radial wind shear becomes sufficiently large [4]. In this case, the vortex ring rolls up into localized vortices as can be seen clearly in Fig. 5. This process again leads to mesovortices, but unlike the vortex stretching mechanism discussed earlier, it does not necessarily involve vertical motion. Fig. 6 is a time sequence showing various stage of a vortex rollup. Fig. 6a shows volume-rendered images of the vorticity in a top-down view. The images in Fig. 6a are the 13th, 30th, and 33rd time step of the vorticity, respectively.

This top-down view allows us to look more carefully at the vortex rollup phenomenon and specifically examine the mesovortex formation process in the lowest part of the storm. The first image in Fig. 6a shows that the eyewall has developed a wavelike perturbation which increases in amplitude subsequently. Vortex rollup begins in the subsequent image and continues in the third image from the top.

In the last image in Fig. 6a, the eyewall vorticity has become concentrated into four or five mesovortices. The illustration style of the same sequence, shown in Fig. 6b, gives a clearer view of the complex 3D nature of vortex rollup. This view shows the vertical alignment of the eyewall mesovortices, and shows the intricate nature of the vortex dynamics occurring in the eyewall. The illustrative style helps the viewer to understand that the vortex rollup

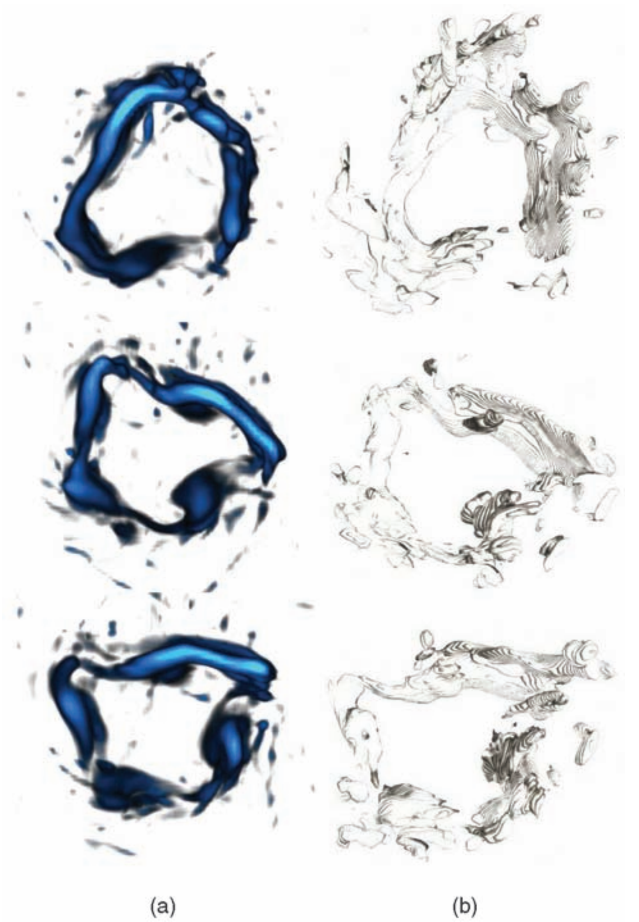


Fig. 6. Time sequence showing various stages of vortex rollup. (a) Shows a series of volume-rendered snapshots of the 13th, 30th, and 33rd time step. (b) Shows an illustration-style visualization of the corresponding time steps. The illustrative images provide an understanding of the 3D nature of vortex rollup.

is a 3D phenomenon and does not occur only at the lower level. The mesovortices can be seen as vertical vortex tubes in the illustrative images.

## 6 Exploring the Time-Varying Nature of a Hurricane

Visualizing a snapshot of each time step individually can provide a limited understanding of the trends and transformations that the hurricane undergoes. For such time-varying data sets, visualizing volume-rendered snapshots of each time step or viewing an animation of rendered images of each time step may be of limited use. These snapshots or animations may not convey change in structure and position of the contained features in the time-varying data set.

Illustrators provide a sense of continuity in spite of the fact that the viewer is looking at still frames [18], [19]. We observed these illustrations and identified techniques such as opacity-modulation techniques where older time steps are shown in a faded representation as well as the use of directional lines to signify motion as in the illustration in Fig. 7. These techniques are extremely effective at conveying directional change. We call these techniques *opacity modulation* and *speedlines*, respectively [13]. We have used

Fig. 7. The illustration uses speedlines to depict the running motion of the man. The lines get thinner and lighter as they approach the running man. Illustration provided courtesy of HarperCollins Publishers and Scott McCloud [19].

these illustration-based principles to convey structural and temporal changes in the hurricane using a single image.

### 6.1 Investigation of the Motion of the Hurricane Center

The linear motion of the hurricane is accompanied by rotation around its axis. The direction of motion of the hurricane center is critical to the understanding of the wobbling motion of the hurricane as it progresses along its path. The wobbling motion, also known as *precession*, is a key component in the investigation of dissipation due to shear in the upper levels.

Illustrators use trailing lines to create the effect of motion in still images as can been seen by the image in Fig. 7 [19]. Our visual system processes these trailing lines as evidence of the object having been there in the past and having moved to its current state. These trailing lines, *speedlines*, have been used to annotate images and animations of time-varying computational fluid dynamics data [13]. Fig. 8 depicts a visualization of the hurricane with speedlines. The eye of the hurricane is tracked automatically by identifying the lowest mean sea level pressure and the minimum wind speeds in every time step. The path for the speedlines is obtained by computing an offset in the direction perpendicular to the long-term motion of the hurricane. The offset is based on the radius of the eyewall of the current time step from the center of the eye. The hurricane itself is visualized in a pen-and-ink shaded style to be consistent with the illustrative paradigm of the image. The annotation of the image with speedlines provides the effect of motion and conveys important information regarding the

Fig. 8. This image depicts a pen-and-ink style rendered visualization of time step 44 of the hurricane. The annotation of the image with speedlines provides temporal context and conveys information regarding the upward curving motion of the hurricane.

Fig. 9. This image shows the use of opacity-based techniques to convey the transformation of a semiorganized cluster of storms into a category 5 hurricane. The hurricane starts out as a disorganized cluster of clouds at time step 10 as shown by the faded representation in the bottom right of the image. Its intensification from time step 10 through time step 35, time step 53 to a category 5 hurricane at time step 71 is shown here.

Fig. 10. This image depicts the use of opacity-based techniques to convey the intensification of the hurricane. The visualization contains a footprint for every category change it undergoes. The first footprint, on the bottom right of the image, is the change to category 2. The hurricane intensifies very quickly after that, as per the subsequent two footprints and then the last footprint signifies the intensification to category 5. The current time step of the hurricane is shown in full opacity with four category change events in the past being shown using opacity-based techniques.

leftward curving motion of the hurricane. Similar to the illustration of the running man, the lines provide a sense of direction of motion for the viewer. The speedlines also show a cycloid motion of the hurricane center due to an overall rotation about the center.

### 6.2 Examining the Rate of Intensification

The speed at which a hurricane intensifies is critical to the overall understanding of the intensification process. For example, an intensification of a category 2 hurricane to a category 5 hurricane in a few hours will prompt a further investigation into the conditions that caused such rapid intensification. Studying the rate of intensification is also crucial in correlating the trends in observed values of attributes of the hurricane.

The intensification process can be effectively visualized using the opacity-based technique where a blurred, desaturated representation is used for older time steps, and bright, crisp representations are used for newer time steps [18], [19]. Such illustrations are generally used to convey past positions and structure of the features in the current time step. This technique provides context to the visualization of the current time step by providing faded visualizations of older time steps that convey change in shape, orientation, and position. To generate a visualization using this technique, "key" time steps are identified. By "key" time steps, we mean time steps that are associated with a certain event such a change in category of the hurricane. In this manner, we provide temporal context to the viewer as the current time step is being observed. Visualizing structural change over time in a single image can be achieved using this technique.

Fig. 9 shows a visualization of the current time step with the older time steps faded out. The oldest time step (time step 10) is visible at the bottom right, which shows a loosely organized cluster of storms. The subsequent time steps (time steps 34 and 53) are when the hurricane seems more organized with an eye and an eyewall. By time step 71 shown toward the upper left of the image, the hurricane is a full-blown category 5 hurricane. The evolution of a hurricane from a small, organized cluster to a category 5 hurricane is conveyed from this visualization. This visualization was created by instancing an actor in VTK for each volume (18-24 hours apart in this case) and varying the maximum opacity in the transfer function for each volume based on the age of the time step being rendered, as compared to the newest time step being shown.

Fig. 10 was generated by leaving faded footprints of the time steps when the hurricane changes its category. This produces a visualization that depicts a current time step of the hurricane with context regarding the stages at which the hurricane changed its category in the intensification process. The four footprints are for the category 2-5 intensification stages and the current time step is rendered with maximum opacity. The hurricane is a category 2 hurricane initially and quickly intensifies in a matter of a few hours to a category 4 after which it intensifies to a category 5 as indicated by the last footprint. The rapid intensification process of the hurricane is conveyed through this image. This visualization was created by instancing an actor in VTK for each time step in which there was a category change and varying the maximum opacity in the transfer function for each volume based on the category of the hurricane at that time step.

Some of these techniques can be used in combination to produce more informative visualizations. For example, Fig. 11 shows the opacity-based technique being applied in conjunction with the speedlines techniques to visualize a combination of the 10th, 35th, 53rd, and 71st time steps. This visualization was created by instancing a volume rendering actor in VTK for each time step (18-24 hours apart). The maximum opacity for each transfer function was kept constant to allow structural visualization of each time step.

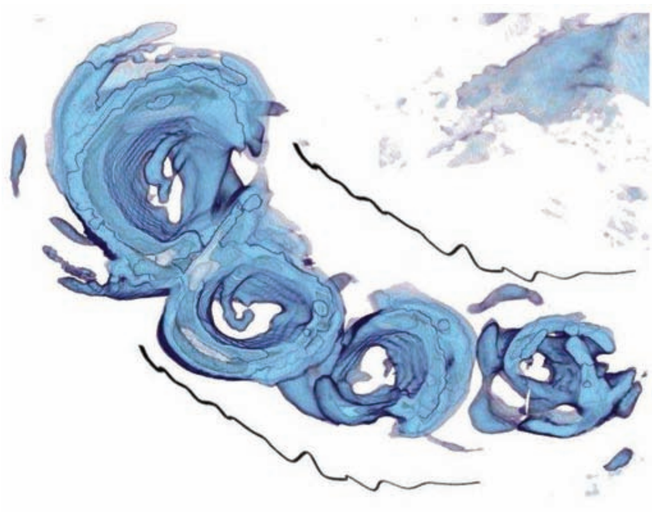

Fig. 11. The image shows the combination of opacity-based techniques and speedlines to convey the motion of the hurricane. The hurricane moves leftward and starts turning upward. The image shows the cloud water quantity in time steps 10, 35, 53, and 71 (from right to left). The footprints of the hurricane from each time step convey the growth in size of the hurricane along with the internal structure of the hurricane at each time step. In addition, the speedlines convey the leftward direction of motion of the hurricane.

The speedlines were drawing using cubic B-splines based on the tracked center of the eye of the hurricane.

## 7 Expert Evaluation

The images generated by our visualization techniques were evaluated by six application scientists who conduct research in weather modeling and forecasting at UMBC, NASA, and Joint Center for Earth Systems Technology (JCET). Our expert evaluation was designed to obtain subjective feedback from the experts. Many visualization researchers [5], [14], [21], [28] have stressed the needs of formally evaluating visualizations. While collaborator Lynn Sparling, who is an atmospheric physics researcher, was a crucial part of the design process, we felt that feedback from a broader array of domain experts would be valuable. The expert evaluation process gave us much more qualitative information regarding what kinds of visualizations were more useful for answering some questions and how in some cases, traditional visualization techniques were better suited for answering a specific class of questions.

### 7.1 Methodology

The evaluation was designed to compare standard visualization techniques that the experts were familiar with (such as 2D contour plots) with our illustration-inspired visualizations. We asked the experts to evaluate the techniques based on whether they were able to visualize the internal structure of the hurricane, the intensification process, or correlations among hurricane attributes. The experts were asked to perform tasks similar to what they would do on a regular basis to investigate a hurricane, its intensification, its instability, and its direction of motion.

### 7.2 Expert Feedback

We found that the experts preferred our illustration-inspired techniques over standard visualization techniques in most cases. The experts found our visualization techniques to be very useful for examining hurricane structure, 3D mesovortex formation, and visualization of current time step with context. For example, Fig. 3 was preferred, over 2D isocontour and the 3D volume rendering images, by all the experts for the ability to clearly visualize the internal structure of the hurricanes. One expert says: "*This is an exceptionally effective portrayal of the cloud water field. Here, we can see a wave perturbation in the eyewall that has an altitude-dependent amplitude. This type of visualization has a lot of potential for investigating the dynamics in the hurricane inner core*." The illustrative visualization in Fig. 3 was found to be more suited for answering questions regarding the internal structure of a single time step in a hurricane.

Experts preferred the illustrative pen-and-ink style visualization in Fig. 6b to the standard volume-rendered vorticity images in Fig. 6a. One expert writes: "*The illustration-based technique on the right is radically different from anything currently used in hurricane research. The cases here show vortex rollup in 3D ... this is a very promising new way to look at hurricane inner core structures and dynamics*." Using the illustrative visualization, the hurricane experts were able to answer questions regarding the presence and structure of mesovortices and further investigate the vortex rollup phenomenon.

The illustrative techniques such as boundary and silhouette enhancements shown in Fig. 1 were preferred over standard volume rendering techniques. The ability of the illustrative images to clearly show features such as eyewall and rainbands was appealing to them. Based on Fig. 2, one expert notes value in using silhouette enhancement and writes "*This is very useful for looking at the effects of vertical wind shear on the hurricane structure*."

Fig. 10 was liked by all the six experts one of whom wrote "*This is a great way to visually track the motion of the storm*." Another expert writes: "*The figure might be very useful in a study of category change in response to topography, etc., during landfall, wind shear, or sea surface temperatures*." Figs. 9 and 11 were both preferred to looking at snapshots of each time step individually or viewing a panorama of constituent time steps. The experts liked the fact that both the storm motion and the structural evolution could be clearly seen in both the images. Fig. 8 was found to be effective and the illustrative style found to be novel. The visualizations helped them answer questions regarding the direction of motion of the hurricane, regarding the rate of intensification of the hurricane as well as the evolution of the hurricane at various stages along its track.

For Fig. 4, an expert wrote: "*This is an effective way of showing the correlation; this particular plot shows that a region of strong, vertically coherent vorticity marks the inner region of upwelling. The problem here is that we cannot tell if the green annular features are displaced in the vertical or if we are seeing secondary eyewall formation. The illustrative visualization helps clarify that by showing that the features are occurring at two different vertical levels*." The visualization led to the experts finding that the two vorticity rings in the hurricane occur at different altitudes.

In some cases, the traditional 2D visualization techniques were preferred. We think that this might be due to the familiarity with a particular tool or due to the experts being trained to use and analyze a particular 2D visualization technique. The integration concept of volume rendering was confusing to the experts, since their training in interpreting 2D visualizations led them to interpret the values as being that of the topmost level. Experts prefer to investigate the values at particular levels separately and so visualizing a composite image seemed unintuitive to them. Despite the fact that volume rendering images were less preferred, our illustrative representations such as the boundary- and silhouette-enhanced visualizations, shown in Fig. 1, were liked due to the fact that they enabled them to look at 3D features such as the rainbands, the structure of which is not as clearly visible in 2D visualizations.

They preferred visualizing the wind quantity in this manner than visualizing just the wind speeds in three dimensions. Visualizing hedgehogs in this manner, even though at a single 2D level, helped them visualize both the magnitude and direction of the winds. In such cases, we believe that texture-advection techniques introduced by Schafhitzel et al. [23] could be easily adapted for 3D visualization of wind vectors.

## 8 Conclusion

We have proposed the use of illustration-inspired techniques to visualize the time-varying data from hurricanes Bonnie, Isabel, and Katrina. Our techniques have facilitated the study of the hurricane and allowed visualization of internal structures of the hurricane. Our main contribution is to demonstrate the use of illustration-based techniques, in a domain where 2D traditional visualization techniques have been used, to help understand the physics behind the phenomenon and assist the investigation of conditions leading to the intensification or dissipation of a hurricane. The silhouette computation method helped in the identification of vertical wind shear which provides answers to crucial questions concerning the weakening and eventual dissipation of a hurricane. An expert evaluation was conducted to identify the effectiveness of our techniques. The experts mostly preferred the illustration-inspired techniques over standard visualization techniques. We are developing methods to visualize energy flow through the system and how it depends on assumptions about the coupling of the storm to the ocean.

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## References

[1] S.A. Braun, M.T. Montgomery, and Z. Pu, "High-Resolution Simulation of Hurricane Bonnie (1998). Part I: The Organization of Eyewall Vertical Motion," *J. Atmospheric Sciences,* vol. 63, pp. 19-42, 2006.

[2] COLA, *Grads,* http://www.iges.org/grads/grads.html, 2008.

[3] H. Doleisch, P. Muigg, and H. Hauser, "Interactive Visual Analysis of Hurricane Isabel with Simvis," *Proc. 15th IEEE Visualization Conf. (VIS '04),* contest entry, 2004.

[4] P.G. Drazin and W.H. Reid, *Hydrodynamic Stability.* Cambridge Univ. Press, 1981.

[5] G. Ellis and A. Dix, "An Explorative Analysis of User Evaluation Studies in Information Visualisation," *Proc. AVI Workshop BEyond Time and Errors (BELIV '06),* pp. 1-7, 2006.

[6] K. Gruchalla and J. Marbach, "Immersive Visualization of the Hurricane Isabel Dataset," *Proc. 15th IEEE Visualization Conf. (VIS '04),* contest entry, 2004.

[7] M. Hadwiger, C. Berger, and H. Hauser, "High-Quality Two-Level Volume Rendering of Segmented Data Sets on Consumer Graphics Hardware," *Proc. 14th IEEE Visualization Conf. (VIS '03),* pp. 40-47, 2003.

[8] A. Helgeland and T. Elboth, "Hurricane Visualization Using Anisotropic Diffusion and Volume Rendering," *Proc. Fifth Ann. Gathering on High Performance Computing in Norway (NOTUR),* 2005.

[9] B. Hibbard, "VisAD: Connecting People to Computations and People to People," *Computer Graphics,* vol. 32, no. 3, pp. 10-12, Aug. 1998.

[10] W. Hibbard and D. Santek, "The VIS5D System for Easy Interactive Visualization," *Proc. First IEEE Visualization Conf. (VIS '90),* pp. 28-35, 1990.

[11] M. Jiang, N. Shareef, C. Zhang, R. Crawfis, R. Machiraju, and H.-W. Shen, "Visualization Fusion: Hurricane Isabel Dataset," *Proc. 15th IEEE Visualization Conf. (VIS '04),* contest entry, 2004.

[12] G.P. Johnson and C.A. Burns, "Openg Gl Visualization of Hurricane Isabel," *Proc. 15th IEEE Visualization Conf. (VIS '04),* contest entry, 2004.

[13] A. Joshi and P. Rheingans, "Illustration-Inspired Techniques for Visualizing Time-Varying Data," *Proc. 16th IEEE Visualization Conf. (VIS '05),* pp. 679-686, 2005.

[14] R. Kosara, C.G. Healey, V. Interrante, and D.H. Laidlaw, "User Studies: Why, How, and When," *IEEE Computer Graphics and Applications,* vol. 23, no. 4, pp. 20-25, 2003.

[15] B. Kuo, W. Wang, C. Bruyere, T. Scheitlin, and D. Middleton, *Hurricane Isabel Data.*

[16] A. Lu, C.J. Morris, D. Ebert, P. Rheingans, and C. Hansen, "Non-Photorealistic Volume Rendering Using Stippling Techniques," *Proc. 13th IEEE Visualization Conf. (VIS '02),* pp. 211-218, 2002.

[17] E.B. Lum, K.L. Ma, and J. Clyne, "Texture Hardware Assisted Rendering of Time-Varying Volume Data," *Proc. 12th IEEE Visualization Conf. (VIS '01),* pp. 263-270, 2001.

[18] E. MacCurdy, *The Notebooks of Leonardo Da Vinci,* vol. 1. The Reprint Soc. London, 1954.

[19] S. McCloud, *Understanding Comics.* HarperCollins, 1994.

[20] M.T. Montgomery, V.A. Vladimirov, and P.V. Denissenko, "An Experimental Study on Hurricane Mesovorticies," *J. Fluid Mechanics,* vol. 471, pp. 1-32, 2002.

[21] C. Plaisant, "The Challenge of Information Visualization Evaluation," *Proc. Working Conf. Advanced Visual Interfaces (AVI '04),* pp. 109-116, 2004.

[22] P. Rheingans and D. Ebert, "Volume Illustration: Nonphotorealistic Rendering of Volume Models," *IEEE Trans. Visualization and Computer Graphics,* vol. 7, no. 3, pp. 253-264, 2001.

[23] T. Schafhitzel, D. Weiskopf, and T. Ertl, "Investigating Hurricane Isabel Using Texture Advection," *Proc. 15th IEEE Visualization Conf. (VIS '04),* contest entry, 2004.

[24] H.-W. Shen, L.-J. Chiang, and K.-L. Ma, "A Fast Volume Rendering Algorithm for Time-Varying Fields Using a Time-Space Partitioning (TSP) Tree," *Proc. 10th IEEE Visualization Conf. (VIS '99),* pp. 371-377, 1999.

[25] A. Stompel, E. Lum, and K.-L. Ma, "Feature-Enhanced Visualization of Multidimensional, Multivariate Volume Data Using Nonphotorealistic Rendering Techniques," *Proc. 10th Pacific Conf. Computer Graphics and Applications (PG),* 2002.

[26] P. Sutton and C.D. Hansen, "Isosurface Extraction in Time-Varying Fields Using a Temporal Branch-on-Need Tree (T-Bon)," *Proc. 10th IEEE Visualization Conf. (VIS '99),* pp. 147-153, 1999.

[27] N. Svakhine, Y. Jang, D. Ebert, and K. Gaither, "Illustration and Photography Inspired Visualization of Flows and Volumes," *Proc. 16th IEEE Visualization Conf. (VIS '05),* 2005.

[28] M. Tory and T. Moller, "Evaluating Visualizations: Do Expert Reviews Work," *IEEE Computer Graphics and Applications,* vol. 25, no. 5, pp. 8-11, 2005.

[29] I. Viola, A. Kanitsar, and M.E. Gröller, "Importance-Driven Feature Enhancement in Volume Visualization," *IEEE Trans. Visualization and Computer Graphics,* vol. 11, no. 4, pp. 408-418, 2005.

[30] J. Wilhelms and A. Van Gelder, "Octrees for Faster Isosurface Generation," *Proc. Workshop Volume Visualization*, pp. 57-62, 1990.
[31] J. Woodring, C. Wang, and H.-W. Shen, "High Dimensional Direct Rendering of Time-Varying Volumetric Data," *Proc. 14th IEEE Visualization Conf. (VIS '03)*, p. 55, 2003.

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