Illustrative Visualization Techniques for Hurricane Advisory Information

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***Abstract*—We have developed new illustrative visualization techniques inspired by artistic brush strokes for graphically representing the National Oceanic and Atmospheric Administration (NOAA) National Hurricane Center's (NHC) hurricane advisory statements. To address the complexity of the advisory information and the limitations of traditional map displays, our techniques offer enhanced representations that map advisory data attributes to the visual features in brush strokes. By condensing the information into a single, comprehensible image, our new representations avoid many perceptual issues that affect the perception and cognition of the current NHC graphical products. In the current work, we describe the motivation and algorithmic details of two variants of our approach: the small brush stroke and long brush stroke methods. We also present the results of applying our techniques to the representation of hurricane advisories from the 2005 season, which include those of the infamous Hurricane Katrina. The results highlight the promise of our illustrative visualization methods as an effective approach for the dispensation of this vital information.**

I. Introduction

Recent advances in environmental sensing and modeling techniques have resulted in tremendous growth in the quantity, quality, and complexity of available weather information. In particular, the National Oceanic and Atmospheric Administration (NOAA) National Hurricane Center's (NHC) hurricane advisories contain several heterogeneous data types that are difficult to represent graphically in a single image. However, the understanding of this information is vital for human safety in areas that are regularly affected by these devastating storms. Therefore, the motivation behind the current work is to develop new graphical representations of the NHC advisories using a single, coherent image, that conveys the past and present information about a particular storm of interest.

Since the NHC advisories are linked to geographical areas of interest, a map-based representation forms the basis of our approach. However, the complexity of the data dictates that conventional maps alone cannot solve the problem. In fact, this limitation is part of a larger problem in geographical data analysis that the cartographic community is attempting to solve with new mapping approaches, which provide flexible interfaces for interacting with and understanding the data. These new displays are designed to better support visual analysis of geospatial patterns and trends. They are operating in the realm of geographical visualization (GeoVis) (e.g., Kraak [1]), where cartographic and geographic information representation techniques are integrated with recent advances in scientific visualization, information visualization, exploratory data analysis, and image analysis (MacEachren et al. [2]). In particular, some researchers are exploring new GeoVis representations that utilize illustrative rendering techniques from the overarching field of computer graphics. Prior investigations of illustrative visualization techniques have shown significant promise in the visual analysis of weather conditions (e.g., Healey et al. [3]), flow visualization (Kirby et al. [4]), and medical visualization (Xie et al. [5]).

In the current work, illustrative techniques inspired by artistic brush strokes are applied to the visualization of the NHC hurricane advisory statements (compare Fig. 1 and Fig. 2). On the NHC website[1], the wind swath information from the advisories are posted graphically as color-filled polygons. Other advisory information, such as storm position and intensity forecasts, are available in separate plots on the website. However, visualization studies have shown that using separate plots can significantly hinder the ability to discover patterns in multiple variable analyses, especially when looking for combinations of conditions (Healey et al. [3]). In addition, the use of color-filled polygons makes it difficult to encode additional information in the plot due to layer occlusion issues.

To alleviate these issues, the current work describes a new representation of the NHC advisory statements that utilizes illustrative visualization techniques to enhance the NHC's graphical advisory products. To begin, we introduce the motivation and related work from the literature. Then, we provide a detailed description of the algorithms behind the new visualization techniques, which operate in one of two modes that simulate either small or long brush strokes. In addition, a temporal stroke fading capability is described that facilitates the contextual display of past storm activity. The paper also includes a discussion of the color labels used to encode the wind swath information. Several results from the active 2005 hurricane season are described, including plots of the infamous Hurricane Katrina track, to demonstrate the promise of the enhanced graphical products. By condensing

[1]The National Hurricane Center's Seasonal Tropical Cyclone Advisory Archive is located at http://www.nhc.noaa.gov/pastall.shtml

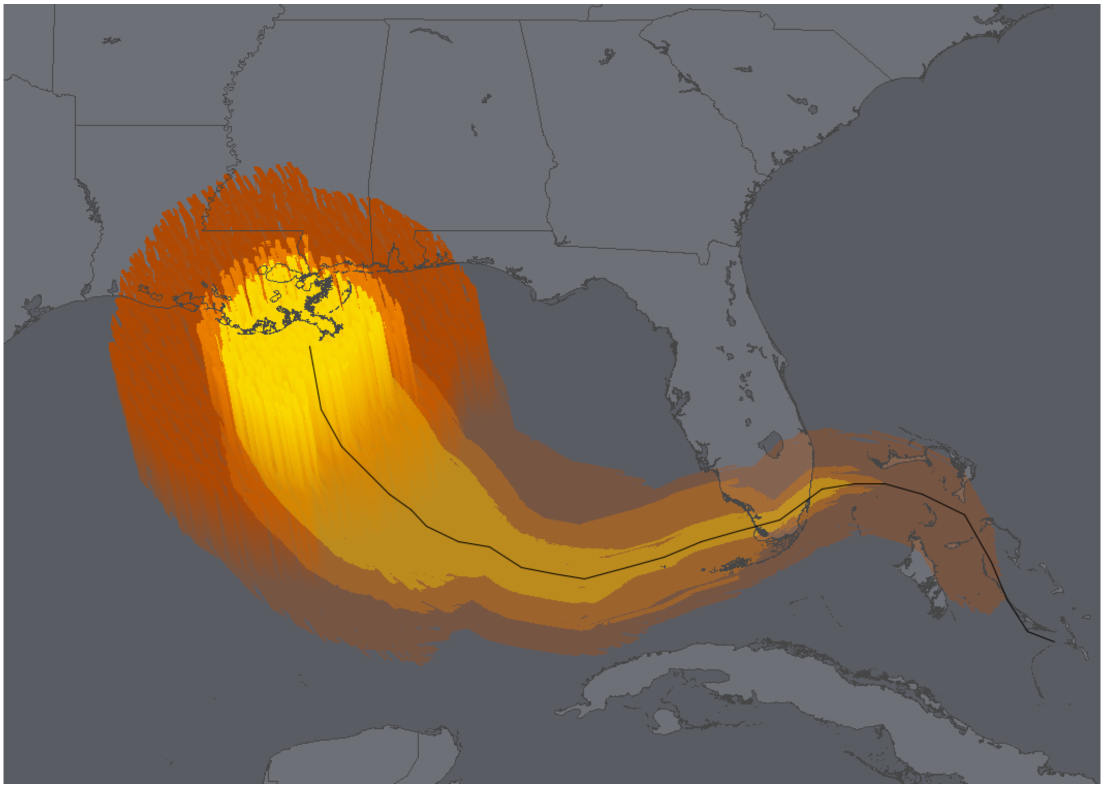

Fig. 1. Using the NHC advisories from the infamous 2005 Hurricane Katrina, our long brush stroke simulation and temporal stroke fading are demonstrated. In this figure, all the advisories just prior to the landfall of the hurricane eye are used to produce an illustrative encoding of the wind swath information.

the NHC advisories into a single image, our illustrative visualization methods for hurricane advisories yield promising and innovative approaches to the dispensation of this vital information.

II. Related Work

In general, illustrative rendering techniques are a class of computer graphics algorithms that produce non-photographic displays that appear to be partially generated "by hand". Instead of completeness and strict adherence to an object's properties, these methods are identified by the use of randomness, ambiguity, and arbitrariness (Strothotte and Schlechtweb [6]). These methods are also called Non-Photorealistic Rendering (NPR) techniques. With illustrative rendering, the underlying assumption is that the techniques of human artists have an "intrinsic merit that is based on the evolutionary nature of art"(Gooch et al. [7]). This hypothesis is confirmed when we consider technical illustration and other situations (e.g., engine manuals, anatomy textbooks) where illustrative techniques are considered more effective than a photograph (Healey et al. [3]). Furthermore, Gooch et al. [7] recognized that despite rising salaries and the decreasing costs of computer graphics technology, photography and computers have not replaced artists, illustrators, and draftsmen. In light of this observation, they developed illustrative methods that attempt to automate technical illustration conventions by capturing several systematic principles employed by illustrators.

Since the late 90s', scientific visualization researchers have been experimenting with illustrative techniques to improve the effectiveness of data displays. For instance, Laidlaw [8] describes how he and his students studied art to find inspiration for scientific visualization. Although they studied many oil paintings from the Impressionist period, most of the techniques developed are based on characteristics from the works of a famous Dutch Post-Impressionist artist, Vincent van Gogh. Like van Gogh, Laidlaw's visualization experiments utilized the concept of underpainting and extended the layered approach of Meier [9] to visualize multidimensional data using a painterly rendering technique. This underpainting shows through overlying, detailed brush strokes to give the visualization structure. Furthermore, the underpainting conveys the complexity of the information using icons, geometric shapes, or textures which invite the viewer to experience the scene rather than view it passively [8]. The underpainting technique has been used to visualize a second-order tensor field (with about 6 variables at each data point) of a mouse spinal cord section by Laidlaw et al. [10], and to show 2D fluid velocity with a number of velocity-derived quantities (about 9 values represented at each spatial location) by Kirby et al. [4].

In Healey et al. [3], the authors applied illustrative visualization to weather data analysis. Like Laidlaw, they studied oil paintings from Impressionist artists to find effective methods to encode multiple variables in a single display. More specifically, their research focused on the combined use of color and texture

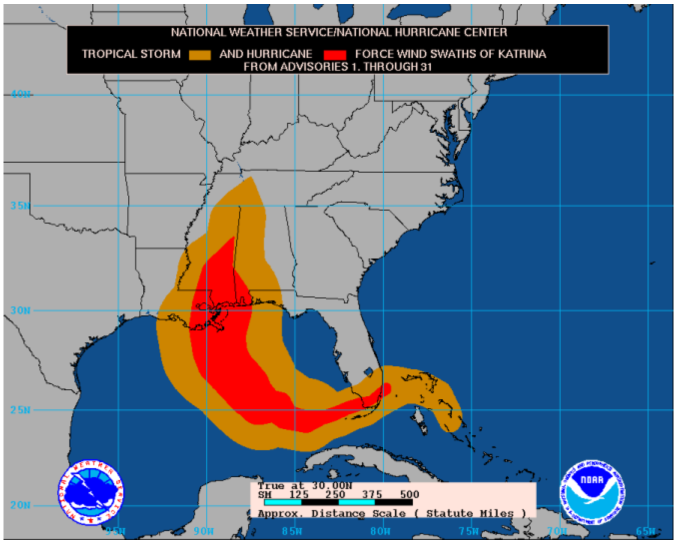

Fig. 2. Plot of the wind swath for Hurricane Katrina in 2005 courtesy of NOAA NHC advisory archive.

to encode multiple attributes in a single display. It is important to note that color and texture are the parameters that artists vary as they apply paint pigment to a canvas. Healey and his colleagues tested their visualization techniques in a system that displays monthly weather conditions by executing a number of human subject experiments. The results of these experiments suggest that the illustrative visualization images were more effective than the traditional side-by-side displays that are usually employed in these types of analyses. In particular, they found that illustrative weather visualization techniques were more effective when the viewer was looking for combinations of weather conditions. Moreover, Lum et al. [11] presented an illustrative technique, called kinetic visualization, that uses particle motion along a surface to illustrate object shape. Illustrative visualization techniques have also been explored extensively in medical visualization, as the recent work by Xie et al. [5] demonstrates.

As stated earlier, the NHC currently publishes graphical advisories on the Internet. As shown in Fig. 2, the wind swath plot is rendered using the advisories up to a certain date and time for a particular hurricane. The wind swaths are rendered by dragging the area affected by the wind along the trajectory of the hurricane and painting the resulting shape as a color-filled polygon. Other graphics are published to show the forecast positions and intensity of the storm over the next 3 or 5 days. Although these graphics are informative, there are several issues that decrease their effectiveness:

- Distributing the information in several separate plots hinders perception and cognition due to our extremely limited memory for information that can be gained from glance to glance – an issue discussed in detail by Rensink [12].
- The current graphics exhibit hard color boundaries which masks the uncertainty of the advisory information.
- The plots that do contain some layered information are opaque which results in the occlusion of information in the underlying layers.
- A consistent color treatment is used despite the fact that the regions that have been most recently affected by the storm are generally more important to the viewer.
- Some of the NHC plots exclude past information, which can provide context to ascertain the storm movement and severity as well as the accuracy of the forecasts.

In the remainder of this paper, we present our new illustrative rendering techniques that consolidate the advisory information into a single visualization and address the issues with the current advisory graphics.

III. NOAA NHC Forecast / Advisory Data

The data used in the current work is from the NHC advisory archive. These advisories contain a listing of the forecast and observation information for a particular tropical or subtropical cyclone. In addition to storm tidal information, the advisory contains a forecast of the storm positions, intensities, and wind fields for 12, 24, 36, 48, and 72 hours from the current time. The NHC issues Atlantic and eastern Pacific tropical and subtropical cyclone advisories every 6 hours; but special advisories may be issued at any time due to significant changes in the storm.

The advisories are issued in an text-based format that is composed of several identifiable sections. Based on the NHC advisory specifications[2], we developed an application to retrieve the advisory statements for a particular storm system for subsequent visualization. In the following sections of this paper, information from the storm advisories issued during the 2005 North Atlantic hurricane season are used.

Although a great deal of information is contained in the advisories, the current work focuses on the wind quadrant radii, or wind swaths. An advisory may contain the wind quadrant radii for tropical storm force winds (34 knots), storm force winds (50 knots), and hurricane force winds (64 knots). The quadrant radii are listed as map coordinates in compass directions radiating out from the center of the storm along the indicated direction and distance given in nautical miles. The following listing shows an example wind radii description.

```
34KT.......140NE  90SE  90SW 130NW
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The above statement means that winds of 34 knots are possible anywhere within the quadrant out to 140 nautical miles northeast (NE), 90 nautical miles southeast (SE), 90 nautical miles southwest (SW), and 130 nautical miles northwest (NW) from the estimated storm center. From these fields, the rendering algorithm discussed in the following section creates wind swath polygons, which are used for simulating the brush strokes of the visualization. Fig. 3 shows the polygon for this wind radii description.

[2]The NHC Advisory Statement Specifications are available online at http://www.nhc.noaa.gov/aboutnhcprod.shtml

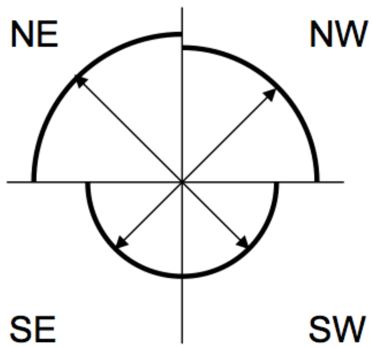


Fig. 3. A polygon generated from the wind quadrant radii description in a NOAA NHC storm advisory. The wind radii are listed as 4 compass directions (northeast, northwest, southeast, and southwest) and distances (measured in nautical miles) that define the geographic area affected by the wind in each quadrant.

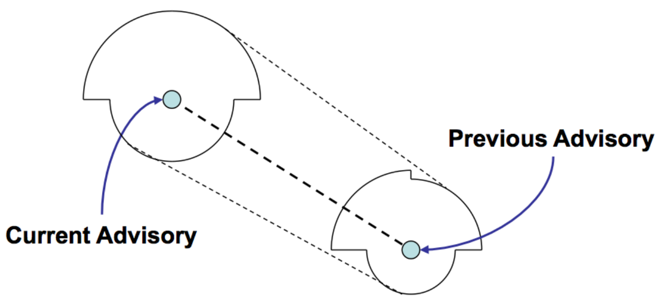


Fig. 4. The NHC advisories' wind quadrant radii are processed in chronological order to create the wind swath polygons. Using the current and the previous advisories, an incremental line drawing algorithm is used to render a line using the polygonal areas as brushes. In the process, the wind swath polygon is morphed from the previous shape to the current advisory shape.

IV. Approach

We have developed a new approach for representing the wind swath information from NHC advisories. After selecting a particular storm from the NHC storm archive, the storm's advisories are read and processed in chronological order. For each advisory, polygonal areas are created for the 34, 50, and 64 knot wind quadrant radii listings.

After calculating the wind swath areas, the rendering algorithm uses these areas as the brush boundaries for drawing strokes along the trajectory of the storm. For each of the 3 wind classes, the strokes are rendered along the trajectory of the storm from the previous to the current advisory. As shown in Fig. 4, the wind swath shape is morphed from its shape at the previous to the current advisory as the algorithm progresses. Using a standard incremental line drawing algorithm similar to the one described by Shirley [13], the wind swath shape is rendered along the storm path by connecting the advisory's estimated center positions. In addition to wind swath rendering, the estimated center position of the storm can be displayed as a line to show the storm track (see the dashed line in Fig. 4).

Three separate images are maintained for each of the wind classes along with an image for the storm track line. When the

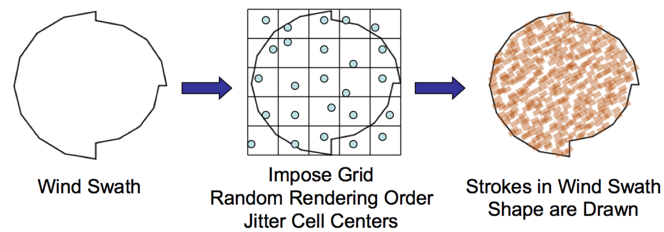


Fig. 5. One method for depicting the wind swath shapes in the storm path rendering is to fill the shapes with many small, randomly placed brush strokes. A grid is superimposed over the wind swath polygon and several small strokes are drawn in each cell. The cells are drawn in random order and the cell center positions are randomly jittered to create a hand-drawn appearance. Also, the orientation of the strokes are determined by the movement direction field from the advisory.

visualization panel regenerates the display, the wind images are drawn over the background image in order of the wind speed beginning with the 34 knot area. The track image is drawn on top of the wind swath images. The resulting visualization highlights the most destructive areas for the viewer by drawing them over the other wind images.

Currently, there are two options available for rendering the interior of the wind swath shapes: a method that fills the shape with small brush strokes and a method that simulates long brush strokes. In addition, a time-based fading effect is applied to the long brush strokes and color labels are used to render the wind swaths in both the small and long stroke methods. The following subsections describe both options in detail.

A. *Small Brush Stroke Method*

One method for rendering the wind swath area is to use small brush strokes, which is similar to the approach taken by Healey et al. [3] to visualize historical weather information. Instead of rendering solid color-filled polygons for the wind swath areas along the storm track, as is done with the current NHC graphical advisories, the wind swath polygon can be used as boundaries for rendering many small, randomly placed strokes. These individual strokes are currently rendered as semi-transparent, rectangular glyphs.

The process of rendering the strokes within the area of the wind swath is illustrated in Fig. 5. First, a regularly spaced grid is superimposed over the wind swath polygon, which dictates where the brush strokes are drawn. Then, a spatial jittering is applied to the brush strokes. For each grid cell, the stroke center point is placed in the center of of the cell. The jittering is then applied by adding noise to the x and y locations independently so that each sample occurs at some random location in the cell area. Only the brush strokes with centers that lie within the wind swath area mask are rendered. The brush strokes are rendered in a random order using a temporal jittering method that reduces the perception of structure in the stroke overlaps.

The spatial and temporal jittering techniques are inspired by Cook's stochastic ray-tracing techniques [14]. These techniques reduce the structure in the wind swath areas, such as the hard polygon boundaries in the current NOAA wind swath

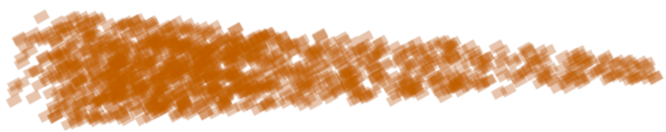


Fig. 6. A straight line drawn using the small stroke filling process. In this case, the shape of the wind swath increases linearly from right to left. The individual brush shapes are rendered as semi-transparent, rectangular glyphs.

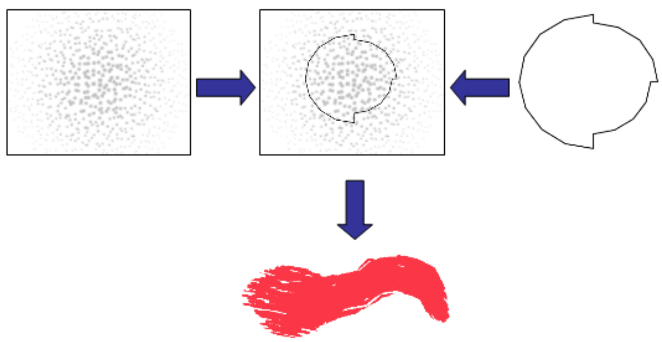


Fig. 7. Illustration of the algorithm used to simulate long strokes for the wind swath areas. The stroke texture is generated procedurally by drawing jittered circles in a regular grid. The wind swath shape is centered in the stroke texture, used to mask the texture, and then the result is applied to the appropriate wind image. The resulting swath rendering resembles the artifacts of a brush with large bristles or several small brushes dragged along the storm track.

graphics (see Fig. 2) that are artifacts of the rendering process. That is, these hard boundaries are not actually in the data from the underlying prediction models. By softening the these boundaries as noise, the underlying data is more perceptually salient.

This process is applied for each increment of the storm track rendering algorithm mentioned in the previous section. In Fig. 6, the result of drawing a line using this algorithm is shown. In this particular example, the wind swath area increases in size from right to left.

B. Large Brush Stroke Method

Another method for filling the wind swath area simulates long brush strokes. The resulting visualization gives the impression that a brush with large bristles or several small separate brushes have been dragged along the storm track.

When the large stroke rendering process is initiated, a texture is generated procedurally for later use. In the current implementation, the texture is created by drawing circles where the radius of the circles are determined by computing the distance from the center of the texture. The circles are drawn on a regular grid using the spatial and temporal jittering techniques discussed in section IV-A. An example of a texture generated by this algorithm is shown the top left image of Fig. 7.

The wind swath polygon for a particular advisory is then used to mask the outer areas of the texture by centering the wind swath polygon on the texture's center. The pixels that lie within the wind swath are transferred to the appropriate wind image for the current advisory position. As the algorithm draws the texture along the storm trajectory, an image of long strokes emerges in the visualization. Fig. 7 illustrates the masking process for simulating the long strokes and provides an example of a storm track generated with this algorithm.

C. Temporal Stroke Fading

In the NHC wind swath graphics (see Fig. 2) there is a consistent color treatment of the filled polygons despite the fact that the areas most recently affected by the storm are generally more important to the viewer. In our long stroke method, a temporal fading of the strokes emphasizes the most recently affected locations while keeping the context of the past storm wind swaths.

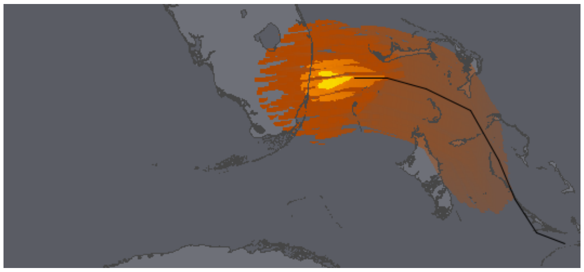
Currently, this feature is implemented with a time counter that is stored for each pixel of the wind image. When a pixel is painted, the time counter is set to the maximum time value. Prior to rendering each swath area, each pixel is visited. If the pixel's time counter is greater than 0, the pixel's alpha value is decreased proportional to the maximum time unit and the time counter is decreased by 1 unit. The maximum and minimum alpha values are used to clamp the new color prior to updating the wind image pixel. Clamping the color's alpha value ensures that the underlying image layers are at least partially visible so that the track does not totally disappear in the visualization.

In Fig. 8, an image sequence captures the resulting temporal fading process as it is applied to the wind swath strokes. In this figure, advisories from the 2005 Hurricane Katrina are used to capture the state of the cumulative wind at three different times as the storm crosses Florida. The temporal fading technique effectively utilizes the lower transparency to distinguish the geographic areas that have been most recently affected by the storm winds.

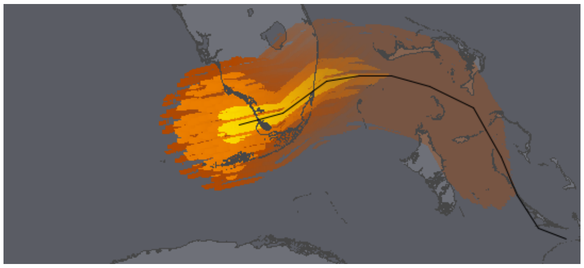
D. Color Labeling

In general, color is best suited for labeling and categorization of information (e.g., Ware [15]). In both the small stroke and long stroke methods described in the preceding sections, the strokes are rendered using a color associated with the wind speed of the wind swath. The color and wind speed combinations are shown in Fig. 9. In this scheme, the 34 knot winds are drawn in a yellow shade, the 50 knot winds are drawn in an orange shade, and the 64 knot winds are drawn in a red shade. In addition to the layered rendering of the wind images, this color scheme emphasizes the most dangerous wind fields.

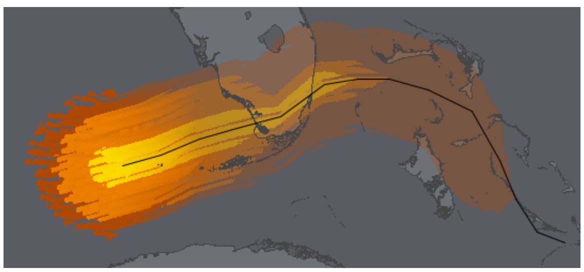
Furthermore, the use of strong colors in the foreground over a dull, muted background in our visualization causes the strong color regions to stand out even more, which emphasizes the areas that are experiencing or have recently experienced the most destructive winds of the storm (e.g., Tufte [16]). Compared to the NHC graphics (Fig. 2), the background is shifted to a bluish gray color, which creates a complementary and an extreme cold-warm color contrast between the background



(a)



(b)



(c)

Fig. 8. In the long stroke method, a temporal fading effect is applied. In this figure, the effect is demonstrated for 3 different points as Hurricane Katrina crossed Florida. As more advisories are drawn the alpha value for the pixels are decreased using a time decay function. The top image (a) is the earliest image, the middle image (b) is some time later, and the right image (c) is the last image in the series. The temporal fading gives the historical context of the storm while emphasizing the most current advisories.

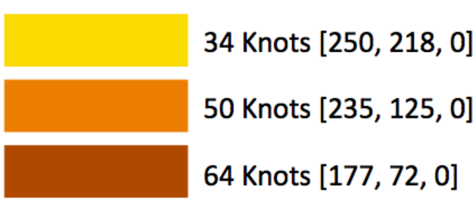


Fig. 9. Strokes within the wind swaths are assigned colors according to the wind speed. These color labels serve to highlight the areas that are subject to more intense winds.

and the wind swath colors. This intensifies the emphasis of the wind swath. Color contrast effects constitute the fundamental resource of color design in graphics; Itten [17] describes them in detail.

V. Results

In Fig. 10, the application of the small brush stroke method to the 2005 Hurricane Katrina storm track is shown. The color labeling helps the viewer identify the area of the most intense winds. Rendering the wind images from lowest wind speed to the highest wind speed ensures that the most destructive wind classes are shown over those that are less destructive.

Rendering semi-transparent glyphs for the individual strokes results in more saturated colors for locations affected for longer durations. Additionally, the more times the wind swath is drawn over a particular area, the more dense the strokes appear. These visual artifacts indicate the amount of time that the storm has dwelt at certain geographic locations. The viewer can find this information using the small brush stroke method by searching the visualization for the areas with dense, highly saturated strokes.

Unlike the long stroke method, the small stroke method allows us to encode additional information using the orientation of the strokes, In Fig. 10, the orientation of the strokes are determined according to the storm movement direction field in the advisory. Additional fields in the statement can be mapped to other visual properties. It is feasible that all of the advisory fields can be mapped to the stroke's visual properties and a single advisory graphic can be distributed rather than several separate graphics.

In Fig. 1, the long brush stroke method has been applied to the Hurricane Katrina storm track. As with the small stroke image, color labeling helps the viewer to determine the wind speed of the wind swath areas. The use of long brush strokes gives a more artistic feel to the visualization result. Furthermore, Fig. 1 also demonstrates the use of the temporal fading effect. Only the areas that have been most recently affected by the storm are drawn at the maximum alpha value. Other pixels have an alpha value that corresponds to the time that has passed since the pixel was last painted. The faded long stroke visualization gives emphasis to the most recently affected areas while also providing the full context of the storm track.

The small and long stroke methods can also be applied to multiple storm tracks to produce images that highlight patterns and similarities in the storm tracks. In Fig. 11a, the storm tracks for Tropical Storm Arlene, Tropical Storm Bret, Hurricane Cindy, Hurricane Dennis, Hurricane Emily, Tropical Storm Gert, Tropical Storm Jos̃e, Hurricane Katrina, Hurricane Ophelia, and Hurricane Rita are shown using the small brush stroke method. In this image, the tight clustering of most intense wind swath glyphs in the area of the Louisiana, Mississippi, Alabama, and western Florida coasts reinforces the destructive effects of the 2005 season on this particular region. Furthermore, this image also highlights an area in the southeastern Gulf of Mexico which experienced the most intense winds from several storms as they each passed over this general vicinity.

In Fig. 11b, the long stroke method is applied to the same storms from the 2005 season. However, in this case the animation of the season was stopped after the September 23 advisory for Hurricane Rita to capture the temporal shading effect. Here the color saturation and luminance emphasis on the most current advisory information intensifies the Rita advisories just prior to the storm landfall in Louisiana. Like

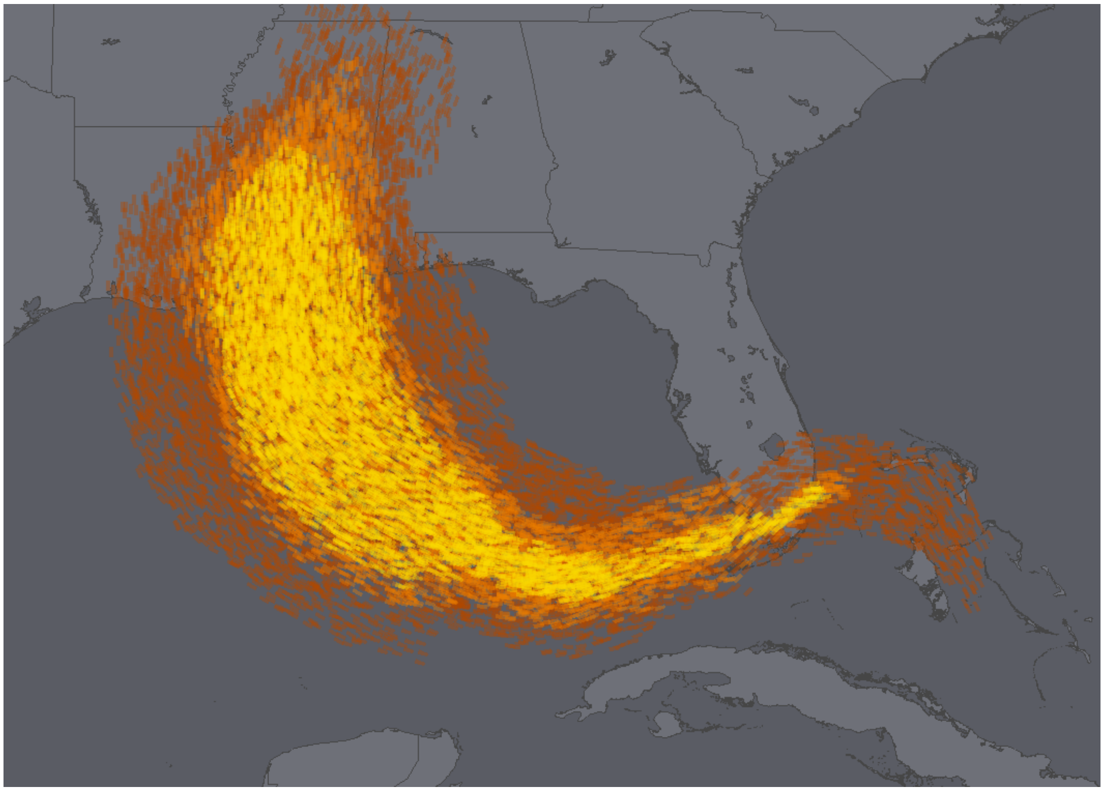


Fig. 10. Using the NHC advisories from the infamous 2005 Hurricane Katrina, our small brush stroke technique is demonstrated for all the archived NHC advisories. The dense packing and large coverage area of the most intense wind swaths are indicative of relatively slow motion and the large size of the storm, respectively. These factors reinforce the devastating impact of this historical storm.

the small brush stroke method, the areas that received intense winds from multiple storms are highlighted. Also, this figure shows the storm tracks, which helps the viewer ascertain individual storm behavior.

VI. Conclusion

We have formulated new illustrative techniques for representing wind swath information in the NHC's hurricane advisory statements. Our approach yields enhanced graphics that overcome many perceptual and cognitive issues in the current NHC graphical products. Specifically, our techniques make the following improvements to the current advisory graphics:

- Our techniques facilitate the encoding of more advisory information in a single image, thereby avoiding human memory limitations.
- The algorithm employs jittering techniques to improve the perception of the information by softening the edges in a manner more reflective of the propagated uncertainty from the underlying storm models.
- The color contrasts, temporal fading effects, and semi-transparency effects that are applied to the glyphs draw the viewer to the most important areas of the visualization and maintain the context of the historical storm track.

In the future, we will expand this research to encode additional information from the advisory statements in the illustrative visualization. For example, it would be beneficial to include the 3-day and 5-day forecast positions and wind swaths for the storm as the track is rendered. Also, the brush rendering techniques will be refined and expanded to address more sophisticated artistic effects like watercolor or pencil strokes. In order to validate our claims of increased effectiveness, we plan to conduct user studies to compare our approach to conventional plots. Our current visualization techniques and these planned future expansion promise to significantly increase the effectiveness of the storm graphics and increase the public awareness and understanding of these vital hurricane advisory statements.

Acknowledgment

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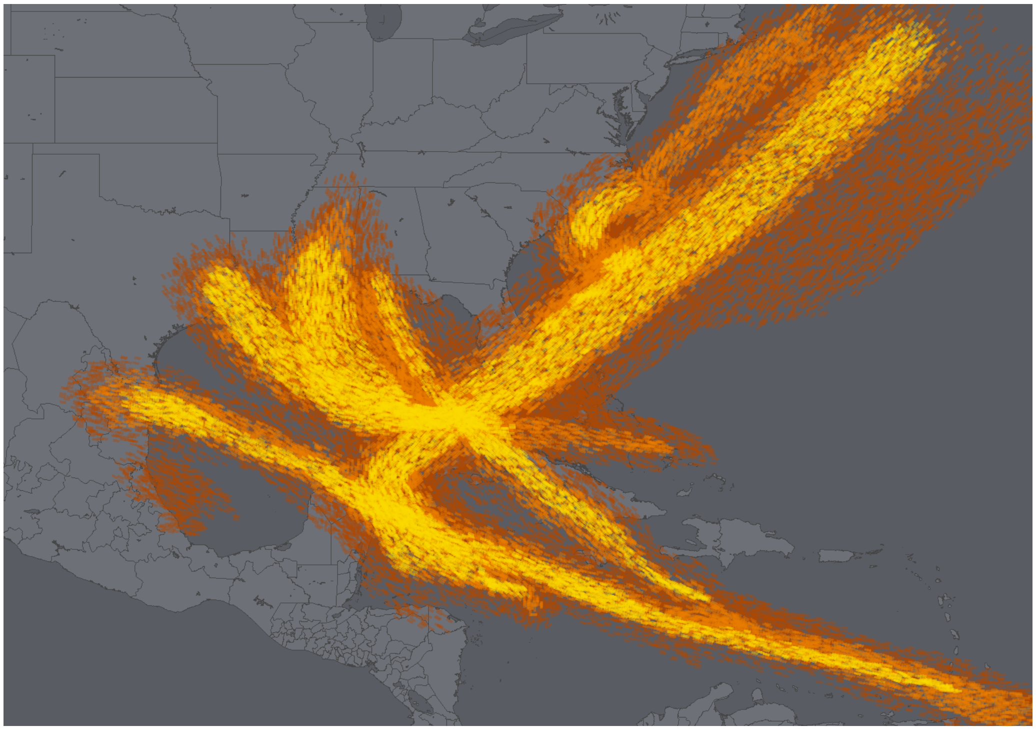
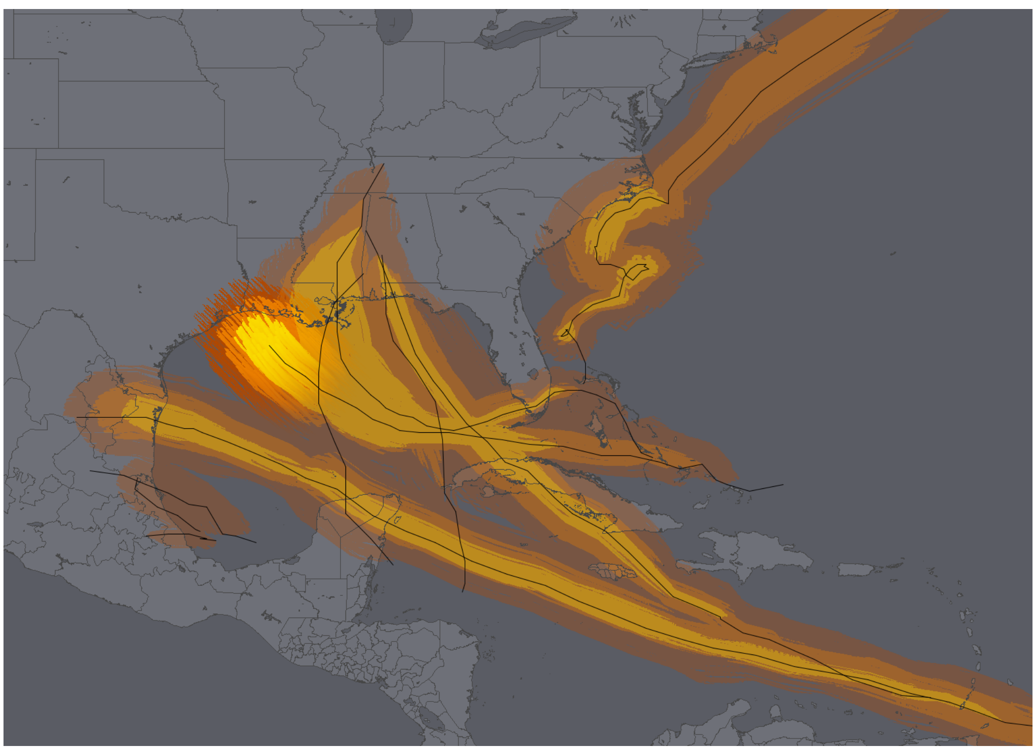


(a) Small Brush Strokes



(b) Long Strokes

Fig. 11. Our illustrative visualization techniques are applied to 10 storm tracks from the 2005 hurricane season. The following storm tracks were used in these images: Arlene (TS), Bret (TS), Cindy (H), Dennis (H), Emily (H), Gert (TS), Jose (TS), Katrina (H), Ophelia (H), and Rita (H). In (a), the small brush method has been applied to all 10 storms. In (b), the long stroke method has been applied to the storm advisories through the September 23 Hurricane Rita advisory.

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