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Visualizing Magnitude and Direction in Flow Fields

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Visualizing Magnitude and Direction in Flow Fields

BY

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THESIS

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5-14-2012

Date

Dedication

To my Wife, Christine, and my Daughters Alaina and Jenny.

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I wish to thank my thesis director, Colin Ware for his generous help and patience with this research and researcher, thesis committee member Matthew Plumlee for coding assistance and much more, and Dan Bergeron for all his help and guidance. Special thanks to John Kelly for advice on matters meteorological, as well as Brendon Hoch at Plymouth State University. Olivia McGlone did an excellent job of running the participants though the study. This work was supported by NOAA Grant # NA05NOS4001153.

Foreword

Chapter 1 of this thesis consists of a paper that has been submitted for publication [Pilar12].

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ABSTRACT

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David H.F. Pilař
University of New Hampshire, May, 2012

In weather visualizations, it is common to see vector data represented by glyphs placed on grids. The glyphs either do not encode magnitude in readable steps, or have designs that interfere with the data. The grids form strong but irrelevant patterns. Directional, quantitative glyphs bent along streamlines are more effective for visualizing flow patterns.

With the goal of improving the perception of flow patterns in weather forecasts, we designed and evaluated two variations on a glyph commonly used to encode wind speed and direction in weather visualizations. We tested the ability of subjects to determine wind direction and speed: the results show the new designs are superior to the traditional. In a second study we designed and evaluated new methods for representing modeled wave data using similar streamline-based designs. We asked subjects to rate the marine weather visualizations: the results revealed a preference for some of the new designs.

Chapter 1

Introduction

Weather visualizations are needed by a wide audience, and there are many operationally generated weather models, such as the North American Mesoscale Model (NAM) run by the National Centers for Environmental Prediction (NCEP), and the Wavewatch III model for marine conditions run by the National Oceanic and Atmospheric Administration (NOAA) and NCEP. Websites and television broadcasts present graphic visualizations of the data generated from those models several times every day. In many cases, a large number of variables, such as wind speed and direction, wave height, direction and period, air and water temperature, barometric pressure, humidity and more need to be displayed and interpreted quickly and accurately. For the captains of ships or pilots of airplanes this information may increase the safety of their passengers, crew, or cargo and help conserve fuel. Common weather forecast images such as those found at Nowcoast, see Figure 1-1, Weather Underground, WavewatchIII, see Figure 1-2(b), and NCAR use specialized glyphs or arrows arranged in grids that show magnitude or direction at sparse locations, but do not show continuous patterns well. Visualization research has developed methods, such as streamlines [Turk96, Jobard97], that show part of the patterns well, but do not simultaneously show direction and magnitude patterns. These visualizations can be improved to show more complete patterns by using well designed glyphs that encode both direction and readable, discrete-magnitudes and are drawn along evenly spaced streamlines.

According to Ware [Ware04] , the human visual system seeks out patterns. Those patterns are easily seen in some representations, but invisible in others. Consider the repre-

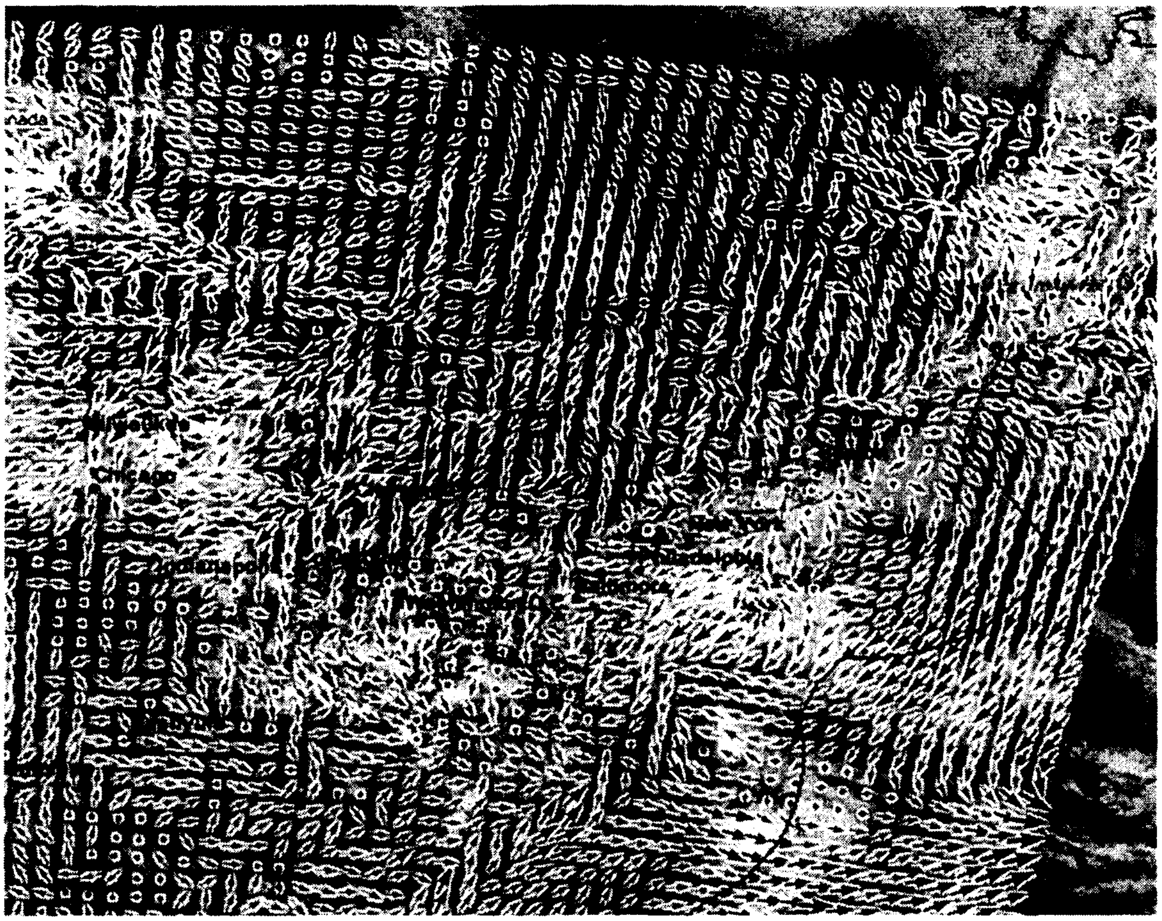


Figure 1-1: Nowcoast using variable sized, color coded arrows for wind speed and direction (nowcoast.noaa.gov).

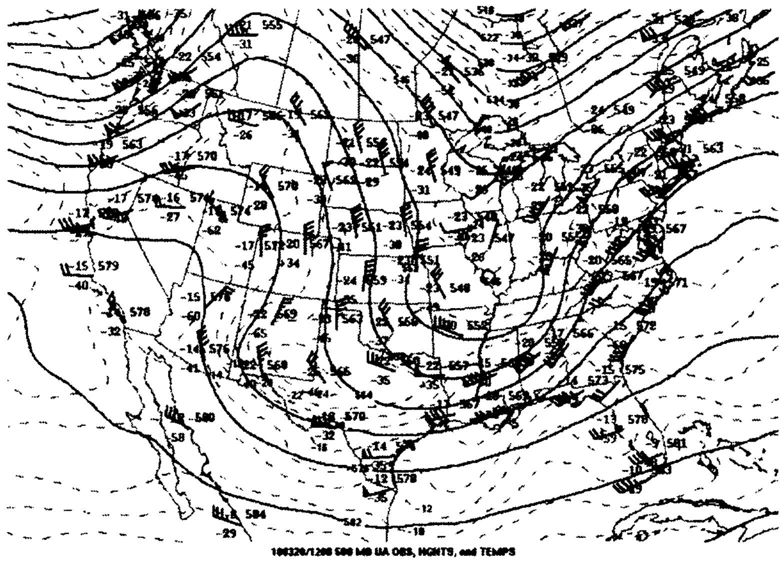
sentation of a river on a street map, it is normally just a colored line indicating a location pattern, with no information about flow direction or magnitude. On a map designed for recreational enthusiasts, a representation of that same river might include arrows indicating solely the downstream flow direction and areas of rapids, and if the map were designed for an environmental agency studying the advection of pollutants through a watershed, even more detail of flow direction and velocity would be required to indicate fine direction and magnitude patterns such as eddies where pollutants might collect. Similarly, the pattern detail requirements of an individual planning a morning commute differ from the requirements of a ship captain planning the safest, most fuel efficient route for their vessel. In the most common weather maps, however, most of the fine detail patterns of wind and waves are invisible, see Figure 1-2.

Visualization research has produced a variety of techniques for representing vector fields. Following is a summary of some of those techniques.

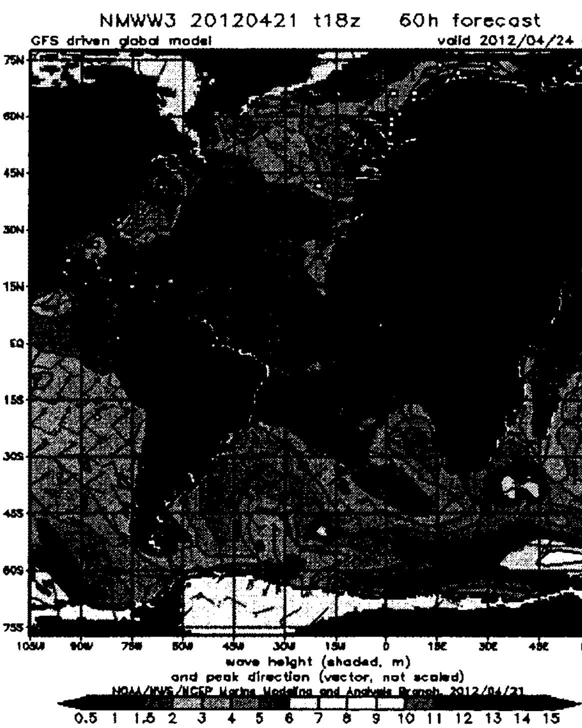
A color background is often used to encode scalar values such as wave height, wind speed or air temperature, and can be a powerful tool to show patterns of magnitude in data. However, at most 12 separable steps may be used before significant errors occur [Ware04], with 6 steps being preferable. Color is not a good choice to show a large range of magnitudes in small steps. Colors must be carefully chosen if color blind people are to be able to read the display, further reducing the set of available steps. As opposed to gray-scale sequences, color sequences are not ordinal [Ware04], except in certain short sequences, so the pattern order of magnitudes are generally not intuitive throughout a large color sequence. Since color does not indicate direction (unless mapped to a key to the exclusion of magnitude) some indication of direction is needed. Use of color sequences for more than one variable should be avoided [Ware04], since simultaneous contrast can lead to errors in interpreting values, and another means such as texture should be used instead.

Textures, like color, may be used to encode magnitude [Bertin83, Ware10]. Textures have the ability to show readable magnitude, they do not interfere with color schemes, and they can be separable from each other and therefore readable from a key across field of textures. As with color, however, the use of texture is limited in the number of discrete steps that can be shown, and textures do not encode direction. Plain roman numerals could be used to encode discrete magnitude in combination with arrows, streaklets, triangles or other directional glyph, but many displays already contain text and numerals used for place names or depth or pressure etc, so the display may rapidly become cluttered.

Arrows and other glyphs are traditionally arranged in a grid, an arrangement which has been shown to have drawbacks. In an evaluation of six flow visualizations Laidlaw [Laidlaw05] found arrows drawn on a regular grid to be particularly poorly suited for judg-



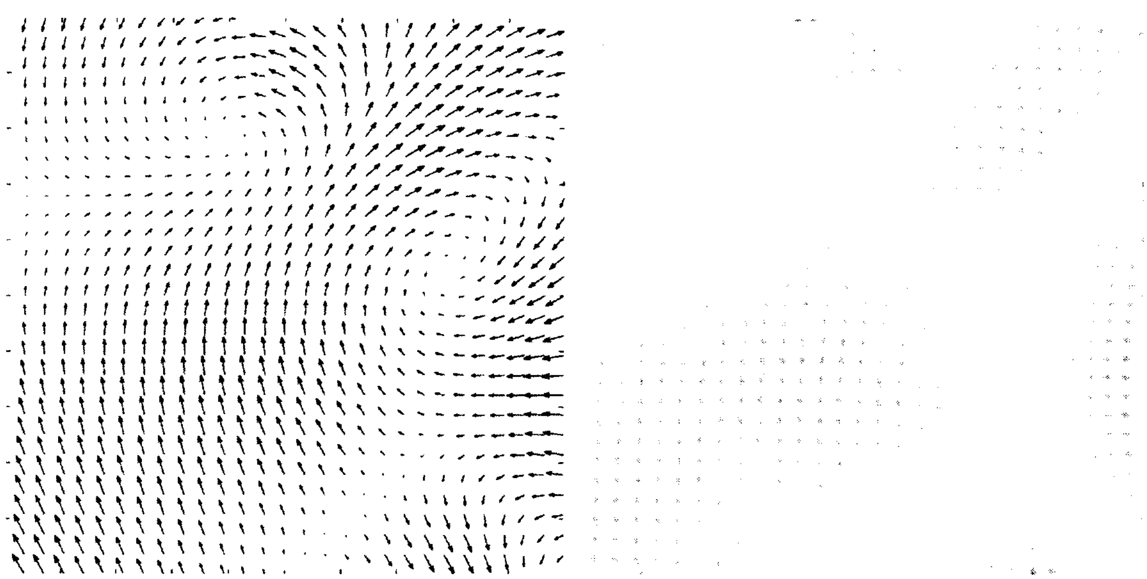
(a)



(b)

Figure 1-2: Common Weather Visualizations. a) A severe weather visualization from `http://www.erh.noaa.gov/gsp` b)Wavewatch III product viewer at `http://polar.ncep.noaa.gov/waves`.

ing advection pathways, see Figure 1-3. A key component of the problem is that the grid is itself a pattern that has no meaning with regard to the data: Figure 1-3(b) is the same image as 1-3(a), blurred using a Gaussian function. The resulting image shows that the grid pattern is more heavily encoded than the direction pattern. Shifting or jittering the grid has been thought to alleviate the problem of false pattern to some degree [Laidlaw05], but Laidlaws user study found there was not much difference in task performance between the two methods.



(a) (b)

Figure 1-3: The grid Pattern. a) Arrows on a grid. Image courtesy of David Laidlaw. b) Arrows on a grid, blurred with a Gaussian function with radius 3.8 px allows the dominant pattern of the grid to be more apparent.

In order to discuss pattern components in the context of existing research into flow visualization, it is useful to decompose the concept of direction into two components: orientation and sign [Ware08]. In a 2D vector field, orientation refers to the angle of the line segment used to represent a vector. If a segment is oriented between east and west, as in Figure 1-4(a), there is no way to tell if the vector points east or west. The additional component of sign is necessary to determine whether that segment points from east to west or from west to east. Figure 1-4(b) shows two arrows where the shaft represents the orientation component, and the arrow head provides the sign component. Bertin [Bertin83] suggested that arrows are effective because they contain a greater weight at the head, and Ware [Ware08] argued that a perceptual mechanism supporting this may be found in end-stopped neurons of the primary visual cortex.

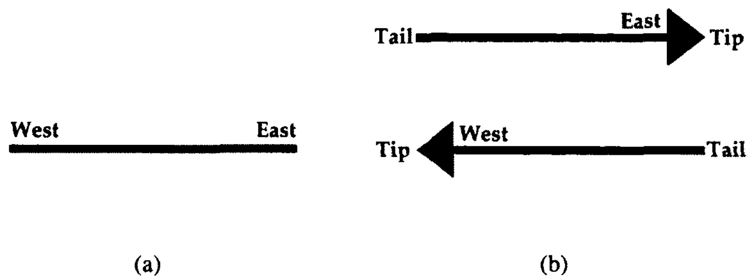


Figure 1-4: Sign and Orientation. a) A line segment in a 2D plane that is oriented east-west or west-east. b) Arrow heads are used to encode sign so that an east-west oriented line segment can be specifically east to west or west to east.

Line Integral Convolution, or LIC, proposed by Cabral [Cabral93], is a vector field visualization method that filters a band limited noise image "along local streamlines defined by an input vector field and generates an output image", see Figure 1-5. LIC encodes orientation, but the method fails to encode information about sign and it does not show relative magnitude let alone discrete magnitudes. Because LIC does not encode sign, the task of advection is not possible. In fact, the only task where LIC performs well is locating critical points precisely, but it is not possible to classify those critical points without sign and magnitude cues [Laidlaw05].

OLIC [Wegenkittl], for Oriented Line Integral Convolution, is a variation on LIC that uses lower frequency textures for convolution which results in a lower frequency (more sparse) image. OLIC encodes sign by fading the traces as they age, and encodes magnitude (speed) by varying the length of the pixel traces, however, OLIC does not encode magnitude in readable steps.

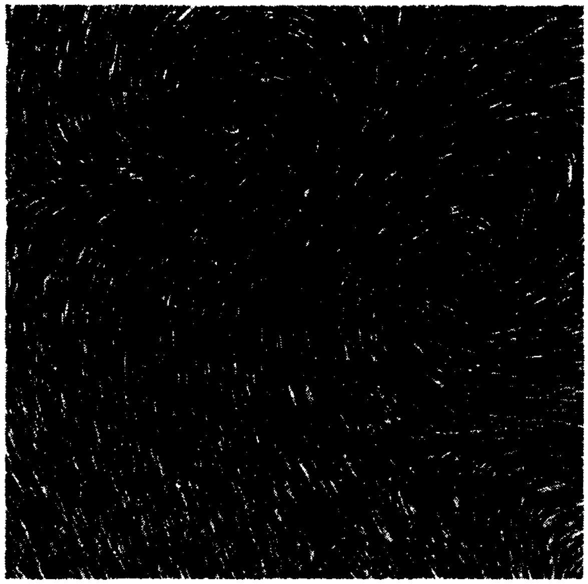


Figure 1-5: Line Integral Convolution. Critical points may be located with precision, but lack of direction and magnitude cues make accurate classification of the critical points impossible.

Another method, referred to as LIT by Laidlaw [Laidlaw05], randomly seeds icons throughout the vector field, keeping only those seeds that result in some defined maximum front-to-back overlap and minimum side-to-side separation. The icons maintain a consistent base to height ratio of 1 : 4 but vary in size based on magnitude, with higher magnitudes being represented by larger triangles. The resulting image shown in Figure 1-6 has the glyphs essentially arranged in lines, head-to-toe. This arrangement shows orientation and sign, suits advection, critical point location and critical point identification well, and shows patterns of relative magnitude, but does not allow discrete magnitude identification.

Streamlines show orientation patterns and critical points well, and can show relative magnitudes by varying the width of the line, but they do not show discrete magnitudes and they do not show sign. However, unlike LIC, streamlines may be drawn sparsely enough to use for glyph placement, yet densely enough to preserve patterns. Streamlines are well suited for showing vector field orientation [Jobard97, Laidlaw05, Turk96], and there are efficient algorithms that enable equally spaced streamlines to be constructed

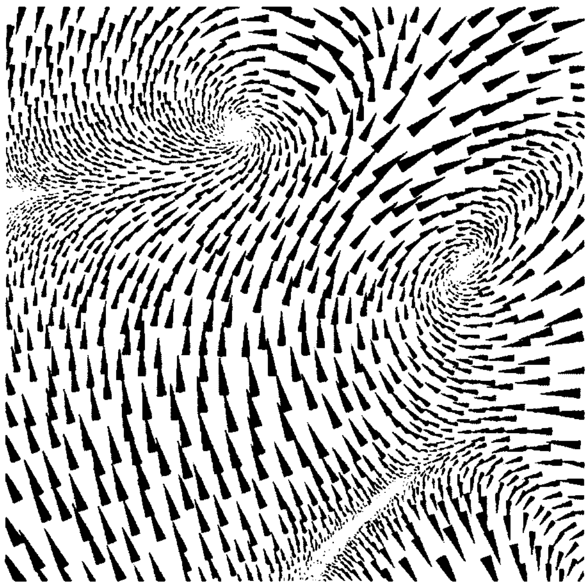


Figure 1-6: LIT: randomly seeded, selectively kept triangles. Critical points may be located with precision, but lack of direction and magnitude cues make accurate classification of the critical points impossible. Image courtesy of David Laidlaw.

[Jobard97, Lui06]. A number of authors have proposed that directional glyphs should be drawn head-to-toe, bent along the flow direction using streamlines to guide placement [Jobard97, Laidlaw05]. Pineo and Ware [Pineo10] showed that this organization best stimulates contour detection mechanisms in the primary visual cortex and argued that this supports both the task of streamline tracing and the judgment of wind orientation at an arbitrary point on a map. Figure 1-7 shows arrows drawn along evenly spaced streamlines according to Turk and Banks [Turk96]. If the arrows were to vary in width and height based on the flow magnitude similar to the streaklets proposed by Mitchell [Mitchell83] or the triangles in LIT [Laidlaw05], this visualization would capture the magnitude patterns in the flow, i.e. the faster areas of flow would appear denser, but there would be no indication of how quickly the flow is moving at any particular point. The addition of a key would not help because the human vision system judges relative size well, but not absolute size; i.e. we can judge an arrow to be smaller than, larger than, or the same size as its neighbor, but we can't accurately make the same judgment between two arrows in separate areas of the flow. To support this last task, a glyph that encodes both direction and readable magnitude is needed.

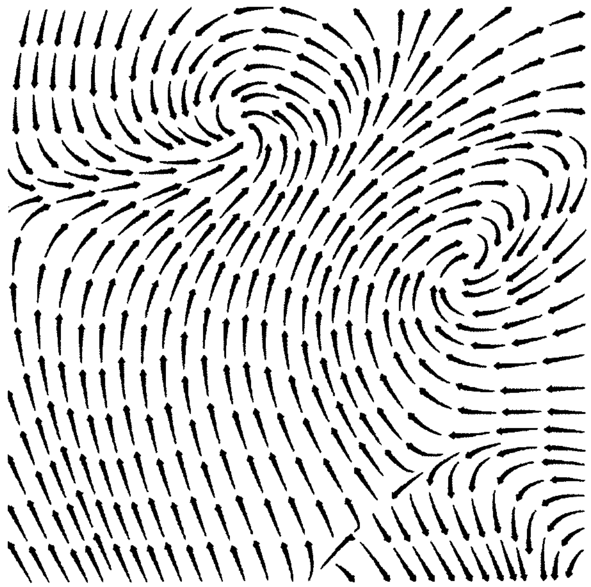


Figure 1-7: Arrows drawn along image guided streamlines. Patterns of orientation and sign as well as critical points can be seen. No representation of relative or discrete magnitude.

Many attempts have been made to encode direction and magnitude simultaneously with glyphs. One approach is to color code the glyphs, but color schemes can only include about 6 to 12 separable steps without incurring significant errors [Ware04], and those colors must be carefully chosen if color blind people are to be able to read the display. Color coding glyphs may also make them difficult to read due to simultaneous contrast if color is used for a background, or for the representation of another variable. The human visual system is not a light meter, and we do not perceive color absolutely, so the exact same color may appear brighter, darker, or of another hue depending on its proximity to another color [Ware04].

Several authors have proposed varying the height and/or the width of arrows according to magnitude [Laidlaw05, Sawant07]. That solution can be visually pleasing and shows patterns of relative magnitude well, since the pattern will be more dense in areas of higher magnitudes. But, similar to the problem with color, we do not perceive absolute sizes well, rather we see relative sizes, i.e. we can not accurately match the size of an arrow with a key because two identical arrows may appear to be different sizes based on their surroundings [Ware04].

Streaklets have been shown to be superior to arrows in encoding direction [Pineo10], and may be varied in size according to magnitude. The resulting displays show magnitude patterns very well, but the same problems of readable discrete magnitudes exist as with variable sized arrows.

The wind barb [Wiki09], illustrated in Figure 1-8 is a common glyph used in weather visualizations for meteorologists. It was designed to show direction and magnitude at a discrete location indicated by its tip. The magnitude is encoded by elements located at the tail. The basic wind barb design has a shaft oriented in the wind direction and a set of bars and/or pennants to encode speed in 5 knot intervals. Each half bar encodes five knots and each full bar encodes 10 knots. The triangular pennant encodes 50 knots. The direction of the wind is from the tail (the part with the bar and pennants code) to the tip. The point of measurement for both magnitude and orientation is at the tip. The speed code is easy to read and to learn, and wind barbs are a standard feature of meteorological maps. However, wind barbs have several design features that interfere with the representation of wind direction and regional wind patterns. First, locating the weight of the wind barb at the back is opposite to the recommendations of Bertin [Bertin83] and Ware [Ware08] so the untrained observer might believe the wind to be headed 180deg from the true direction, or believe it functions like a weathervane that heads into the wind [Martin08], which it does not. Second, the bars and pennants create their own orientation pattern at approximately 45 degree angles to the flow. Bars also introduce sharp changes in contour direction that break continuity and make it difficult to identify patterns such as wind fronts, or cyclones. Third, wind patterns curve continuously but because of its long straight shaft, only a very small part of the wind barb contour is actually aligned with the wind direction.

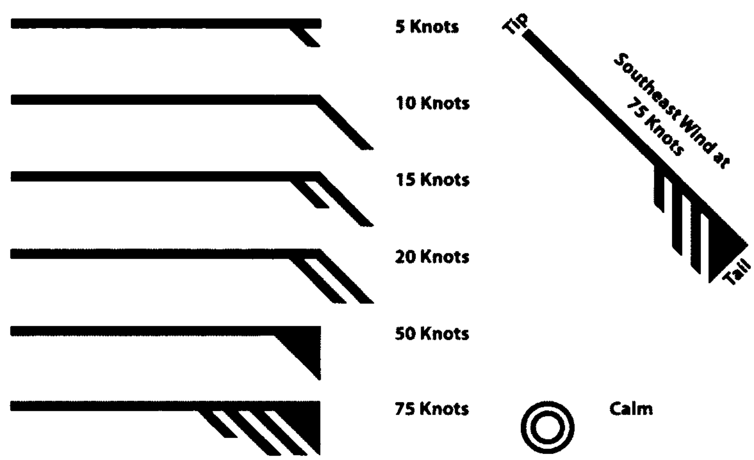


Figure 1-8: The classic wind barb glyph commonly used in meteorological visualizations.

Martin et al. [Martin08] showed that users tend to underestimate wind speeds and show a consistent counter-clockwise bias in estimating wind direction when using wind barbs (shown in Figure 1-8) arranged on a grid. This bias persisted even when the wind barbs were flipped along the shaft so that the coding elements at the tail pointed to the opposite side.

We are left with a fundamental problem: there are glyphs that encode magnitude in discrete steps, but do not show direction and magnitude patterns well. There are methods such as variable sized arrows drawn along evenly spaced streamlines that show magnitude and directional patterns well, but do not encode magnitude in discrete steps.

This thesis consists of two parts that examine several methods for representing flow data that combine the virtues of the wind barb in the representation of quantity with the virtues of flow visualization methods that better show sign, orientation, and magnitude patterns. Chapter two is the reproduction of a paper dealing with wind visualization that has been submitted to IEEE-TVCG for publication [Pilar12]. The paper introduces three designs to address the need for better pattern representation and readability: two adaptations of the wind barb, and a new design called the wind arrow. Chapter 3 applies the concepts from Chapter 2 to a new domain, water wave visualization, and uses orthogonal streamlines and orthogonally arranged glyphs to encode wave height and direction. Chapter 3 also explores an animated application for the wind glyphs from chapter 2 and introduces a new wave front animation as well. Chapter 3 forms the basis for a future paper on wave data visualization. Chapter 4 concludes the thesis.

Chapter 2

Building a Better Wind Barb[1]

Most professional wind visualizations show wind speed and direction using a glyph called a wind barb. Research into flow visualization and glyph design has suggested better ways of visualizing flow patterns, but the application of such techniques has yet to make its way into the weather domain. We argue that these methods lack a key property–unlike the wind barb they do not accurately convey the wind speed. With the goal of improving the perception of wind patterns and at least equaling the quantitative quality of wind barbs, we designed two variations on the wind barb and designed a new quantitative glyph. All our new designs space glyph elements along equally spaced streamlines. To evaluate these designs we used a North American mesoscale forecast model. We tested the ability of subjects to determine direction and speed using two different densities each with three new designs as well as the classic wind barb. In addition subjects judged how effectively each of the designs represented wind patterns. The results showed that the new design is superior to the classic, but they also showed that the classic barb can be re-designed and substantially improved.

2.1 Introduction

MODERN weather visualizations normally indicate wind speed and direction using a glyph called a wind barb [Wiki09]. The basic wind barb design has a shaft oriented in the wind

[1]This chapter is a reproduction of Pilar and Ware [Pilar12]

direction and a set of bars and/or pennants to encode speed in 5 knot intervals (Fig. 2-1). Each half bar encodes five knots and each full bar encodes 10 knots. The triangular pennant encodes 50 knots. The direction of the wind is from the tail (the part with the bars and pennants codes) to the tip. In the weather displays (e.g. Fig. 2-2), wind barbs are either drawn on a regular grid or at the locations of wind measurement stations with the measurement location given by the position of the barb tip.

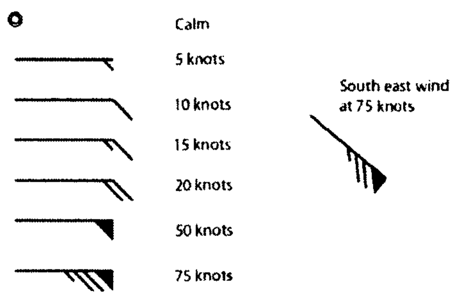


Figure 2-1: The wind barb glyph code used in meteorological maps

The 5 knot code of the wind barb means that they can be read to an accuracy of +/- 2.5 knots. The speed code is easy to read and to learn, and wind barbs are a standard feature of meteorological maps. However, wind barbs have several design features that interfere with the representation of wind direction and regional wind patterns.

In the present paper we report on an effort to develop a method for representing wind data that combines the virtues of the wind barb in the representation of quantity with the virtues of flow visualization methods that better show overall wind patterns.

We begin with an analysis of the strengths and weaknesses of different methods that have been developed to represent flow patterns in comparison with the wind barb. We organize our analysis around a breakdown of the components of a 2D vector. Vectors are usually defined in terms of two components: direction and magnitude. For the purposes of analyzing the effectiveness of flow visualization it is useful to break the concept down even further, separating direction into two parts, orientation and sign [Ware08]. The orientation is simply the angle as expressed by a line segment, and the sign differentiates the two ends of that line segment. A streamline trace, for example, shows orientation at every point along its length, but no direction. Arrowheads are one method for encoding direction.

2.1.1 Orientation

With a wind barb the shaft orientation indicates wind orientation at the tip location. There are a number of perceptual problems with this. Firstly, untrained observers may judge wind orientation to occur in the middle of the barb, or at some other point, perhaps even the tail where the visual weight is greatest. Secondly, the bars and pennants create their own orientation pattern at approximately 45 degree angles to the flow. Bars also introduce sharp changes in contour direction that break continuity and make it difficult to identify patterns such as wind fronts or cyclones. Thirdly, wind patterns curve continuously but because of its long straight shaft, only a very small part of the wind barb contour is actually aligned with the wind direction.

Streamlines are well suited for showing vector field orientation [Jobard97, Laidlaw05, Turk96] and there are efficient algorithms that enable equally spaced streamlines to be constructed [Jobard97, Lui06]. A number of authors have proposed that directional glyphs should be drawn head-to-toe, bent along the flow direction using streamlines to guide placement [Jobard97, Laidlaw05]. Pineo and Ware [Pineo10] showed that this organization best stimulates contour detection mechanisms in the primary visual cortex and argued that this supports both the task of streamline tracing and the judgement of wind orientation at an arbitrary point on a map.

In an evaluation of six flow visualizations Laidlaw et al. [Laidlaw05] found arrows drawn on a regular grid to be particularly poorly suited for judging advection pathways. Part of the problem is that the grid is itself a pattern that has no meaning with regard to

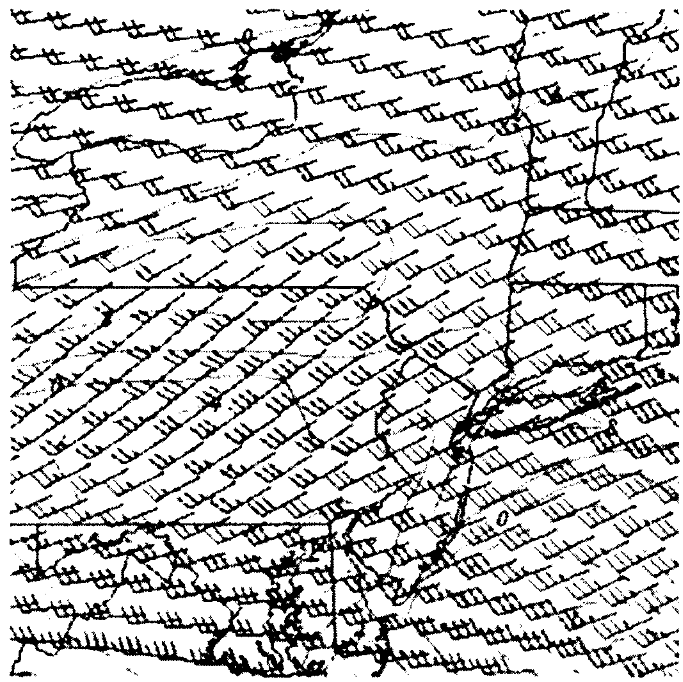


Figure 2-2: The output from a wind forecast model obtained from a NOAA website.

the data. Fig. 2-2 for example shows strong oblique patterns in the upper part of the map that have nothing to do with the flow direction. These patterns are artifacts of the grid and they contain a stronger orientation signal than do the individual wind barbs that make up the pattern. Shifting or jittering the grid has been shown to alleviate the problem of false pattern to some degree [Laidlaw05].

2.1.2 Direction Sign

Bertin [Bertin83] suggested that arrows are effective because they contain a greater weight at the head and Ware [Ware08] argued that a perceptual mechanism supporting this may be found in end-stopped neurons of the primary visual cortex. The wind barb, however, has its greatest visual weight at the tail of the barb and may be confusing to the non-expert for this reason.

2.1.3 Magnitude

In order to show wind speed effectively a method is required that maps wind speed to some monotonically increasing visual attribute, such as line width or line weight [Ware04]. Wind barbs achieve this to some extent, because barbs representing stronger winds tend to have more bars or pennants, increasing their visual weight. Nevertheless, many of the methods developed by the visualization community are far better at representing the pattern of wind speeds, for example by varying the line weight, the degree of contrast, or the glyph size [Bertin83, Fowler89, Healy83, Mitchell83]. Another method for showing wind speed is to use the background color to encode wind speed; this can be effective if it is done using a perceptually monotonically increasing scale [Ware88]. Still, color coding speed is not always possible because color may be needed to show some other scalar variable, such as surface temperature.

The greatest strength of the wind barb, presumably the reason why it is so widely used, is that it is quantitative in a way that most visualization techniques are not. Arrow length, glyph size, line width and other smoothly varying visual attributes used to convey speed all suffer from the same perceptual problem, namely simultaneous contrast [Ware04]. The visual system is very good at judging relative size, color or texture density, but it is very poor at judging absolute size, color or density; these properties are altered by contrast with surrounding elements and this can lead to systematic errors [Ware04].

Our study had both a design phase and an evaluation phase. In the design phase we evolved a series of new designs, each of which incorporated some change that improved on the previous one. We took advantage of design principles suggested by previous work.

2.2 Design

We started with the assumption that it should be possible to create a method that combined the virtues of wind barbs in encoding a clearly readable wind speed, with the virtues of streamlines in encoding orientation and showing the wind patterns.

Our design goals were as follows.

1. Create a coding that, like the classic wind barb, enables wind speeds to be read with an accuracy of +/- 2.5 knots.

2. Make the wind orientation and direction patterns as clear as possible.

3. Make the wind speed pattern as clear as possible. Ideally the viewer should see at a glance where the areas of high and low wind speeds are located.

4. Show as much wind orientation pattern detail as possible.

We carried out a staged approach to the re-design. First we were interested in seeing if the classic barb could be re-designed to show the wind patterns better.

2.2.1 Design 1: Bent, Aligned Wind Barbs

Since wind barbs are so well established in wind visualization we explored designs that retained the basic coding scheme. The design has the following features.

- The shaft of the barb is curved so that it conformed to a stream-line.
- Curved barbs are placed head-to-tail along an extended streamline created using the Jobard and Lefer algorithm [Jobard97].
- To create greater visual density where wind speeds are stronger, the width of the line making the streamline is increased according to wind speed. Dotted lines are drawn for speeds less than 7.5 knots.

This design is illustrated in Fig. 2-3b, 2-4(b) and 2-5(b). For these barbs, the point of speed measurement is at the head as it is for the classic barb.

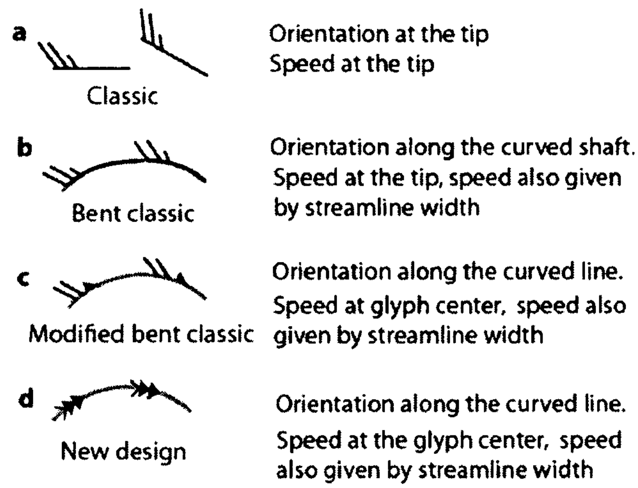


Figure 2-3: The four designs that we evaluated. (a) The classic wind barb. (b) The classic with a curved shaft. (c) Modified classic on a streamline. (d) The new arrow glyph design on a streamline.

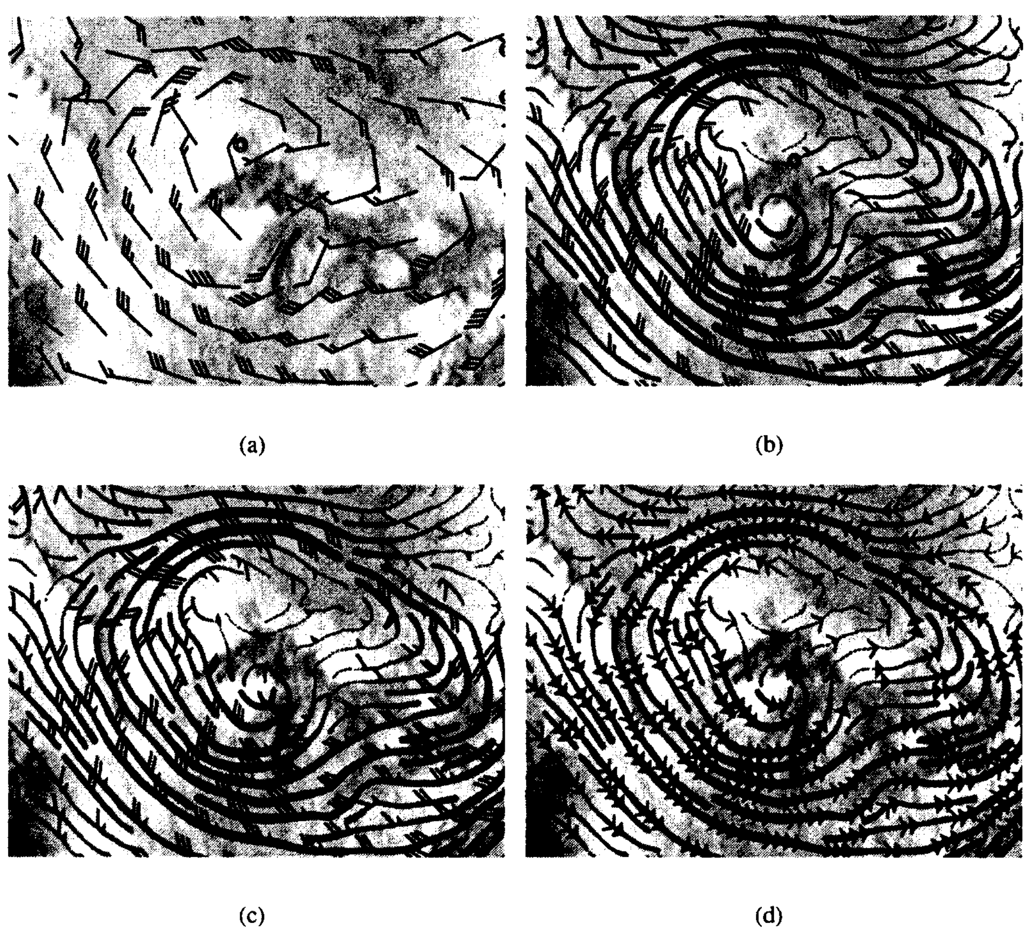


Figure 2-4: Low density representations from top: (a) The classic wind barb drawn on a grid; (b) The classic with a curved shaft; (c) Modified classic on a streamline; and, (d) The new arrow glyph design on a streamline.

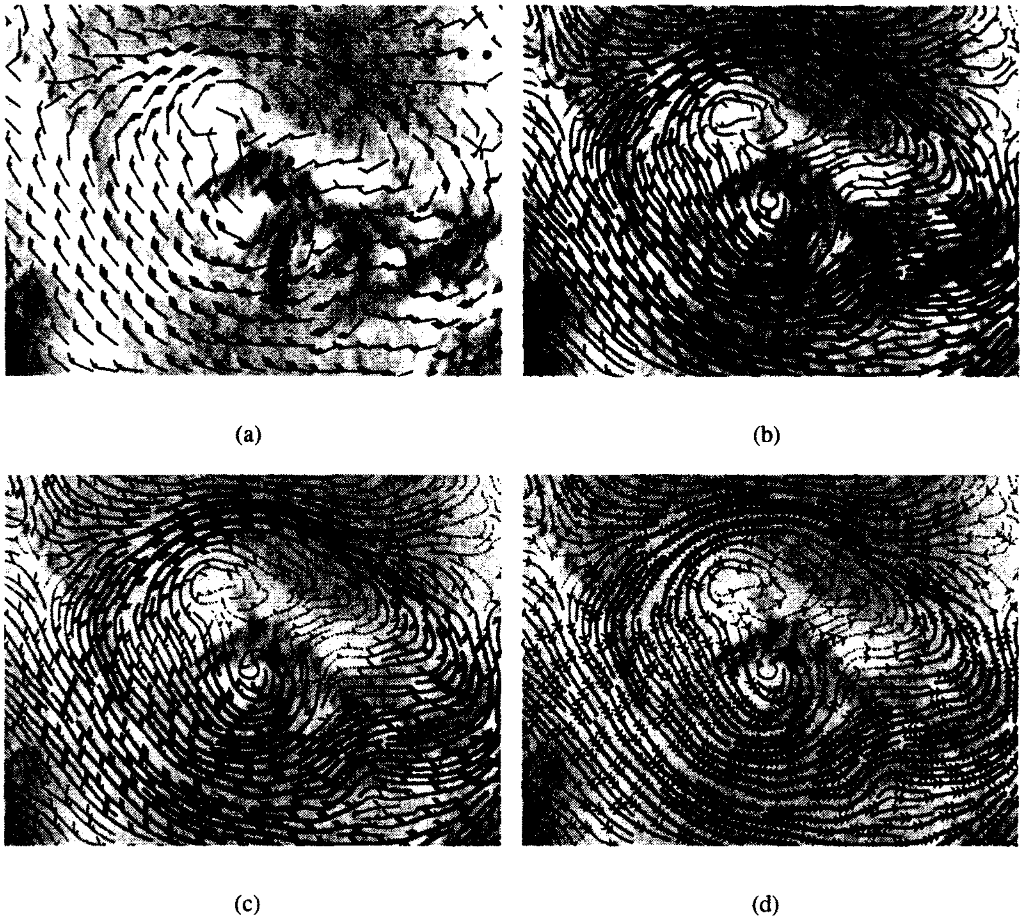


Figure 2-5: High density representations from top: (a) The classic wind barb drawn on a grid; (b) The classic with a curved shaft; (c) Modified classic on a streamline; and, (d) The new arrow glyph design on a streamline.

2.2.2 Design 2: Modified Barb Coding on Streamlines

The second design makes somewhat greater modifications to the standard wind barb.

- The short (5 knot) bar of the speed code can sometimes be confused with the longer (10 knot) bar. To remedy this, a small triangle is used to represent 5 knots. This is a smaller version of the 50 knot pennant.

- The barbs are arranged along continuous streamlines generated using the Jobard and Lefer algorithm [Jobard97]. Also, wind speeds are represented on the contour at the location of the bars and pennants.

- To create greater visual density where wind speeds are stronger, the width of the line making the streamline is increased according to wind speed. With speed less than 7.5 knots dotted lines are drawn.

This design is illustrated in Fig. 2-3c, 2-4(c) and 2-5(c).

2.2.3 Design 3: New Arrow Glyphs on Streamlines

The third design is a much more radical departure from the classic barb. It retains the coding in 5 knot units but uses a different symbology.

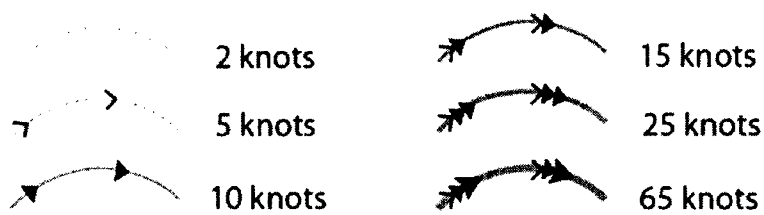


Figure 2-6: The new arrow glyph code.

- The coding, like wind barbs, has design elements for 5 knots, 10 knots and 50 knots. It is illustrated in Figure 2-6.

- Symmetrical arrow heads are used. This is intended to reduce the visual aliasing effects that can arise with the classic barb. It also is designed to allow for closer placement of streamlines.

- The arrow glyphs are arranged along a continuous streamline generated using the Jobard and Lefer algorithm [Jobard97]. Also, the quantity that is represented is at the center of the glyph.

- To create greater visual density where wind speeds are stronger, the width of the line making the streamline is increased according to wind speed. With speed less than 7.5 knots dotted lines are drawn.

This design is illustrated in Fig. 2-3d, 2-4(d) and 2-5(d).

2.3 Implementation

The designs were implemented using using the Jobard and Lefer [Jobard97] algorithm to calculate streamlines. The glyphs were drawn along the streamlines using pre-drawn texture images, one for each 5 knot interval. This made it possible to change the glyph design simply by changing the texture images.

The model data used to evaluate the different representations came from the NOAA National Centers for Environmental Prediction (NCEP) North American Mesoscale forecast model. Three different forecasts were used in order to provide sufficient variation in wind patterns and speed fluctuation.

In order to evaluate how well the different designs could accommodate higher densities of information we implemented each design with two different line spacings, and with glyph sizes scaled accordingly. The detailed parameter settings were as follows.

The parameter used to control line spacing in the Jobard and Lefer algorithm is Dsep. This was set to 5 pixels for the small styles, and 9 pixels for the large styles. Dtest, the minimum allowable distance between streamlines, was 0.75 * Dsep. In practice, this resulted in streamlines with spacings between 3.75 and 7.5 pixels. There were 37.59 pixels/cm. The result is 1-2 mm line spacing for the small styles and 1.5-3 mm line spacing for the larger styles.

The width of the classic, curved classic, and modified classic was 0.133 mm for small and 0.239 mm for large. The length of the classic and curved classic shafts was 0.4522 cm for small and 0.771 cm for large. The modified classic and the new arrow glyph were spaced along the streamline at 0.532 cm for small and .9577 cm for large. The width of the triangles that represent the value 10 for the new arrow glyph was 0.133 mm for small and 0.239 mm for large.

Line width was determined using the formula:

$width = 0.5 + speed/12$

Where width is in pixels and speed is in knots. Streamline sections where speeds were less than 8 knots were drawn as dotted lines according to the algorithm:

If $speed < 4$, $sp = 6 - speed$

Else if $speed < 6$, $sp = 2$

Else if $speed < 8$, $sp = 1$

where sp is spacing in pixels.

The window was 27.5 cm wide by 18 cm high with a wind field of 24.5 cm by 17.1 cm. See figure 2-7. The background image was a map of North America and its adjacent oceans color coded by height.

2.4 Evaluation

In order to evaluate the four designs we carried out an experiment using the NCEP forecast model data as a basis for creating the wind patterns. For each of the designs we measured the accuracy with which a subject could judge the wind speed and direction at various points, selected at random from the map.

2.4.1 Tasks

On each trial the subject was required to estimate wind speed and direction at a point on the map designated by a white cursor. The cursor consisted of four triangles converging on a single point at which the values were to be interpolated. Figure 2-7 illustrates the screen.

To make a wind direction estimate, subjects used a widget resembling a compass with

Figure 2-7: The display used for the experiment. The participant rotated the compass arrow at the top right to indicated direction and the scale below to indicate speed at the center of the white cross.

a needle in the upper right hand corner. Clicking and dragging with the mouse altered the orientation of the needle. Subjects used a slider below the compass to enter their wind speed estimate measured in knots. Both widgets were primarily manipulated with a mouse, but could be "fine tuned" with the keyboard arrow keys. The keyboard enter button was used to finalize selections. Both selection widgets were initialized to zero and both must have been used prior to the enter button being selected in order to progress to the next trial.

2.4.2 Conditions and Trials

The independent variables consisted of 4 different designs: Classic Barb, Classic curved, Modified, and New, each with 2 spacings yielding 8 conditions.

For each condition there were 18 trials: 3 different sets of weather model data were used, and for each set 6 different points were randomly selected.

The subject first completed a training session consisting of 16 trials, 2 each from the 2 different sizes of the 4 different styles. Subjects were provided with feedback for their selected measurements.

2.4.3 Participants

There were 13 participants, all undergraduate students who were paid for taking part.

2.5 Results

Some irregularity in the dataset occurred due to areas of very low wind speed (<5 knots), or in areas of turbulence, where direction may change rapidly over a small area. In such areas, all representations suffered from large angle errors because bent and streamline designs filter out tight spirals by design and straight representations are too sparse to capture the pattern. We used the log of the errors in the anovas in order to lessen the effect of these extreme errors on the results and to make the distribution of errors more nearly normal.

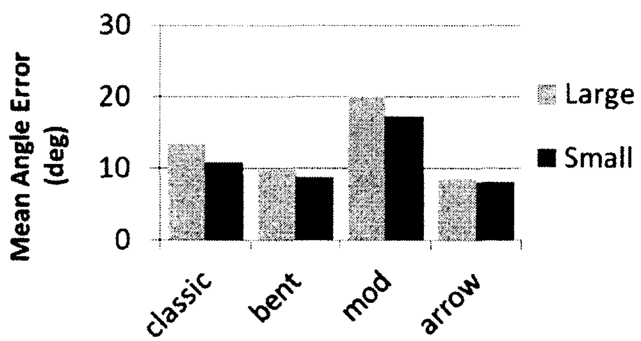


Figure 2-8: Average angle error for the different designs.

Fig. 2-8 shows the average angle error for the different designs. An ANOVA revealed a main effect for the different designs (F[3,39] = 8.5; p <0.001) with an effect for the size (F[1,13] = 8.3; p <0.05) and no interaction. A Tukey HSD test showed the arrow and bent classic designs to have the lowest error with no statistical difference between them. The classic design came next and the modified design resulted in the greatest mean error.

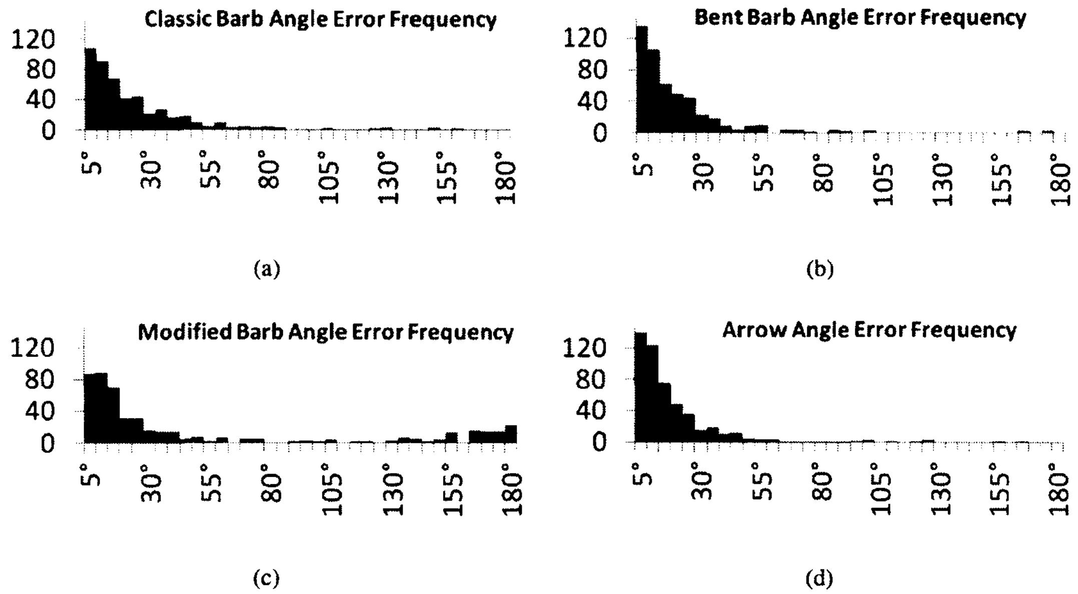


Figure 2-9: The distributions of angular errors for the different designs.

To try to account for the failure of the modified design we examined the distribution of angular errors. These results are shown in Figure 2-9 and they show that for the modified barb design there was a bimodal error distribution, approximately 17% of the results were at 180 degrees to the true direction. The number of 180 deg errors was negligible for the other conditions.

Fig. 2-10 shows the mean speed error for the different designs. An ANOVA revealed a main effect for the different designs (F[3,39] = 3.47, p <0.05) with no main effect for the size and no significant interaction. Tukey HSD tests showed the arrow and the modified to be indistinguishable and the modified barb to have lower errors that the classic and bend designs.

Figure 2-10: Average speed error for the different designs.

2.6 Discussion

Despite the fact that wind barbs are not well suited to showing wind patterns they are often used for this purpose. This is undoubtedly because of their ability to provide quantitative information about wind speed. Better alternatives for showing patterns have existed for some time, such as the Jobard and Lefer method [Jobard97], but these provide qualitative and not quantitative information. Our solution, given in this paper, has been to combine the idea of a quantitative glyph with continuous streamlines to show patterns. Two of our new designs turned out to be measurably better than wind barbs in terms of the accuracy with which wind speed and orientation can be read. Our second re-design (the modified barb) was less successful, producing the largest angle errors. We attribute this to the fact that direction sign could be ambiguous, because sometimes the speed lines could completely span the gap between the streamlines resulting in 180 degree errors.

For applications where it is important that the traditional wind barb coding be retained, we suggest placing wind barb symbols along streamlines and curving the shaft of the barb to conform to the streamlines. In addition, varying the streamline thickness with wind speed makes it easier to distinguish high wind from low wind areas. Our new design, based on arrow glyphs, is perhaps capable of better revealing the details of complex wind patterns. It is more accurate than the classic barb in terms of the wind speed error for larger-spacing designs and more accurate than the bent version of the classic for the smaller-spacing design.

The ideas in this paper may have broader applications for visualization problems where quantitative codes must be combined with densely patterned streamlines. It is often argued that the purpose of data visualization is to show patterns in data, not absolute values in data. Sometimes, however, people do need to know the absolute wind speed as well as to understand the swirling pattern of the winds. Aside from wind barbs, there are two common ways of showing accurate quantities; one is to provide a color coding, along with a separate key for the values represented by the colors, the other is to scatter small numbers over the display. Sometimes both of these options are unavailable. For example, color coding may already be used to show temperature in a weather display, and numbers may already be used to show atmospheric pressure. In such cases a form of quantitative glyph may be useful. We are currently investigating ways of using quantitative glyphs as a method for representing the output of computational models of wave height.

Chapter 3

Water Wave Visualization

3.1 Introduction

A relatively new feature of some weather models is the ability to forecast waves. The WavewatchIII [NOAA12] provides updated wave model data approximately every 6 hours, with visualizations based on those models being disseminated to ship captains, meteorologists, and the general public. Unfortunately, those visualizations continue to use visualization techniques such as poorly designed glyphs or other elements oriented to a grid. For instance, the WavewatchIII [NOAA12] "product viewer" uses classic Wind Barbs [Wiki09] on a grid for displaying wind speed and direction, and arrows anchored on the same grid for displaying wave direction. The problem with anchoring glyphs, including wind barbs and arrows, on a grid is discussed by Laidlaw [Laidlaw05]: the pattern of the grid can obfuscate or dominate the patterns in the data.

In 1997 Jobard and Lefer [Jobard97] published an algorithm for calculating and drawing evenly spaced streamlines, partly inspired by the work of Turk and Banks [Turk96]. Research suggests that such streamlines can be used effectively to guide placement of glyphs [Jobard97, Laidlaw05] along a path. Pineo and Ware [Pineo10] explained the neurological science behind the head-to-toe placement method that makes it effective. Pilar and Ware [Pilar12] created and evaluated a new wind glyph specifically designed for streamline guided placement and showed the placement method and glyph combination to be superior for visualizing wind direction patterns without sacrificing accuracy in depicting wind speed.

In this chapter we apply the same concepts used to create the wind arrows [Pilar12] to the task of visualizing wave direction and height. To achieve a clearer visualization when combined with wind data, we adapted the Jobard Lefer algorithm [Jobard97] to calculate orthogonal streamlines, shown in Figure 3-1. We also created a new animated visualization that uses moving, bent line segments called *wave fronts* for depicting wave direction, and bent wind arrows on a jittered grid for depicting wind.

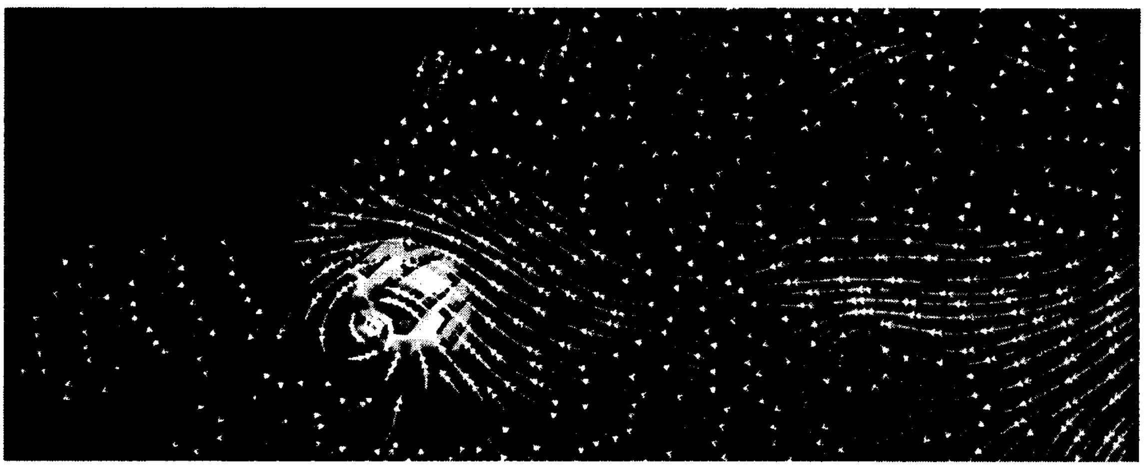


Figure 3-1: Wind Arrows and Orthogonal Wave-Front streamlines. Hurricane Earl (August 25, 2010) model data is shown.

3.2 Introduction to Wave Data

Wavewatch III [NOAA12] is a set of 5 computational wave models developed at NOAA and NCEP. The models produce gridded data files from temperature information, hurricane forecast data (when available), ice conditions, and sea surface temperature data. The output files contain data for wind direction, wind speed, U and V components of wind, significant wave height, mean wave direction and period, peak wave direction and period, and wind wave direction and period. Wind waves are local waves created by local wind, and swell refers to long waves that were formed elsewhere as wind waves and traveled into the local area. Although there can be thousands of swell fields in a given area, the term "swell" in the model output is used more restrictively to refer to the dominant swell field for the area. Significant wave height is the average height of the largest 1/3 of (the combination of wind and swell) waves in a given period, with the largest individual wave height being up to twice as large as the average height. The particular Wavewatch III model data used in this study is from the regional Western North Atlantic model.

Important components of waves are direction, height, and period. Visualizations commonly focus on direction and height with less emphasis on period. Waves can travel through each other and often there are many unrelated sets of waves occupying the same area at the same time, each having different direction, height, and period. At any given time and location the dominant wave field may be either wind waves or swell waves. Additionally, when large wave sets travel through each other at an angle, the seas may become less predictable and more dangerous. It is desirable to display wind and wave data in a way that allows the user to determine the sea conditions caused by the interaction between the two quickly; e.g., waves are steeper where the wind is in opposition to the waves, but build faster where strong wind and waves are traveling in the same direction. A complete visualization of a section of ocean should show both wind waves and the most significant swell waves at the same time, along with wind speed and direction. An even more complete visualization would also show wave period.

A web-based "product viewer" is provided on the NOAA Wavewatch III website [NOAA12] for viewing the model output. An example screen shot is shown in Figure 3-2. The product-viewer does not allow for wind wave and swell direction to be displayed simultaneously. Significant wave height is represented with a color map as is wave period, so height and period can't be displayed at the same time. Ideally, it should be possible to adapt the viewer to display–simultaneously–wind-waves, swell, significant wave-height, and period.

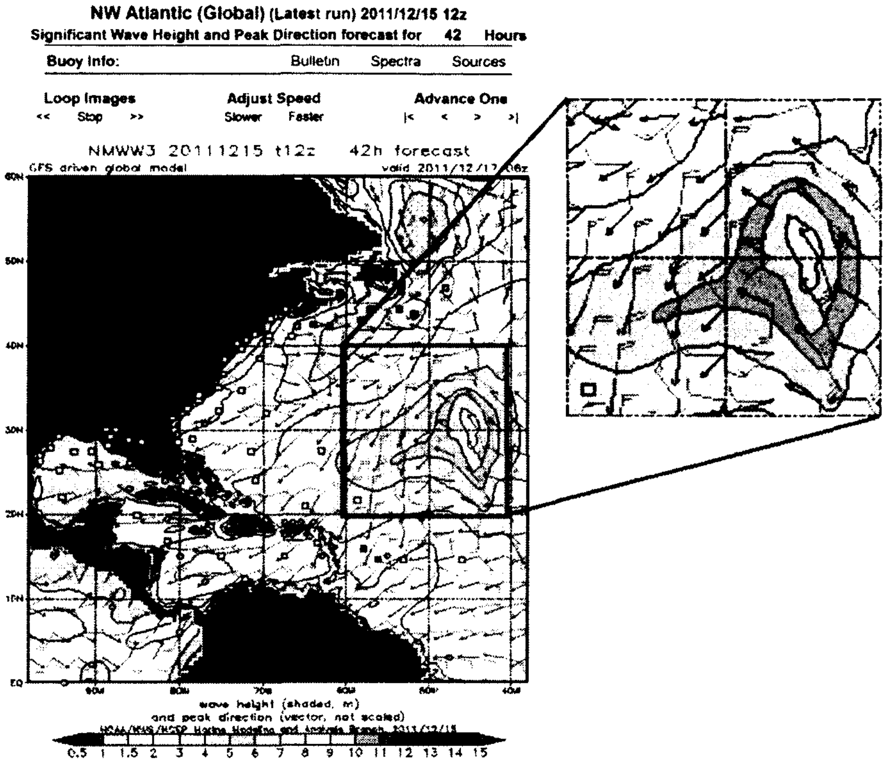


Figure 3-2: `http://polar.ncep.noaa.gov/waves`

3.3 Design

Two new wave visualizations were designed, a static version showing a single time-step of model output, and an animated version showing an animated sequence of a few days of model output. We begin with the static design.

The design goals are the following: 1) show wave direction in a manner that does not detract from the wind direction representation; 2) show significant wave height simultaneously with wind speed and direction; 3) produce a design that is more effective than the existing WWIII product viewer visualization.

We based our design on the fact that a water wave is roughly orthogonal to its direction of travel. Because wind waves travel in the direction of the wind, using wind barbs to show wind direction along with arrows to show wave direction leads to arrow shafts and wind barb shafts which are mostly parallel, causing visual interference. This parallel arrangement is used by Wavewatch III shown in Figure 3-2. A novel feature of our new design is that it shows the waves using contours that are orthogonal to the direction of travel and parallel to the wave fronts. For the most part, this means that they will be at nearly right angles to the wind direction, reducing visual interference. This concept is illustrated in Figure 3-1 which shows wave-front streamlines and wind arrow streamlines with a color map background depicting wave height.

We chose to use evenly spaced streamlines–for the static designs–based on several research papers [Jobard97][Laidlaw05][Turk96] that indicated streamlines are a good choice for showing orientation. We placed directional glyphs end to end (side to side for orthogonal designs) along the streamlines, which was shown to be effective by Pineo and Ware [Pineo10]

3.3.1 Static Orthogonal Streamlines

To draw the wave-front streamlines, we adapted the Jobard-Lefer algorithm [Jobard97] to integrate streamlines based on right angles to the vectors. For the representation of sign in Figure 3-3 (curved black lines), we used fading, with the dark end being the front, and the faded end the back. Orientation of wave propagation is orthogonal to the tangent (blue lines) of the front of the streamline. This design does not encode magnitude which can be shown as background color. This faded line design is abbreviated as FL.

3.3.2 Static Orthogonal Glyphs

A second design was developed to explore the application of a directional and quantitative glyph [Pilar12] to show wave direction and height. For this design we applied the same concepts used to design the arrow-glyph [Pilar12] adapted to address the challenges of de-

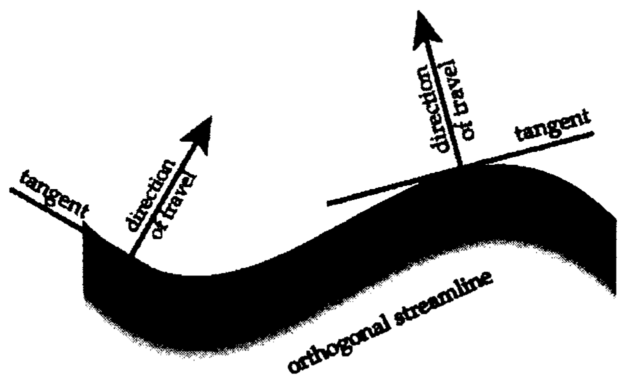


Figure 3-3: Orthogonal streamline, direction encoded via fading, dark-edge is leading-edge.

picting an orthogonal direction. Our initial design followed the advice of Bertin [Bertin83], who suggests that the weight of a directional glyph should be at the head, and had the wave glyphs trailing the streamline. Later, we revised the design based on critique from several meteorologists who stated that pressure bars depict movement in the opposite manner. The orthogonal glyph is shown in Figure 3-4. This design is abbreviated GH for glyph height when the background map also encodes wave height, or GP for glyph period when the background encodes wave period.

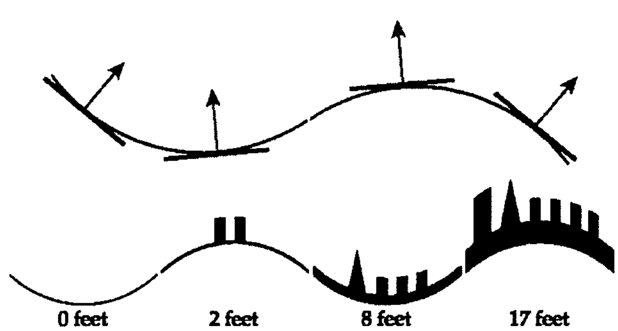


Figure 3-4: Orthogonal glyph sign, orientation and code.

- The coding has design elements consisting of:

- A small rectangle represents 1 foot.
- A large triangle represents 5 feet.
- A large rectangle represents 10 feet.

- Coding elements indicate magnitude and direction of movement while the streamline indicates orientation of the front (orthogonal to direction of travel).
- The height coding glyphs are arranged along a continuous streamline generated using the Jobard Lefer algorithm [Jobard97]. The quantity that is represented is at the lateral center of the speed coding glyph, and on the streamline.
- The glyphs are placed side-to-side along the streamlines, similar to the head-to-toe arrangement proposed by other authors in [Jobard97][Laidlaw05].
- To create greater visual density where wave heights are stronger the width of the line making the streamline is increased according to wave height.

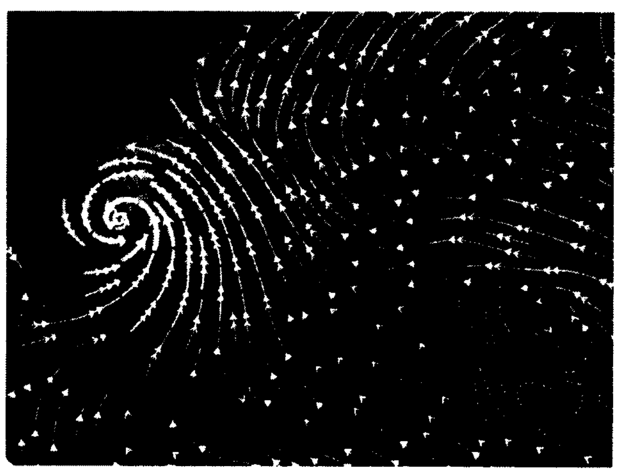


Figure 3-5: Wind arrows on streamlines, wave-glyphs on orthogonal streamlines, wave-period is mapped to color.

Implementation of Static Design

The designs were implemented using OpenGL and C++. The Jobard and Lefer algorithm [Jobard97] was used to compute the streamlines. The glyphs for the static streamline designs were drawn using images created in a vector graphics design program and loaded as textures at runtime.

3.3.3 Animated Orthogonal Wave Fronts

It is common for meteorologists to use an animation to interpret developing weather events because it provides a quick overview of a time period, with static views used for the detailed time slice analysis. We believe some of the same concepts used in the static designs can also be applied to animated visualizations, specifically orthogonal representations of wavefronts.

To show the wave patterns we replaced the standard anchored arrows on a grid that are used in the WWIII product viewer with curved orthogonal line segments (wave fronts, see figure 3-6). Wind wave and swell wave direction is shown as moving orthogonal lines, black for wind waves, white for swell waves. Wind direction is shown with bent magenta wind arrows on a jittered grid. Significant wave height is shown using a color background. To show the wind patterns we replaced the gridded wind barbs with curved lines using the wind speed coding scheme shown in the previous chapter. In this way wind-wave and swell patterns are shown more clearly, particularly where the two intersect and there may be large areas of confused seas. This design is abbreviated WF.

Implementation of Animated Wind and Waves

The animated wave fronts are drawn by randomly seeding points into the display field. These seed points become the centers of individual wave fronts. From each center, two line segments are drawn, left and right relative to the direction at the center. The segments

Figure 3-6: Animated orthogonal wave fronts and the jittered-grid statically-located animated wind-glyphs.

are bent orthogonal to the wave direction being represented. The result is bent orthogonal lines similar to short streamlines. Motion is achieved by advecting the center point in time according to wave speed. Wave speed is calculated using the formula $S = \frac{2}{P^2 \cdot H}$ where S denotes speed, P denotes wave period and H denotes wave height. However, simply scaling this result caused the smaller, less significant waves to move very quickly and the larger, building waves to move very slowly, causing the viewers focus to be drawn to less important weather features. Since wave speed is less important than wave height, speed was used as a tool to draw attention to more important areas where the waves were largest, such as around a hurricane, by causing the higher wave fronts to move faster than the smaller waves. The end effect is that the wave fronts appear to move faster in areas where, in reality, the real waves would be moving more slowly. The animated wave arrows were seeded on a jittered grid with the seed point anchoring the center of the glyph. At each time slice, the path of the glyph was calculated forward and backward with respect to the wind direction, and a texture was bent along that path. In this way, the wind arrows continuously bend to show the direction of the wind, but the centers do not move.

3.4 Evaluation

For comparison to our proposed visualization methods, we chose the web-based product-viewer from the Wavewatch III model website [NOAA12]–shown in figure 3-2–that can present the data as a static image or an animation, although the animation is simply a time series of the static images. This design is abbreviated TD for both the static and animated versions.

3.4.1 Subjects

We evaluated the new designs as using two surveys. There were 12 subjects for the static survey: 8 identified themselves as students; 1 identified him/herself as staff; and 3 did not indicate, although there were several faculty members in attendance. There were 13 subjects for the animated survey: 7 identified themselves as students; 1 identified him/herself as staff; 1 identified him/herself as faculty; and 4 did not indicate. The subjects were not paid for their participation. All subjects were from the meteorology program at Plymouth State University.

3.4.2 Task

The subjects were shown multiple static and animated representations of wind and wave patterns where wind data consisted of direction and speed, and wave data consisted of height, direction, and sometimes period. The subjects were asked several questions pertaining to the designs and then selected a rating on a Likert scale [Wiki12] for each.

3.4.3 Static Representation of Wind over Waves

We evaluated the static methods of representing wave direction showing the principal component (wind waves) of waves and the wind speed and direction (see figure 3-7) by showing pictures of the following four conditions:

1. Traditional design (TD): wind barbs, wave arrows, color coded wave height. This design is based on the Wavewatch III product viewer and shown in figure 3-7(a).

2. Faded lines (FL): wave lines, wind arrows and color coded wave height. This new design is shown in figure 3-7(b).

3. Glyph with height background (GH): wave line glyphs, wind arrows and color coded wave height. This new design is shown in figure 3-7(c).

4. Glyphs with period background (GP): wave line glyphs, wind arrows and color coded period. This new design visualizes an additional variable, period, and is shown in figure 3-7(d).

Survey for Static Representations

The questions for the static designs are shown in Table 3.1. The survey was based on a Likert scale shown in table 3.2.

3.4.4 Animated Representation of Wind over Waves

We evaluated the animated method of representing wave direction showing both wind waves and swell along with wind in an animated sequence for each of two conditions: traditional design (TD), and wave fronts (WF). These designs are shown in figure 3-8. In both conditions, background color represented wave height.

Survey for Animated Representations

The questions for the animated versions are shown in Table 3.3. The survey was based on the same Likert scale used for the static designs, see Table 3.2.

- **TD** Wavewatch swell and winds, wave height as a colored background
- **FL** New orthogonal fading lines, wave height as a colored background
- **GH** New glyph with redundant color coding, wave height as a colored background
- **GP** New glyph with period as colored background.

1. How well can you see the wave height?
2. How well can you see the wave patterns (direction / circulation / propagation)?
3. How well can you see the spiral wind pattern around hurricane Earl?
4. How well can you visually separate wind patterns from wave patterns?
5. How well can you see where the wind is blowing in the opposite direction to the swell in the vicinity of Hurricane Earl?
6. Ranking:
   - Which do you think is the best overall?
   - Which do you think is second best overall?
   - Which do you think is the worst overall?

Table 3.1: Questions for Static Displays

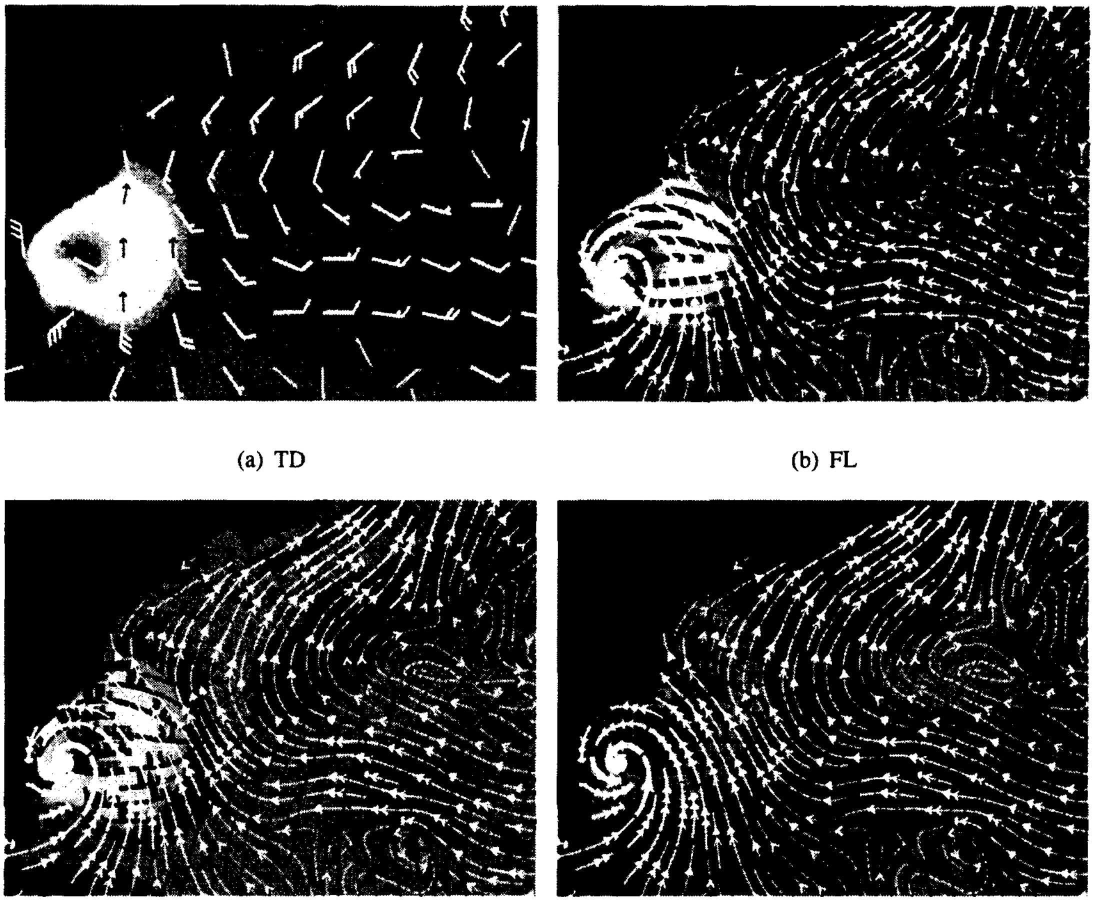
Likert Scale								
very poorly		poorly		fair		well		very well
1	2	3	4	5	6	7	8	9

Table 3.2: Rating Scale

- **TD** Wavewatch III with swell and wind waves as well as wind. Height as colored background.
- **WF** Animated wavefronts and bent wind arrows anchored on a jittered grid.

1. How well can you see both sets of wave patterns (swell waves and wind waves)?
2. How well can you see the wind circulation patterns around hurricane Earl?
3. How well can you visually separate wind wave patterns from swell wave patterns?
4. How well can you visually separate wind patterns from swell wave patterns?
5. How well can you see where the wind is blowing in the opposite direction to the swell?
6. Which do you think is the best overall?

Table 3.3: Questions for Animated Displays



(a) TD (b) FL

(c) GH (d) GP

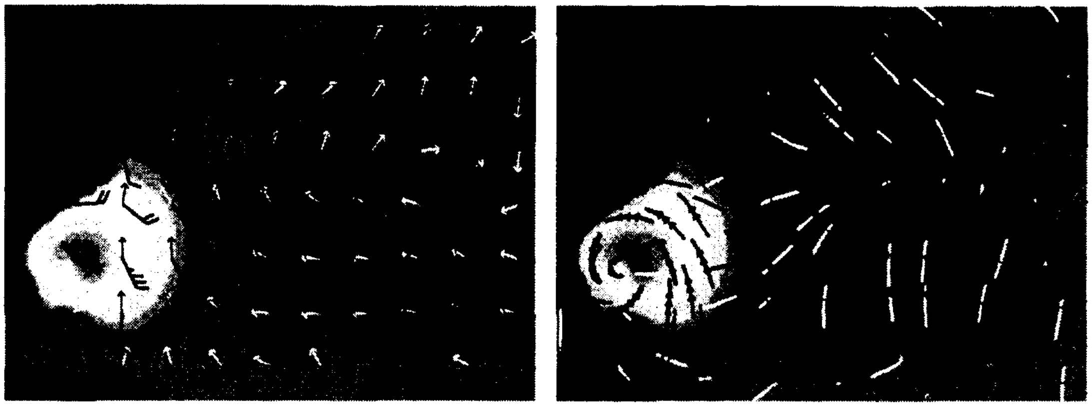
Figure 3-7: Static representations of swell wave direction and significant wave height with wind direction and wind speed: (a) TD: wave arrows and wind barbs; (b) FL: wave streamlines and wind streamlines with wind arrow glyphs; (c) GH: wave streamlines with height glyphs and wind streamlines with arrow glyphs, height as color map;(d) GP: wave streamlines with height glyphs and wind streamlines with arrow glyphs, period as color map.

3.5 Results

3.5.1 Static Designs

A one-way analysis of variance (ANOVA) was calculated for each of the following 6 questions. The results for each question are shown in Figure 3-9.

1. How well can you see the wave height? The analysis revealed significant differences, $F(3,92) = 23.61$, $p < 0.001$. A Tukey HSD test showed the traditional design al-



(a) TD (b) WF

Figure 3-8: Animated representations of swell wave and wind wave directions along with significant wave height, wind direction and wind speed: (a) TD: wave arrows with wind barbs, and (b) WF: wave fronts with bent wind arrows.

lowed the wave height to be seen better than all other designs, the FL design came second, and the GH and GP designs were last with no statistical difference between them. See Figure 3-9(a).

2. How well can you see the wave patterns (direction / circulation / propagation)? The analysis revealed no significant differences, $F(3,92) = 0.067$: n.s., p is greater than .05.

3. How well can you see the spiral wind pattern around hurricane Earl ? The analysis revealed significant differences, $F(3,92) = 34.87$, $p < 0.001$. A Tukey HSD test showed FL, GH, and GP all to be superior to TD but not statistically different from each other. See Figure 3-9(b).

4. How well can you visually separate wind patterns from wave patterns? The analysis revealed no significant differences, $F(3,92) = 1.739$: n.s., p is greater than .05.

5. How well can you see where the wind is blowing in the opposite direction to the swell in the vicinity of Hurricane Earl? The analysis revealed no significant differences, $F(3,92) = .755$: n.s., p is greater than .05.

6. Rank in order of preference. The analysis revealed significant differences, $F(3,92) = 10.53$, $p < 0.001$. A Tukey HSD test showed the faded line design, FL to be preferred over all other designs. The traditional design, TD was preferred over wave Glyph Period, GP, and no statistical differences between Glyph Height, GH, and GP or between GH and TD. See Figure 3-9(c).

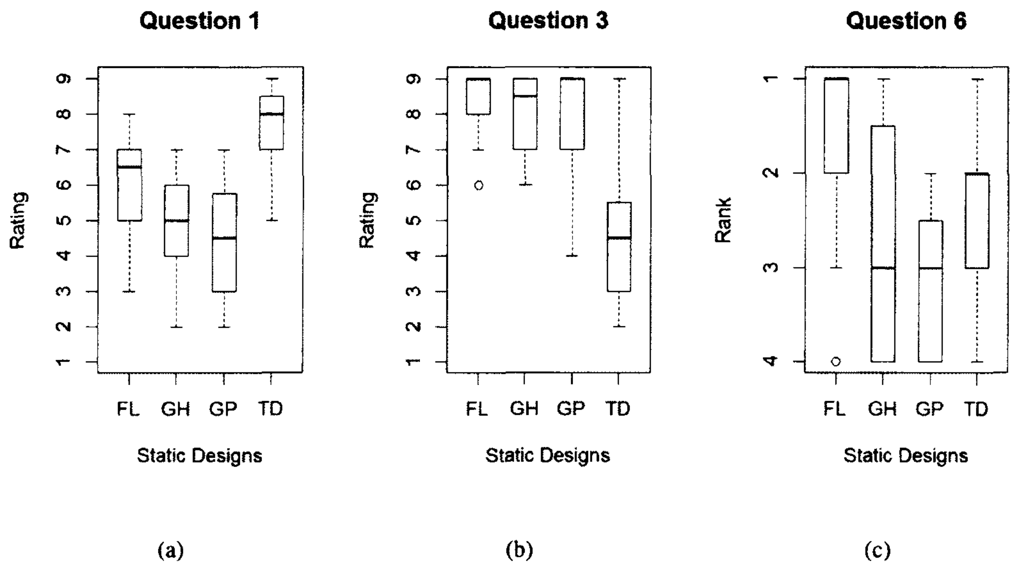


Figure 3-9: Results from a user study comparing static visualizations. FL is faded-lines, GH is wave glyph with height background, GP is wave glyphs with period background, TD is traditional design (wind barbs and wave arrows, height background). A rating of 1 means very poorly, and a rating of 9 means very well, except for question 6, which is a ranking of first through fourth: (a) How well can you see the wave height? (b) How well can you see the spiral wind pattern around hurricane Earl? (c) Rank in order of preference.

3.5.2 Animated Designs

A Welch Two Sample t-test was calculated for each of the following 6 questions. The results for each question are shown in 3-10.

1. How well can you see both sets of wave patterns (swell waves and wind waves)? $t(32.147) = -3.679$, $p < .001$. Wave Fronts, WF had a mean of 7.80, which was

better than the Traditional Design, TD, which had a mean of 6.48. See Figure 3-10(a).

2. How well can you see the wind circulation patterns around hurricane Earl? $t(44.578) = -2.9198$, $p < .01$. WF had a mean of 7.68, which was better than TD, which had a mean of 6.68. See Figure 3-10(b).

3. How well can you visually separate wind wave patterns from swell wave patterns? $t(37.121) = -2.8304$, $p < .01$. WF had a mean of 7.826087, which was better than TD, which had a mean of 6.347826. See Figure 3-10(c).

4. How well can you visually separate wind patterns from swell wave patterns? The analysis revealed no significant differences, $t(38.199) = -1.3147$: n.s., p is greater than .05.

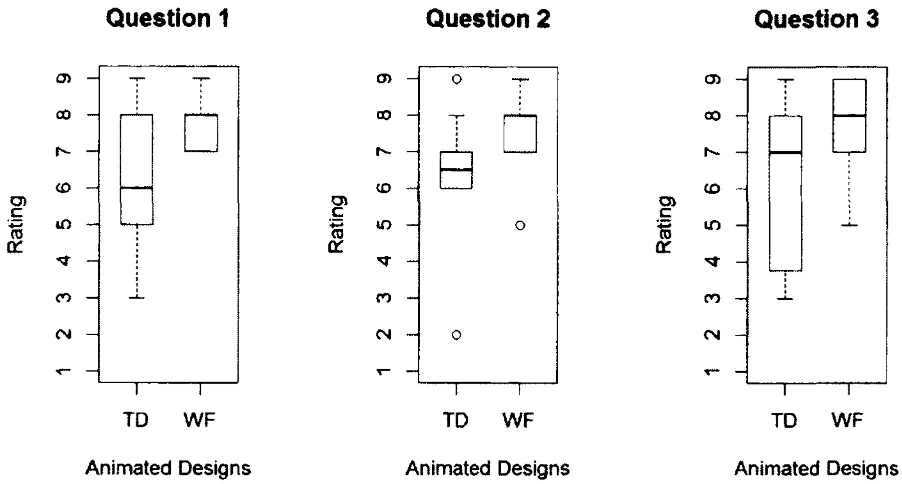
5. How well can you see where the wind is blowing in the opposite direction to the swell? The analysis revealed no significant differences, $t(47.931) = 1.8216$: n.s., p is greater than .05.

6. Which do you think is the best overall? The analysis revealed no significant differences, $t(48) = 1.4142$: n.s., p is greater than .05.

3.6 Discussion

3.6.1 Static Designs

The traditional design (TD) was rated best for showing wave height. Even though TD, glyph height(GH), and faded line (FL) designs used the exact same color coded representation for wave height, most subjects rated each design differently for wave height. This could mean that designs were rated higher when the color background was least occluded,



(a) (b) (c)

Figure 3-10: Results from a user study comparing animated visualizations of wind and wave data. TD is traditional design (Wind Barbs and wave arrows), WF is wave fronts(with wind arrows). A rating of 1 means very poorly, and a rating of 9 means very well, except for question 6, which is a ranking of first, second: (a) How well can you see both sets of wave patterns (swell waves and wind waves)? (b) How well can you see the wind circulation patterns around hurricane Earl? (c) How well can you visually separate wind wave patterns from swell wave patterns? .

even in cases where there was a redundancy between the glyph representation and the color code. Denser representation of direction and magnitude patterns while using streamlines and glyphs for wind and wave representation made the color background less apparent. Specifically, the large wave glyphs and the strong wind spiral pattern of the wind arrows at Hurricane Earl provided more wind direction and magnitude information and more wave direction information at the expense of the color coded height background. A more selective comparison for the directional wave patterns encoded by glyphs would use a neutral background and either omit the wind information, or use the same wind representation for all designs.

The preference for FL, GH, and GP designs to show the wind direction patterns reinforces the findings of Pilar and Ware [Pilar12], since each used bent wind arrows on streamlines, while TD used straight wind barbs on a grid. Overall, the FL design was preferred to each of the other designs, TD preferred over GP, and there were no statistical differences between GH and GP or between GH and TD. The subjects commented that they liked the orthogonal streamlines but the wave glyphs made the images too busy.

3.6.2 Animated Designs

The WF design was better able show both wind waves and swell waves, and the subjects were better able to separate the patterns of each when compared to the TD design. For visualizing wind patterns, the bent wind arrows of the WF design showed an advantage over the wind barbs in the TD design, which is consistent with the findings of Pilar and Ware [Pilar12].

Chapter 4

Conclusion

The results suggest that both wind visualizations and wave visualizations can be improved through the use of modern flow visualization techniques. The new wind arrow design outperforms the classic wind barb for speed accuracy, and we showed that placing either the wind arrow or the wind barb itself head-to-toe and bent along streamlines is an improvement over straight wind barbs located on a grid. Additionally, we showed the wind arrows to be better than wind barbs at showing patterns in an animation where the arrows are anchored on a jittered grid, but bent with the flow.

For the wave study, the results suggest that the orthogonal streamline, faded to encode direction, is preferred by meteorologists for visualizing wave direction patterns. The orthogonal glyph design did not rate as well as we expected. Comments from the survey indicated that the display was too cluttered when the wave glyphs were used, especially when distorted over hurricane earl. Some of the participants commented that the height code of the glyph was not needed since the background color already encoded height. Although the background color encoded period for GP, subjects commented that the glyphs were harder to read compared to the color coded height. The wave glyph was designed for cases where the color background would be used for some other scalar value, but TD only has color to encode height. To avoid a possible prejudice for color patterns, we chose to use the same background for each design. A better evaluation of sign and orientation patterns would have used some other background such as period or water temperature. To assess the readability of the glyph, a methodology more similar to that used to test the wind arrow should be used, such as a task to measure angle error and a task to measure height error.

Meteorologists are trained in the use of wind barbs and arrows for representing vectors, and much of their software uses them. In order to update to new visualization methods, the new designs would need to be clearly superior to the old designs in every aspect. A similar situation was encountered by a team evaluating visualizations of Artery flow for the diagnosis of heart disease by Borkin et al. [Borkin11] where surgeons were satisfied with the visualization techniques for which they had been trained, yet studies showed the new designs resulted individually in significant increases in correct diagnosis, and when used in combination showed an even more significant increase in diagnosis. The advantage Borkin had was involving the medical community in a non-trivial role from the start. A similar collaborative effort between computer science and meteorology students/faculty could achieve similar results.

Flow visualization has broader implications than weather forecasting, and other visualizations may benefit from better pattern presentation with stronger directional content and magnitudes encoded in discrete steps, e.g. ocean and river currents, blood flow, automobile traffic analysis, crowd movement analysis and hydraulic systems to name a few.

Future Work

The definition of what constitutes "patterns" in flow fields seems to vary from study to study, and person to person. For comparison between different designs and different studies, a standard evaluation methodology should be designed. Some goals would be to test the sign and orientation patterns more objectively in addition to discrete point velocity errors and average velocity over a region. Artificial data sets containing known patterns such as the wind spirals at high and low pressure areas or suddenly changing winds at cold fronts could be used to generate images, but many more patterns such as sinks and saddles exist. A cross-discipline survey of what patterns are important in flow fields could involve fluid dynamics and aeronautical engineers as well as meteorologists and ship captains could be carried out. The Borkin et al. study [Borkin11] suggests that what subjects believe to be the best visualization is not always what turns out to be the most accurate: subjective evaluation in its own is not enough.

Possible Applications

We close with two mock-up images of what the new designs could look like on an existing visualization. Figure 4-1 shows what the new wind arrows would look like in the Nowcoast display, and Figure 4-2 shows what the orthogonal wave glyph would look like in the Nowcoast display.

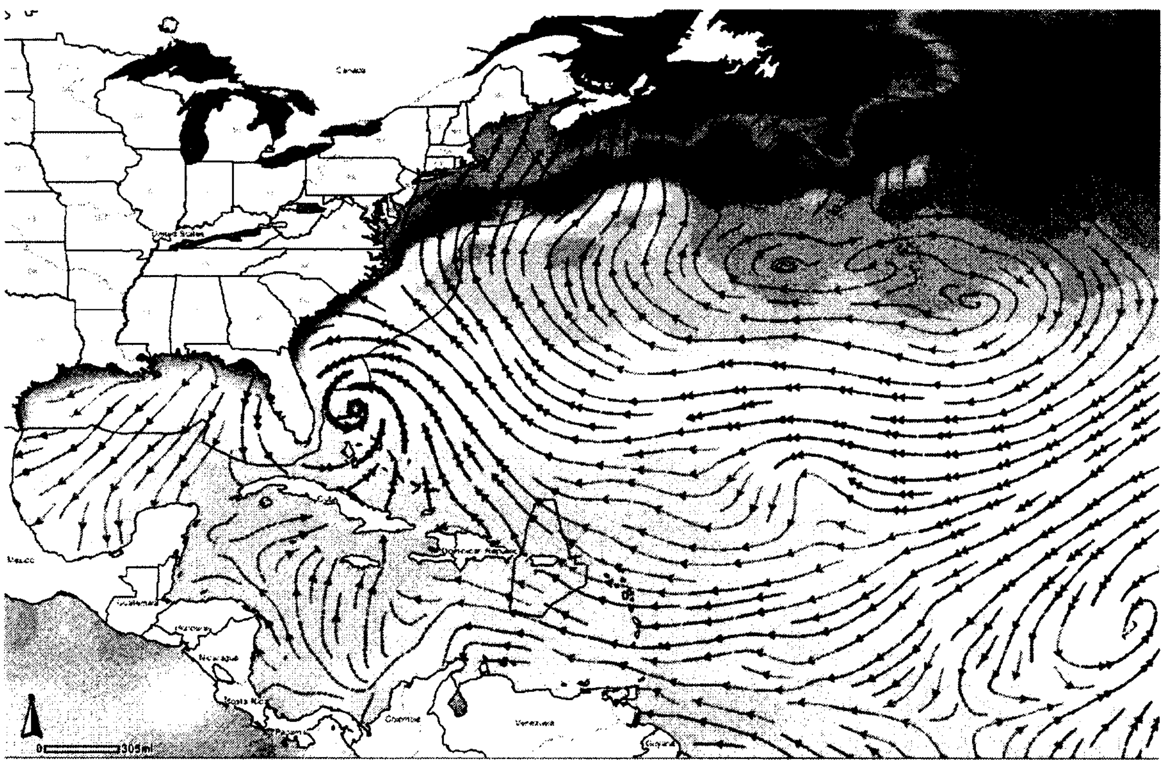


Figure 4-1: A mock-up of what the wind arrow streamlines would look like in an existing weather display (Nowcoast). The color background encodes sea surface temperature.

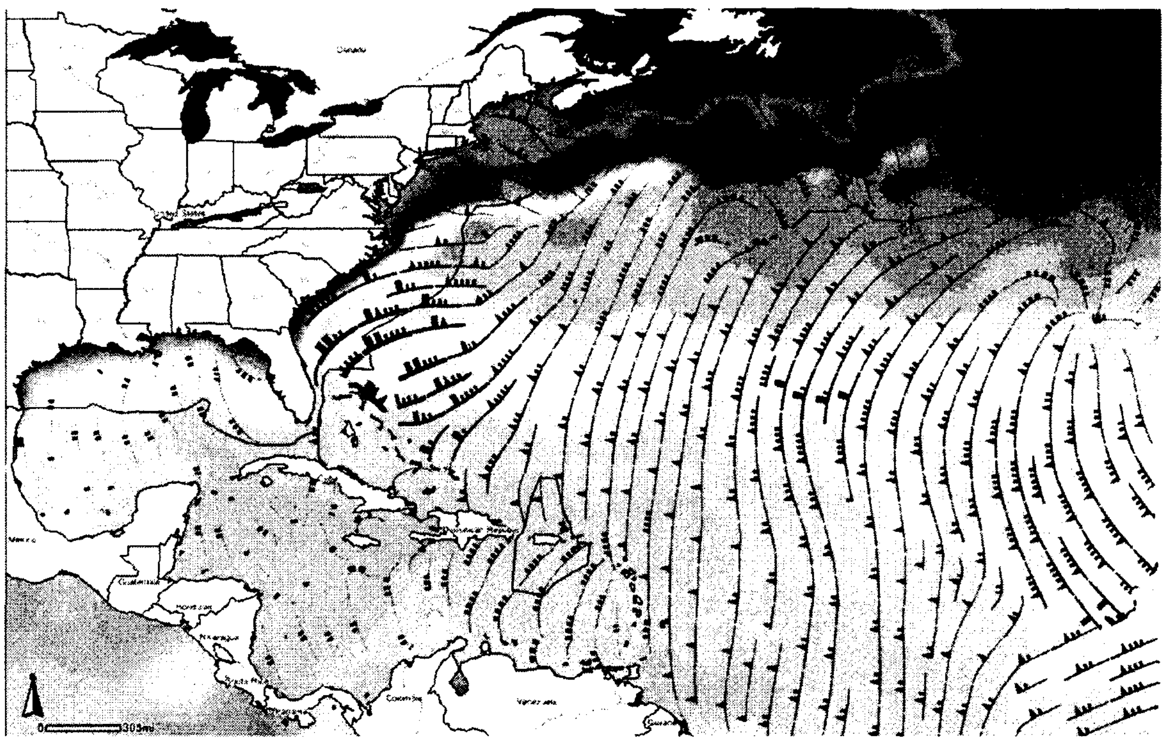


Figure 4-2: A mock-up of what the orthogonal wave glyph streamlines would look like in an existing weather display (Nowcoast). The color background encodes sea surface temperature.

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Appendix A

IRB Approval Form

University *of* New Hampshire

Research Integrity Services, Service Building
51 College Road, Durham, NH 03824-3585
Fax: 603-862-3564

12-Aug-2011

Ware, Colin
Computer Science Dept
Ocean Engineering Bldg
Durham, NH 03824

IRB #: 3013
Study: Perceptual Optimization for Data Visualization
Review Level: Expedited
Approval Expiration Date: 26-Aug-2012

The Institutional Review Board for the Protection of Human Subjects in Research (IRB) has reviewed and approved your request for time extension for this study. Approval for this study expires on the date indicated above. At the end of the approval period you will be asked to submit a report with regard to the involvement of human subjects. If your study is still active, you may apply for extension of IRB approval through this office.

Researchers who conduct studies involving human subjects have responsibilities as outlined in the document, *Responsibilities of Directors of Research Studies Involving Human Subjects.* This document is available at http://unh.edu/research/irb-application-resources or from me.

If you have questions or concerns about your study or this approval, please feel free to contact me at 603-862-2003 or Julie.simpson@unh.edu. Please refer to the IRB # above in all correspondence related to this study. The IRB wishes you success with your research.

For the IRB,

Julie F. Simpson
Director

cc: File
Allen Hubbe

UNIVERSITY OF NEW HAMPSHIRE

Office of Sponsored Research
Service Building
51 College Road
Durham, New Hampshire
03824-3585
(603) 862-3564 FAX

LAST NAME	*Ware*	**FIRST NAME**	*Colin*
DEPT	*Computer Science/Center for Coastal & Ocean*	**APP'L DATE**	*8/26/2003*
OFF-CAMPUS ADDRESS (if applicable)	*Computer Science/CCOM* *Chase Engineering Lab* *24 Colovos Road*	**IRB #**	*3013*
		REVIEW LEVEL	*EXP*
		DATE OF NOTICE	*8/26/2003*
PROJECT TITLE	*Perceptual Optimization for Data Visualization*		

The Institutional Review Board (IRB) for the Protection of Human Subjects in Research reviewed and approved the protocol for your study as Expedited as described in Federal Regulations 45 CFR 46, Subsection 110 (b) (1)category 7.

Approval is granted for one year from the approval date above. At the end of the approval period you will be asked to submit a project report with regard to the involvement of human subjects. If your project is still active, you may apply for extension of IRB approval through this office.

The protection of human subjects in your study is an ongoing process for which you hold primary responsibility. In receiving IRB approval for your protocol, you agree to conduct the project in accordance with the ethical principles and guidelines for the protection of human subjects in research, as described in the following three reports: Belmont Report; Title 45, Code of Federal Regulations, Part 46; and UNH's Federalwide Assurance of Protection of Human Subjects. The full text of these documents is available on the Office of Sponsored Research (OSR) website at http://www.unh.edu/osr/compliance/Regulatory_Compliance.html and by request from OSR.

Changes in your protocol must be submitted to the IRB for review and approval prior to their implementation; you must receive written, unconditional approval from the IRB before implementing them. If you experience any unusual or unanticipated results with regard to the participation of human subjects, report such events to this office within one working day of occurrence. If you have questions or concerns about your project or this approval, please feel free to contact this office at 862-2003. Please refer to the IRB # above in all correspondence related to this project. The IRB wishes you success with your research.

For the IRB,

Julie F. Simpson

Julie F. Simpson
Regulatory Compliance Manager

cc: File

Appendix B

Participant Consent Form

Perceptual Optimization for Data Visualization

A study carried out under the direction of Dr. Colin Ware in the Data Visualization Research Lab at the University of New Hampshire. You can contact him at any time with questions about the study (email: cware@ccom.unh.edu, phone 862-1138).

Purpose: The purpose of this study is to find more effective ways of displaying scientific data. The potential benefit of this research is that data displays will be better designed in the future.

Description: In this study you will be asked to repeatedly rate how well you can see patterns in the display. You will be trained for 10 to 15 minutes, followed by 45 minutes when you will be asked to make repeated judgments. It will last about one hour overall. There are no known risks associated with this research.

PLEASE READ THE FOLLOWING STATEMENTS AND RESPOND AS TO WHETHER OR NOT YOU ARE WILLING TO PARTICIPATE:

1. I understand that the use of human subjects in this project has been approved by the UNH Institutional Review Board for the Protection of Human Research Subjects.
2. I understand the scope, aims, and purposes of this research project and the procedures to be followed and the expected duration of my participation.
3. I have received a description of any potential benefits that may be accrued from this research and understand how they may affect me or others.
4. I understand that the confidentiality of all data and records associated with my participation in this research, including my identity, will be fully maintained.
5. I understand that my consent to participate in this research is entirely voluntary, and that my refusal to participate will involve no prejudice, penalty, or loss of benefits to which I would otherwise be entitled.
6. I understand that if I have any questions regarding this research and my rights as a research subject, I can to call or email Dr. Colin Ware(ph 862-1138, cware@ccom.unh.edu) and be given the opportunity to discuss them in confidence.
7. I further understand that if I consent to participate, I may discontinue my participation at any time without prejudice. Also I may contact the UNH Institutional Review Board if I have any concerns relating to the experiment (ph 862-2003).
8. I confirm that no coercion of any kind was used in seeking my participation in this research project.
9. I understand that I will be paid $18.00/hr for my participation.
10. I understand that any information gained about me as a result of my participation will be provided to me at the conclusion of my involvement in this research project at my request.
11. I certify that I have read and fully understand the purpose of this research project and its risks and benefits to me as stated above.

I, ______________________________ ☐ CONSENT

☐ REFUSE

to participate in this research project (check one).

______________________________ ______________________

Signature Date

Invoice

Meteorological Display Experiment

For participation in Human Factor's Study in the Data Visualization Research Lab.

Amount:__________________ Date:_____________Time:________

Name:___________________ Signature:____________________

Address: __________________________

____

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