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Investigating Flow Visualizations using Interactive Design Space Hill Climbing

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***Abstract*—Optimizing complex displays is difficult because there are many alternative ways of mapping the data to its graphical representation. In this paper we report on a study employing a method we call "interactive design space hill climbing". This involves first parameterizing the mapping from data to display. Next, using an interactive interface, designers and domain experts attempt to construct good designs by interactively changing parameters settings based on a random starting point. In our study we applied this method to the problem of 2D flow visualization: users adjusted 22 different sliders under each of 11 mappings to try to create an optimal display of a flow field from an ocean flow model. The results suggest that some variables should have settings in a narrow range. We conclude that employing designers with a human in the loop hill climbing interface can be a good overall solution for complex visual display designs in cases where a relatively simple parameterization is possible.**

***Keywords*—flow visualization, oceanography, vector fields**

I. Introduction

To understand patterns of winds or currents we mostly resort to graphical representation such as wind barbs, streamlines or grids of little arrows representing the vectors. Which of these is chosen is usually a matter of what the data analysis package supports and skill of the user. By far the most common choice is the arrow grid method. This is unfortunate since in many cases arrow grids result in the flow patterns being barely legible. Experiments by Laidlaw et al [8] compared several flow visualization methods and showed that for the task of perceiving advection pathways, a pattern where the arrows are arranged head to tail was much more effective than an arrow grid. Laidlaw's ground-breaking study was the first time anyone had attempted to evaluate the effectiveness of different flow visualization methods. However, because each of their representations could have had variations that were as good or better we cannot conclude that the particular solution they found to be most effective was actually the best.

In this paper we report an investigation into what it takes to produce a reliably high quality visualization of 2D flow patterns. It is also an investigation into a methodology for creating good designs of complex visualization problems that we call interactive design space hill climbing (IDSHC) that uses human designers in the hill climbing loop to produce a large set of good design solutions to be considered. Starting with perceptual theory and efficient algorithms from computer science, together with insights gained from Laidlaw et al's [8] prior results, we built a package that allowed for many mappings between the flow model output and its representation. We put this in the hands of designers, meteorologists and non experts to understand the characteristics of a good representation. The end result is a set of guidelines that constrain what makes an effective flow visualization. These guidelines have been incorporated into a software package we call flowVis2d that produces high quality graphical representations either in a design mode or in a production mode on a server for web dissemination of images.

The task of interpreting a flow pattern (such as a pattern of winds or ocean currents) can be thought of in perceptual terms as related to the problem of how the brain picks out extended contours from the visual environment. Well established theories about the mechanisms of contour perception exist in cognitive neuroscience [5], and these make clear predictions about what representation should be most effective [9]. In particular they suggest that head to tail glyphs, such as those shown in Figure 1 should be much more effective than either grids of arrows or jittered arrows. This argument is made in detail in [9].

If we accept the idea that flows should be represented by either head to tail elements or long, continuous contours we have a number of remaining problems. What should the spacing of streamlines be? Are there better methods than using an arrowhead to show the direction along a contour? There are good perceptual reasons why simple arrow-heads are not likely to be the best solution [1, 9]. A design that blends from the background color to another contrasting color may a better solution as illustrated in Fig 1(b, d, e and f) than using arrow-heads, because the along path asymmetry may be more pronounced [6]. Another problem is the representation of flow speed. Options include mapping speed to glyph width or length or color. We undertook an investigation of these questions in a study that involved a software package capable of producing a

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great variety of mappings between the flow field and its representation.

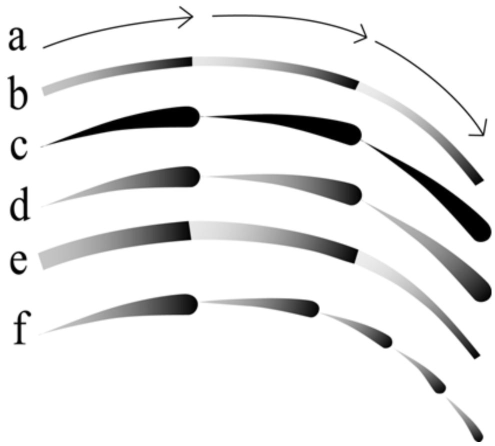


Figure 1. A few of the variations that are possible once the idea of head-to tail arrows has been adopted. (a) Curved conventional arrows. (b) Shading along steaklet to show direction. (c) Width change along streaklet to show direction. (d) Combined width and shading variation to show direction. (e) Width for speed, shading for direction. (f) Length for speed. Width and shading for direction.

II. The Metaproblem: Complex Display Optimization

The present study is part of a program that we (House et al) have been carrying out to understand how best to optimize displays for even moderately complex visualization problems. The fundamental difficulty is that a typical information display—for example, one used in GIS—has somewhere between 8 and several hundred variables controlling its design. Even a simple symbol may have six to control color (3) shape (1) and size (1). Then there are parameters to control line width and style for different classes of lines. Color sequences for pseudo-colored background maps can each involve a large number of parameters, and the same is true for texture overlays.

To understand why this is such a difficult problem consider how it might be solved using the kind of parametric study commonly used in psychology experiments. In such studies typically a simple task is defined, a few settings of two or three variables are manipulated and task performance measured under all combinations of settings. Unfortunately this method does not scale because the number of trials grow exponentially with the number of parameters controlling the display design. In the present study, we found even a pared-down parameterization of a simple flow visualization problem to have 22 display variables and many possible mappings of data to variables. A complete factorial design examining four levels of each would result in more than a trillion conditions (4^{22}). Fractional factorial method can drastically reduce this number but still will result in an impossibly large number of conditions [10].

Another solution we have explored in previous work we is whether a genetic algorithm combined with human judgment to provide a fitness function could produce good designs [3]. The answer was yes, but the process was extremely laborious involving 50 hours of observation from several participants. Much less than a lifetime but this would not be considered an acceptable approach for most applications. The solution we explore in this paper is *human in the loop hill climbing*.

A. Human in the Loop Hill Climbing

Hill climbing is a technique used in numerical optimization of complex multi-parameter designs. It works as follows: Suppose we have 30 parameters *defining the design of a system* that solves a problem. The computer sets all the parameter values randomly, then somehow measures how good the resulting system is in solving the specified problem. Next, one or more parameters are adjusted a little and the new solution is tested. If it is better, the parameters are adjusted again in the *same direction*, essentially “climbing the hill” towards an optimal solution. If it is worse then parameters are adjusted in the opposite direction. The process is repeated until the results get no better. The system has climbed the hill to a locally optimal solution. But there may be many hills in the solution space and the one climbed may not have been the highest. Thus the hill-climbing process must be repeated with many random starting points in the hope of climbing the slope of the highest peak to achieve the overall optimum.

In interactive design space hill climbing we use people instead of computers to both adjust the parameters and judge the goodness of the solution. The idea is to parameterize the mapping between the data and the display and provide participants with the ability to rapidly change parameter settings to come up with good design solutions with a minimal effort. By beginning with random starting points in the solution space we hope to be able to discover many good solutions. Later analysis of the data will hopefully reveal the important general characteristics of good solutions.

In outline, our approach has the following 5 steps:

Step 1: Parameterize the mapping between data and display. A set of parameters must be designed that control how color, shape texture, and other perceptually important display attributes, are used to represent the underlying data. Because there are likely to be too many parameters for all of them to be used in the hill climbing process the most promising candidate parameters and mappings must be somehow identified.

Step 2: Create an interface allowing users to change parameter values interactively. To make it possible to rapidly explore a complex design space the design must be updated rapidly when the user changes a parameter. Also, it may be necessary to allow for the data to display *mappings* to be changed as well as the parameter values. For example, glyph color may be used to show flow speed, or it may simply be used to show direction (as illustrated in figure 1).

Step 3: Hill climb in the design space from random starting position. Starting with random settings participants “hill climb” towards an optimal design by changing each of the sliders one or more times with the goal of improving the design with each interaction. The interaction stops when the participants feel they have reached a high quality solution. Hill climbing must be done as many times as is practical to get a reasonable chance of finding the higher peaks in the design space.

Step 4: Evaluate the set of solutions. The result of the process can be a quite large set of what should be good solutions. The final problem is to extract from this data the general characteristics of good solutions. Alternatively, one of the solutions can be chosen directly in an application

III. METHOD

In order to explore the effectiveness of human in the loop hill climbing we use 2D flow visualization as a test case. In particular we chose a data set representing the ocean currents in the gulf of Maine together with the surface temperature. Our choice was guided by the fact that looking at currents and temperature together is a common visualization requirement.

A. Parameterization of flow visualization

Our starting point, based on the perceptual theory we have already outlined, was that the basic representation should be a set of glyphs arranged head to-tail along streamlines. We called these glyphs "*streaklets"* and the streaklets were arranged head-to-tail along the path of streamlines.

1) Optionally speed could be mapped to width
2) Optionally length could be mapped to speed.
3) The head color, width, length and transparency of streaklets (6 params),
4) The tail color width, length and transparency of each streaklet.

In addition to the set of parameters listed above there are many possible *mappings* between the vector field and its representation. For example, streaklet width can be made to vary with speed, or it can be fixed. The same is true for streaklet length, transparency or color. Some of the options seemed less promising than others. For example, streaklet color might be mapped to water temperature, but since water temperature is commonly displayed using the background we eliminated this option. Even so, it was only with considerable effort that we managed to reduce the number of parameters to 22 and the set of mappings to include only the 11 that seemed likely to produce good results. This set was arrived at though a series of informal design meetings.

The set of 22 Parameters we chose fall into seven categories. (HSV refers to Hue, Saturation and Value. These were transformed to Red, Green and Blue monitor values using [ref]).

1) Streaklet spacing [1 parameter]: max spacing.
2) Streaklet Length [1 parameter].
3) Streaklet Head [6 parameters]: width (1), HSV color (3), transparency (1), head circle diameter (1).
4) Streaklet Tail [5 parameters]: Width (1), HSV color (3), transparency (1).
5) Background temperature scale [6 parameters]: Max HSV color (3). Min HSV color (3).
7) Color of the land area [3 parameters]: HSV color (3).

The mappings we chose are given in Table 1.

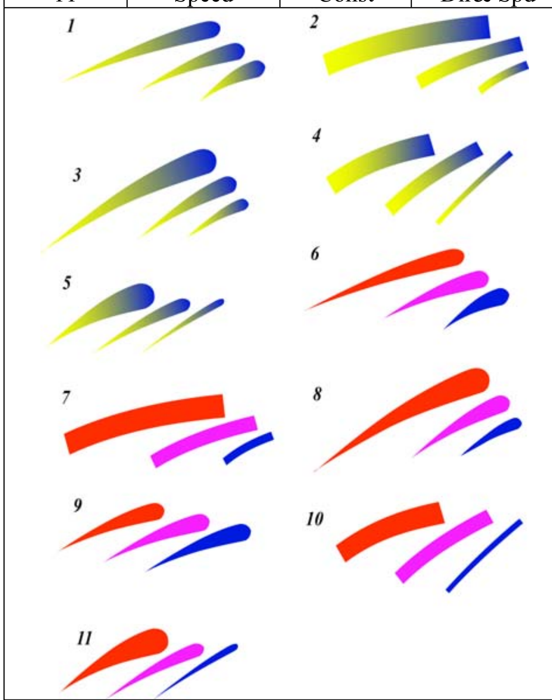
B. Notes on the mappings

1) Opacity was always used to support direction.

2) When direction is the mapping for color, HSV sliders control the minimum and maximum color, such that minimum occurs at the tail of each streaklet and maximum occurs at the head of each streaklet. When speed is the mapping for color, the streaklet color is proportional to the flow speed. In this case the minimum color occurs in regions of the lowest speed and maximum color occurs in regions of the highest flow.

TABLE I. MAPPINGS

Mapping	Color	Length	Width
1	Direction	Speed	Direction
2	Direction	Speed	Speed
3	Direction	Speed	Dir&Spd
4	Direction	Const	Speed
5	Direction	Const	Dir& Spd
6	Speed	Speed	Direction
7	Speed	Speed	Speed
8	Speed	Speed	Dir& Spd
9	Speed	Const	Direction
10	Speed	Const	Speed
11	Speed	Const	Dir& Spd



3) When length is mapped to speed, the length of each streaklet is proportional to the speed and the slider controls the maximum length. When it is mapped to constant all streaklets have the same length and the slider controls that length.

4) When direction is the mapping for width, the sliders control the minimum and maximum width, such that minimum occurs at the tail of each streaklet and maximum occurs at the head of each streaklet. When speed is the mapping for width, the streaklet width is proportional to the flow speed. In this case

the minimum setting applies in regions of the lowest speed and maximum setting applies in regions of the highest flow. (Note it is quite possible to have wide streaks in low flow areas and narrow steaks in high flow areas as well as the reverse).

5) When dir&spd is the mapping each streaklet both gets bigger along its length and both length and width are proportional to the flow speed. Participants can adjust the maximum width.

C. Hill Climbing Interface

We created an application interface that enabled participants to use a set of sliders to control the 22 parameter values (see figure 4). Sets of Hue, Saturation and Value Sliders was provided for the streaklet head and tail color and transparency. Other sliders controlled the other listed parameters such as width and length. The experimenter was provided with an additional interface in order to change the mappings between these parameters and the aspects of the display they controlled (see the Notes on the Mappings Section).

D. Procedure

The optimization process was as follows. To begin, the subject repeatedly clicked on a button that caused the parameters to be randomized and a new solution to be drawn based on the setting. Once they saw an example that looked promising they cycled through the set of 22 sliders adjusting each to improve the representation. (The slider panel is illustrated in Figure 2). Subjects were asked to use each of the sliders at least twice during this process. Each subject carried out 22 optimizations, two with each of the mappings.

E. Participants

There were 8 participants. Two were design professors from the Rhode Island School of Design. One was a professional meteorologist. Two were the authors of this paper. The remaining three were graduate students in computer science.

F. Display

The software was run on a 20in LCD monitor with a native resolution of 1280x1024. The map part of the display was 800x800 pixels and this measured approximately 21 cm square. The viewing distance was approximately 75 cm although participants were not restricted in their head movements.

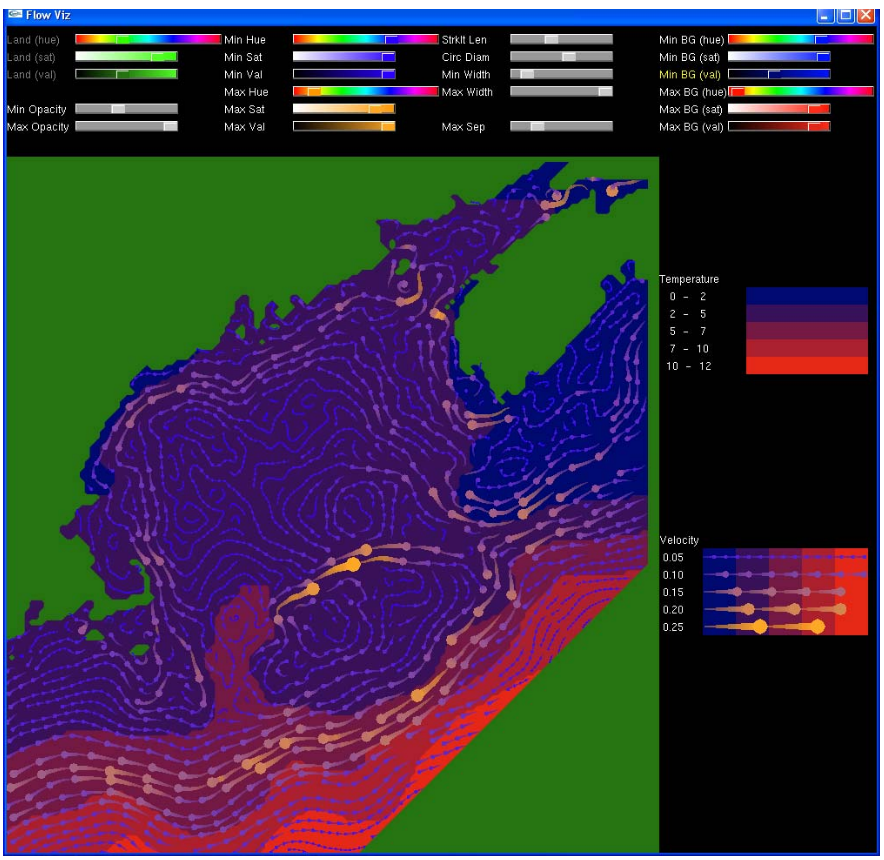


Figure 2. In this example speed is mapped to both color width and length (mapping 8).

IV. Results

The experiment produced 8*22 optimized solutions. These were rated independently by the first two authors of the paper and by two designers other than those in the initial study (Note that the authors did not pick their own solutions more often than the other judges). On the larger question of whether certain mappings are inherently superior, there was no clear answer. All of the mappings produced at least one solution rated in the top quartile. Also all of the participants produced at least two solutions in the top quartile.

We examined the top 22 most highly rated solutions (12.5% of the total) for consistencies in parameter settings. For some of the parameters the settings were highly consistent, suggesting possible design guidelines. The following is a list of the means for most consistent settings for highly rated solutions with standard deviations given in brackets. Dimensions are given in millimeters, but for the 57cm viewing distance used in the study these can be converted to degrees of visual angle by dividing by 10.

Transparency for direction. One of the most consistent and reliable finding was that participants made the tail of the streaklets much more transparent (opacity = 0.93(0.1)) than the head (opacity=0.28(0.24)) presumably liking the way this indicated direction.

Head width for direction. With some of the mappings participants had independent control of the head and the tail of the streaklet (mappings: 1, 6, 9). For every highly rated solution in this group participants made the tail much narrower than the head to indicate direction. The mean head width was 1.65(0.6) mm and the mean tail width was 0.2(0.05) mm.

Width for speed. In the mappings where width was used to indicate speed (mappings: 2,4,7,10) participants always used larger streaklets to show greater speed. The mean width for maximum speed was 2.3(0.4) mm and the mean width for minimum speed was 0.17 (0.18) mm .

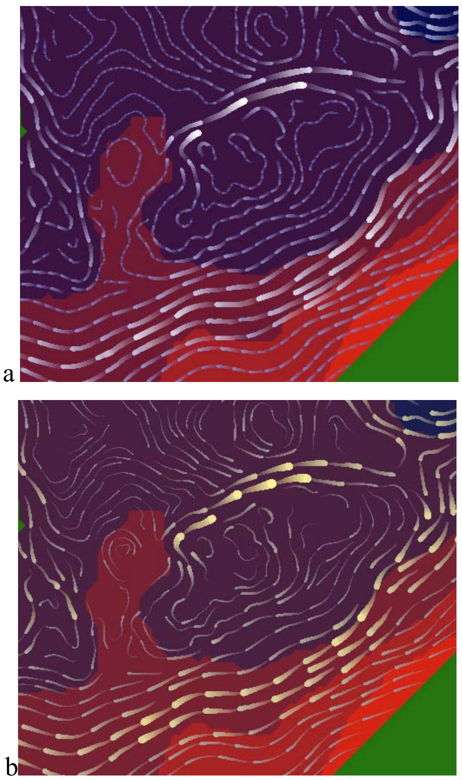
Length for speed. In all solutions where length was used to indicate speed (1,2,3,6,7,8) the mean maximum length was 25.0 (2.6) mm. Note that because of the algorithm the minimum length was zero.

Fixed Length. In all of the fixed length mappings (4,5,9,10,11) the average length was 12.5 (3.75) mm

Streaklet spacing. The average maximum spacing was 4.5 (1.9) mm. The average minimum separation was a bit smaller 4.0 (1.9). There were, however, almost as many instances where the minimum was greater than the maximum. Overall these results suggest that a single spacing of just over 4 mm may be optimal at the viewing distance we used.

Streaklet head color. The value setting of the head color was mostly close to the highest setting for 20 of the 22 cases (mean = 0.92(0.1)) with two cases where the streaklet head was set to black. Because the tails of the streaklet were mostly transparent the tail color is largely irrelevant. Saturation was varied widely but there was some bias towards low saturation values, meaning that streaklet heads tended to be close to white.

Other parameters were not set very consistently. In particular both head and tail hue were given a wide range of settings, as were the saturation values. However it is worth noting that since the tails of streaklets were almost always made nearly transparent, tail color setting would have little overall effect on the appearance.



a

b

Figure 3 Two designs using the most consistent settings. (a) A solution with streaklets having width and length proportional to speed; transparency provides the direction cue. (b) Similar to (a) but in addition streaklet heads are larger than the tails giving an additional direction cue.

V. Conclusion

Overall the results indicate that the space of good solutions is large, in that all of the mappings were capable of production highly rated solutions within the constraints imposed by the software. However, there were many consistencies among the results. These can be summarized as follows. The heads of streaklets were always made more visually distinct than the tails. This was done either by making the heads of the streaklets more opaque than the tails, or larger than the tails, or both. In cases where this was not done by transparency, it was done by means of width. The streaklet length was set to an average of about 12 mm (max 25mm) and the spacing was set to just over 4 mm. Narrower streaklets were used to show slower flow rates. Figure 3 shows two solutions generated using typical settings. In Figure 3a width and length are used for speed and the color is set to neutral and as light as possible.

What did we learn about the human in the loop hill climbing methodology? This exercise showed that it was possible to explore a 22 parameter design space in about one and a half hours. Also, although our software was custom developed, the key concepts could be made generic to display design software. The basic ingredients are a method for creating a slider panel and a method for parameter mapping. Creating a box of sliders that will allow a designer to interactively change a large number of parameters should certainly be feasible for many design projects, although it would clearly add to the development burden. It is also relatively easy to design software so that color choices can be reflected in the design in near real time. What is more of a challenge is creating an interface where parameters control aspects of visualization layout that interact with one another. Also, more radical design alternatives are unlikely to be achievable using a simple parametric interface.

All of the participants produced different styles especially in the use of color. As a result we found that there was considerable value in having several participants go through the design exercise. In addition, many of the settings were similar for all of the participants. The settings where there was close agreement are likely to be the most trustworthy.

We found the results of this study to be sufficiently compelling that we have incorporated them into an application that is currently under beta testing for NOAA's Nowcoast portal to show the ocean currents in different sections of the world's oceans. This uses one of the most highly rated mappings (mapping 3) together with the spacing, width and transparency settings that were close to the averages obtained in the study, although since monitors vary widely both in pixel size and color quality, the properties will only be approximated on any individual end-user's screen. We were able to directly use many of the parameter settings used in the study. But we also made a number of minor design changes, such as adding arrowheads to the streaklets.

The major problem that we see with the approach in general is that we only really dealt with a relatively simple visualization problem. What about the case where different backgrounds are needed? For example, we may need to display the same flow patterns over color backgrounds color coded to display either salinity, temperature, or speed where the user selects which Each background might have its own best color sequence. Ideally the same streaklet designs could be used with all the backgrounds, but this would be a much more complex optimization problem.

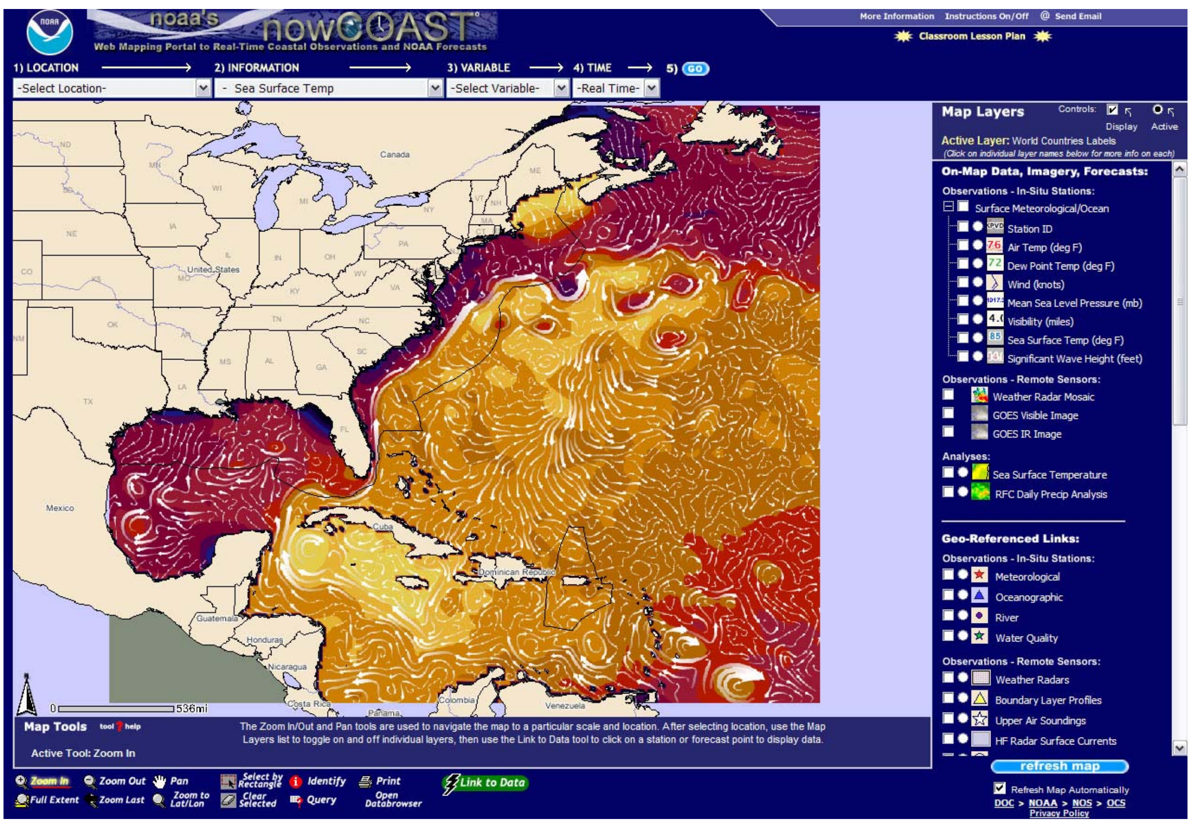


Figure 4. The display as it appears in the Nowcoast portal. Sea surface height is shown as the background.

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