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Multivariate Visualization of Oceanography Data Using Decals

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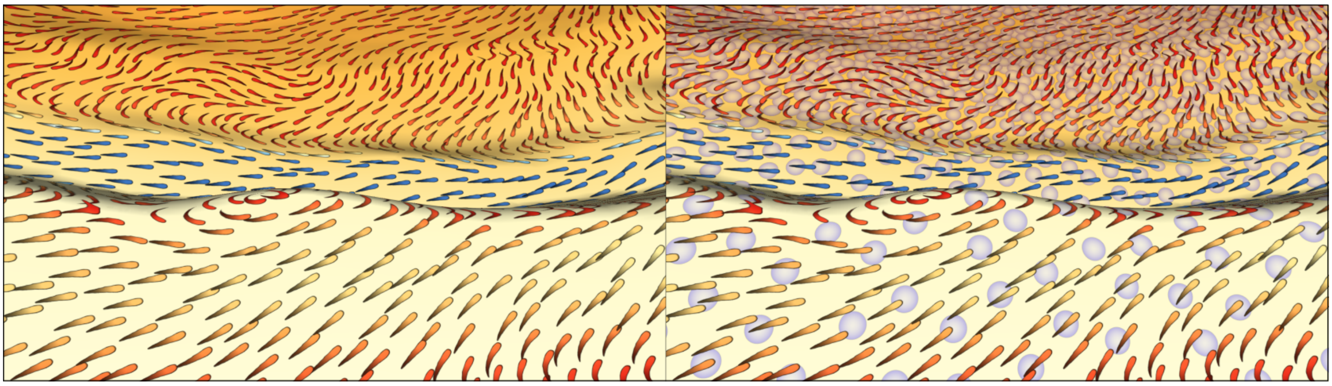

Figure 1: *Multivariate visualization displayed over a temperature isosurface extracted from an oceanography model, with three main visual features. (1) A sequential light yellow-to-orange colormap displays density; (2) the clustering of circular decals represents salinity; and (3) streamlet decals combined with a cool-to-warm colormap illustrate the vector field direction and magnitude of ocean currents.*

Abstract

In this paper, we present our results on the 2016 Compute Canada Visualization Contest, which centers around the visualization of multiple oceanographic data attributes. Our goal is to help researchers better understand the correlation between these attributes by providing an integrated data visualization. To accomplish this goal, we combine decals and colormaps in a layered fashion over temperature isosurfaces extracted from an oceanography model. We describe how decals can be deformed and animated over isosurfaces to convey the sense of flow given by the ocean currents. Our visualization design focuses on addressing requirements from experts, tailored for such datasets. The results highlight the potential of our approach towards accessing the tridimensional multivariate nature of such complex data.

Categories and Subject Descriptors (according to ACM CCS): J.2 [Computer Applications]: Earth and Atmospheric Sciences – I.3 [Computer Graphics]: Applications

1 Introduction

Multivariate datasets are commonly explored by scientists to understand natural phenomena. Examples in Earth Sciences are atmospheric and oceanography studies conducted to understand climate change and its implications [JBMS09]. These datasets are typically multifaceted (e.g. multiscale, multimodal) and understanding them is a challenge for experts [KH13]. Visualization research has supported the process of data exploration by designing visualizations to understand complex environmental data [FH09, KH13]. For example, meteorological data visualization commonly represents multiple atmospheric attributes (e.g. wind, pressure) as well as oceanography data attributes (e.g. ocean currents, temperature) displayed on 2D maps [WP13, SK16]. Such datasets are 3D in nature, but, due to limitations of current visualization tools [WHP*11], and difficulties in data acquisition [Ros89], these datasets are usually studied and interpreted using 2D visualizations.

Our goal in this paper is to move one step forward towards addressing the multivariate aspects of an oceanography dataset, in view of the applicability of our approach to more general oceanography models [Mil16]. These multivariate aspects are essential to understanding how ocean currents behave, as their behavior depends on several other variables such as salinity, temperature and density, which are functions of time and space (geographic location). Experts explore trends in these properties to understand phenomena caused and related to the oceans such as the transfer of heat. However, the task of understanding multiple time-varying variables in the tridimensional context of oceanography models is difficult since multiple variables need to be visualized and correlated simultaneously.

Previous approaches propose 2D multivariate visualizations for oceanography data on maps [MWK09, NL15, WKP14], which are definitely useful but do not capture the tridimensionality of the data. Here, we take a different approach by visualizing multiple attributes displayed on isosurfaces extracted from the oceanography data. Isosurfaces and streamsurfaces have been helpful in accessing and understanding 3D datasets in several application domains [FH09, BCP*12, MLP*10], because (albeit still being 2-manifolds) they need not be flat. Moreover, correlating multiple attributes on arbitrary surfaces is a difficult technical and design problem to address. Here, we target the second problem by proposing a visual design of multiple oceanography attributes. Figure 1 illustrates the visualization of density, salinity and ocean currents in a layered fashion over a temperature isosurface. Our visualization builds upon a visualization technique proposed by Rocha *et al.* [RASS17] to design multivariate layered visualizations on arbitrary surfaces using decals combined with colormaps. By using these isosurfaces, researchers can contextualize the aforementioned variables with the depth of their sampling in the ocean (around 5 km at its deepest in our data).

The results we here present were developed for the 2016 Compute Canada Visualization Contest organized by Compute Canada's Visualization Team [Comb]. The goal was to create a visualization solution for an oceanography model contributed by an Earth Sciences researcher. The contest focused on addressing the following requirements: (**R1**) simultaneous display of multiple variables, (**R2**) animation of the ocean currents, (**R3**) visualization of the 3D nature of the data, and (**R4**) interactivity. Having these requirements in mind, we present our design and implementation as a contribution to the Visualization Contest.

2 Related Work

In early oceanographic studies, experiments were generally conducted on 2D datasets [Ros89]. Nonetheless, this barrier is being pushed by recent technological advances, which (coupled with the non-stopping increase in computational power) have allowed scientists to simulate ocean dynamics and to obtain rich 3D spatial time-varying datasets [HLC*97, PBI04, LHWS08, LLC*12].

Even though the availability of such high-resolution 3D datasets is increasing, most multivariate visualizations for this domain remain in two dimensions [WP13, NL15, SK16]. Even in 2D, the visualization of multiple attributes is still challenging and has been consistently targeted as a research problem by the visualization community [War12, Mun14]. Ware *et al.* present a study on how to improve the display of wind patterns and ocean currents to combine them with other variables such as pressure and temperature in a layered fashion [WP13]. Another example is *OceanPaths*, which provides a tool to visualize multivariate oceanography data on 2D maps along ocean currents, the latter being previously defined by the user [NL15]. In these examples, the process of layering was applied to 2D maps to visualize weather and ocean data. Despite its usefulness, the simplicity of this approach does not capture the tridimensionality of the phenomena, and can introduce distortions when spherical coordinates are unwrapped on the plane.

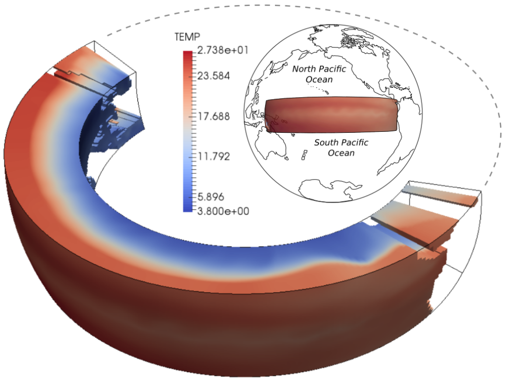

Figure 2: *Visualization of an oceanography model (tropical Pacific area) using Paraview [Hen07]. Temperature (degrees Celsius) is visualized using a cool-to-warm colormap; it increases near the ocean surface and decreases near the seabed.*

The challenge of capturing tridimensionality while visualizing multiple attributes has led to the development of visualizations that superimpose the data on 3D surfaces to provide some of the missing depth cues. Crawfis and Alisson [CA91], and Taylor [Tay02] discussed strategies to present multivariate data on surfaces in a layered fashion. Layering is also commonly applied to flow visualization by combining line integral convolution (LIC) [CL93] (to depict the flow pattern) with a colormap (to depict magnitude) [MLP*10].

Inspired by previous work [CA91, LAK*98, KML99, Tay02], Rocha *et al.* extended the layering concept to arbitrary surfaces by introducing decals for multivariate visualization design [RASS17]. As a result, the authors designed a multivariate visualization of six geological attributes on the surface of a reservoir model. This allows the new possibility of adapting to general surfaces (*i.e.* surfaces that can freely curve in 3D space), glyph-based techniques and design considerations that have worked so well in 2D. While still being two-dimensional objects, general surfaces can help in capturing part of the tridimensional nature of the data. Here we follow this direction and apply the *Decal-maps* technique [RASS17] combined with colormaps to design a multivariate visualization on surfaces extracted from a 3D oceanography dataset.

3 Data Representation

The oceanography dataset used in our work is part of a relatively low-resolution full-earth (i.e. land and ocean) climate simulation run with 1-day timesteps for 365 days. It consists of the tropical Pacific area represented by a curvilinear tridimensional grid (longitude, latitude and depth) stored in a NetCDF format (Figure 2). Each cell of the grid is associated with six time-varying variables – density, salinity, temperature and three velocity components. This dataset possesses a number of interesting features. Figure 2 depicts a sloping *thermocline* (a steep temperature gradient in a body of water); thermoclines vary seasonally according to meteorologic and oceanographic conditions and provide hints on climate change [WWL99].

4 Visualization Approach

4.1 Surface extraction

In our approach, we first analyzed the dataset using Paraview [Hen07] to identify interesting features to visualize. Figure 2

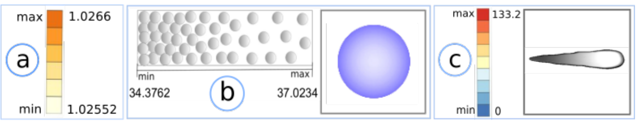

Figure 3: *Summary of the visual mapping. (a) Density, (b) salinity and (c) velocity field (adapted from [RASS17]).*

uses a cool-to-warm diverging colormap to visualize temperature. For our visualization, we extracted temperature isosurfaces (for different time steps) in the thermocline area at 15 degrees Celsius. We then used these isosurfaces as basis to apply a layered visualization technique whereby the following attributes are visualized simultaneously: salinity, density and the vector field of the currents. In Sec. 4.2, we present our visualization design followed by our implementation in Sec. 4.3.

4.2 Visualization Design

We use the format presented in [RASS17] to describe our visualization design. Table 1 summarizes our visual mapping. Each of our design choices is explained in more detail as follows.

Base layer: We use a sequential colormap from light-yellow to orange to represent density (Figure 3(a)). This choice is suitable since density is quantitative and ordinal data. The purpose of this colormap is to emphasize trends in density (3 to 5 ranges). Because it is a base layer and covers large areas, we use light tones and secondary colors (e.g. orange) as recommended by design guidelines [War12].

Salinity layer: Similar to porosity in [RASS17], salinity is quantitative data that can be visualized by clustering circular shaded (radial gradient) decals (Figure 3(b)). One can liken this illustrative representation to the variation of grains of salt in the ocean. Each circular decal is visualized in a light purple tone (secondary color). To generate the clustering, we implement an importance Poisson sampling technique [CCS12] to vary the concentration of decals according to salinity. We choose the radius of the Poisson sampling to generate a relatively coarse distribution. We also overlap the circular decals slightly to increase the sense of connectivity and continuity [War12, RASS17].

Currents layer: Ocean currents are given by a 3D vector field consisting of direction and magnitude. However, to apply layering on isosurfaces we only consider the 2D horizontal components. Moreover the vertical component is considerably smaller than the other two. For the 2D vector field representation, we consider the following requirements: (1) an object-space representation that maximizes the visibility of the underlying layers; (2) convey the direction and magnitude of the flow; (3) allow easily manipulation of the size and distribution of the visual representation. These requirements are not met by established techniques such as LIC and streamlines; due to occlusion and depth problems, they are not suitable for layering of multiple variables. Instead, we choose to use decals to represent streamlets. Streamlet decals meet the aforementioned requirements, are simple to compute and are independent of mesh connectivity/quality (marching cubes may produce low quality meshes). As described in Sec. 4.3, streamlet decals can also deform and be animated based on the underlying vector field. The deformation technique is robust for low quality meshes [RASS17], and does not suffer from the problem of Z-fighting [Zf] which becomes an issue when rendering streamlines on surfaces.

oceanographic data	**visual mapping**
density	sequential colormap (one hue)
salinity location	circular decal placement
current direction	streamlet decal
current magnitude	streamlet decal color variation

Table 1: *Mapping oceanographic data attributes to visual representations.*

We applied principles of perceptual studies in 2D flow visualization to our 2D vector field visualization using streamlet decals. Ware *et al.* study ways to visualize vector fields using streamlets to represent wind patterns and ocean currents on maps [WKP14]. In their work, the authors' recommended solution to show a vector field map is to "use a dense pattern of streamlines and along each streamline place elements that have a much stronger head than tail" [WKP14]. Streamlet decals are precisely such elements and we have designed them following these guidelines. Figure 3(c) shows our representation. The white-to-gray gradient gives the sense of flow, and the head represents the direction of the currents. To represent magnitude, we use an extended cool-to-warm diverging colormap [Kit17] to color each streamlet decal. In order to modulate the decal's gradient with the magnitude of the vector field, we apply the magnitude colormap over the entire surface and retain only the pixels covered by the streamlet decals. This allows us to easily mix the colors in the fragment shader. Furthermore, this approach allows us to increase the size of the decals to emphasize the magnitude using the colormap. For placement, we also distribute the decals using a Poisson sampling [CCS12]; this leads to a better alignment of the elements which in turn improves the sense of flow [WKP14].

4.3 Implementation

For our implementation, we need the isosurfaces as well as attributes referent to each geographic location. Using Paraview [Hen07], we extracted the isosurfaces and exported the geometry. The attributes were exported to CSV files. Even though we performed these operations using Paraview, they could be performed directly using VTK [SML06].

Rendering: Our visualization is implemented on the GPU using OpenGL and GLSL. The implementation consists of a multi-pass approach to create each layer as described by Rocha *et al.* [RASS17]. For the attributes salinity and ocean currents, we precomputed the respective Poisson distributions to place decals. *Sphere masking* [RASS17] was then applied in a layered fashion to map the corresponding decals. For better context, our final rendering consists of the outlines of the curvilinear grid (exported using Paraview) and the temperature isosurface. All layers are rendered over the isosurface following the order described in Sec. 4.2.

Deforming Decals: Decals can be deformed locally based on a given vector field. This is accomplished by changing the reference vector of the angular coordinate of the local parametrization while computing the texture coordinates; this deforms the texture coordinate space [RASS17]. One important point regarding the local deformation is that the center of a decal should not coincide with a singularity point of the vector field. This severely distorts the decals

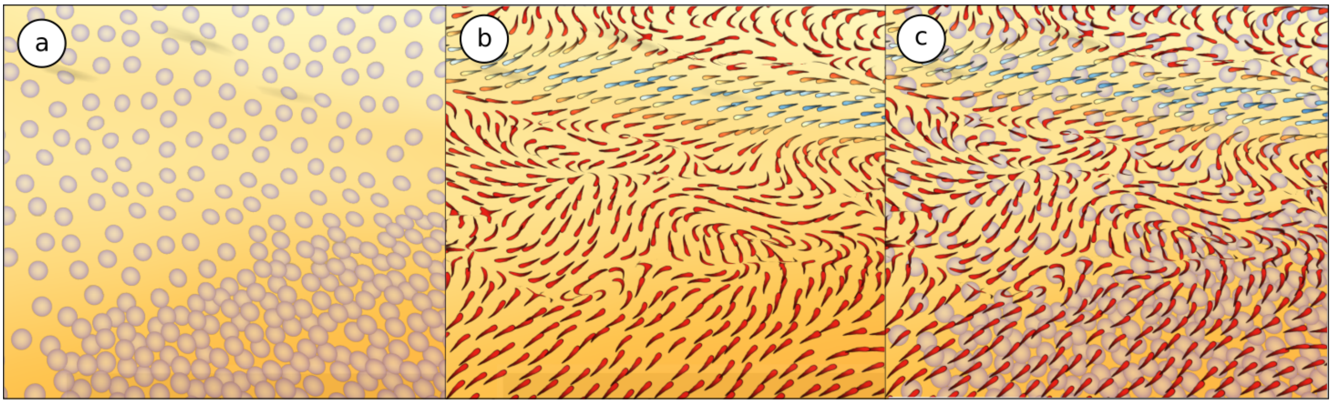

Figure 4: *Layering on a temperature isosurface combining density, salinity, and current flow.*

causing them to 'break'. However one can argue that this also provides visual cues on the location of the singularity points. Studying local deformations related to vector fields is an interesting topic; however we consider it to be outside the scope of this paper.

Animating Decals: To animate the decals, we simply need to offset the horizontal coordinate u (or the vertical depending on the local coordinate system) of the Cartesian texture coordinate system (after conversion). In our implementation, this offset is modulated by the magnitude of the vector field, which makes our streamlet decals move slowly if the magnitude is low and faster otherwise.

Recent studies strongly support that animation is the most effective way of showing flow direction in 2D steady flow patterns [WBM*16]. Ware *et al.* highlight that animated vector field patterns are costly to generate; this however is not the case in our implementation. There is yet another advantage of combining layering with animation. Since animation employs a separate visual channel, there is less visual interference between an animated layer and other background information [WBM*16, War12].

4.4 Results

Layering: Our design choices for the representation of the attributes address the inter-layer interference of the visual elements. Factors such as complexity of the attributes, degree of visualization interest (trends vs. details) and importance of the phenomenon need to be considered during the design. Our focus was to represent trends in density and salinity while visualizing details of the currents. For the salinity attribute for example, we chose circular decals which are bigger than the streamlet decals and have a 50% opacity to avoid interference (Figure 4(a)). We also highlight two other visual cues: circular decals are shaded which leads to the *cornsweet effect* [War12] which helps us separate the current layer from the salinity layer (Fig. 4(c)); the circular decals have a light purple tone which helps us distinguish between predominant primary colors used to represent the streamlet decals' magnitude (cool-to-warm) (Fig. 4(b and c)). For the current layer, we chose a thin black outline around each streamlet decal (like a halo) to separate this layer from the other ones (Fig. 3(b)).

We would like to point out two other aspects of our design: color contrast and surface lighting. The contrast between the primary (e.g. red, blue) and the secondary colors (e.g. orange, purple) enhances the understanding between layers and reduces visual interference. We obtained good shading results by bounding the coefficient of the diffuse light between 0.5 and 1.

Interaction: Apart from basic interactions such as rotation and zooming, the users can turn on/off each layer, scale the decals and animate the vector field currents. These interactions can help the user focus on a single attribute; they also reduce clutter in case of an overview while preserving the same context.

Performance: We tested our multivariate visualization (all layers) on an Intel® Core™ i7 laptop with an Nvidia GeForce GTX 960M 2G GPU. The rendering resolution was 1920 × 1080 pixels with 8x MSAA (multisample antialiasing). The decal-maps technique only calculates textures coordinates for visible decals [RASS17]; in our tests with decals distributed over the whole screen, we achieved an average rate of 49 frames per second without fine optimizations.

5 Conclusions and Future Work

We have provided a multivariate visualization (**R1**) over isosurfaces extracted from the data (**R3**). Users can animate the ocean current streamlets to get a better sense of flow (**R2**) and explore the multivariate visualization by interacting with the layers and decals (**R4**). It is important to highlight that our design can be improved since the design space is vast [SK16]. Preliminary feedback from experts using the system highlighted that the simultaneous display of density, salinity and the velocity field enhanced their perception of the oceanographic patterns. Moreover, the interactivity of the fluid flow animation provided better insights into the correlation between salinity, temperature and trends in the ocean currents. As future work, other variables such as pressure could also be included. Strategies to address clutter, emphasize important features and de-emphasize unimportant ones are essential for an effective design and should be considered. We would like to automate our implementation so that the user can interactively explore different isosurfaces corresponding to different isovalues. Lastly, we would like to further evaluate our application with domain experts to investigate how effectively it can help address complex tasks in this domain.

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