Geospatial Visualization Using Hardware Accelerated Real-Time Volume Rendering

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***Abstract*-We present a visualization framework using direct volume rendering techniques that achieves real-time performance and high image quality. The visualization program runs on a desktop as well as in an immersive environment. The application is named HurricaneVis, and it uses OpenGL, GLSL and VTK. For immersive visualization VRJuggler is added.**

To achieve real-time rendering rates for 4D scalar data we use the programmability of the GPU and in particular store the transfer functions as well as the 3D volume of scalar data on the GPU in texture memory.

The initial use was visualization of scalar data from numerical weather model simulations of tropical cyclones, namely Hurricanes Isabelle and Lili. We are expanding that to include visualization of other types of data sets. We conducted a user study to compare the implemented volume rendering technique with state-of-the-art isosurface rendering. The subjects were students in the Dynamic Meteorology II and Physical Meteorology classes in the Department of Geosciences at Mississippi State University. The results establish that both volume rendering and isosurface visualizations are effective in examining data from computer simulations of hurricanes. Because of the higher image quality and the higher frame rates, direct volume rendering using ray-casting or view-aligned texture slicing was preferred.

I. Introduction

Through the years weather forecasts have become more accurate because of improved observations and enhanced understanding along with ongoing technical development. Nevertheless there are still many unanswered questions, especially in the prediction of both track and intensity of hurricanes. The frequent appearance of severe hurricanes in recent years, such as Ivan (2004) and Katrina (2005) demonstrated the need for research in this area. A more detailed and interactive visualization achieved through the rendering of 4D data in real-time can enhance the understanding of hurricanes, hopefully leading to better predictions in the future.

The latest developments in graphics cards offer new possibilities in the field of visualization. Computationally expensive techniques like volume rendering can now be implemented directly on the Graphics Processing Unit (GPU) and offload this processing from the Central Processing Unit (CPU). This heterogeneous computing holds great promise, not only for entertainment applications but also for scientific visualization. Both performance and image quality can be significantly improved [1]. Although the application started with visualizing hurricane data, it is flexible enough to adapt to any type of 4D data set, either computed or measured. We demonstrate this by visualizing ocean data as a second type of gridded data.

II. Background

A. *Motivation from an ongoing interest in 3D visualization of severe storms*

Numerical models such as the Mesoscale Model 5 (MM5) or the Weather Research and Forecasting Model (WRF) are used by meteorologists in the prediction and study of severe storms. The output from such models varies greatly depending on the model parameterizations, the initialization conditions, the simulation resolution and the computational resources available. The massive amount of data that is generated can become very difficult to comprehend using traditional 2D visualization techniques.

Most meteorologists use statistical and visual analysis tools to gain insight into the data. The visualization tools commonly used generate 2D slices through the 4D (latitude, longitude, altitude, and time) grid. These 2D slices can be difficult to understand, requiring substantial training and experience. We contend that 4D representations of this computed data can aid researchers and operational personnel in their understanding and investigation of these large, complex data sets.

B. *Interaction is valuable and important*

The hardware accelerated rendering on the GPU provides real-time interaction to the user. Interaction provides meteorologists with the possibility to investigate the 4D data in arbitrary views on their desktop computer. Also, properties of the visualization can be changed in real-time. Therefore the spatial visualization is more dynamic and compelling than the commonly used static 2D slices.

C. *Shading languages – making it possible to interactively review data*

Shading language concepts were introduced to the computer graphics and visualization communities in Cook's Shade Trees paper [2]. The dramatic increase in quality of computer generated images has been apparent in movies from the time of Toy Story. Recently customized shading has enabled video games to have this type of impressive realistic rendering because the GPUs in desktop and laptop computers now allow customization of the rendering pipeline through shading language programs. There are three primary shading languages available, OpenGL shading language, Cg and DirectX High-Level Shader Language. OpenGL shading language (GLSL) [3] was designed by the OpenGL Architecture Review Board and is now supported through modern GPU drivers. Cg [4] was developed by NVIDIA but can be used with GPUs not only from NVIDIA but other chip sets as well. DirectX High-Level Shader Language (HLSL) was developed by Microsoft and is similar to Cg. All of these languages are C-style languages that operate on the GPUs. This is not the same as languages such as CUDA by NVIDIA, which are intended for general purpose computing on GPUs.

III. VISUALIZATION SOFTWARE

The software program created during this effort, HurricaneVis, is based on the Visualization Toolkit (VTK) [5] because it is a powerful and comprehensive framework for visualization. Additionally, HurricaneVis uses a framework for hardware accelerated ray casting by Ralph Brecheisen [6]. We extended this framework to include further visualization techniques, namely object-aligned and view-aligned texture slicing. Additionally, we provided user interaction for modification of the transfer function.

The portion of the software that does the volume rendering is implemented through shader programs written in the OpenGL Shading Language (GLSL). This results in rendering that is significantly faster than CPU-based algorithms.

VRJuggler [7] enabled us to move the HurricaneVis application from a desktop to a CAVE environment. We used vjVTK [8] to make this move easier.

IV. RESULTS

A. *Hurricane Data Sets*

We present results of working with two hurricane data sets created from numerical weather models. Hurricane Lili was unique as it dramatically weakened from a category 4 hurricane to a category 1 in a period of just over 13 hours. Zhang, Xiao, and Fitzpatrick [9] found that this weakening can be attributed to a shaft of dry air moving into the hurricane core from the Southwest. Hurricane Isabel was chosen because it is one of the most closely observed hurricanes and a number of simulations and visualization experiments have successfully used this data.

Hurricane Lili originated on September 16, 2002 and crossed mainland Cuba on October 1st with wind speeds of over 90 knots, gradually turning northward. On October 3rd, it exhibited sustained wind speeds of 125 knots over the Gulf of Mexico before dramatically weakening to maximum wind speeds of 80 knots before making landfall in Louisiana. .

Hurricane Lili's track provided by the National Hurricane Center is in Figure 1.

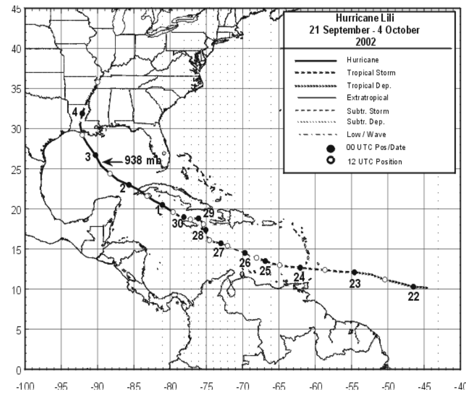

Figure 1: Hurricane Lili's track

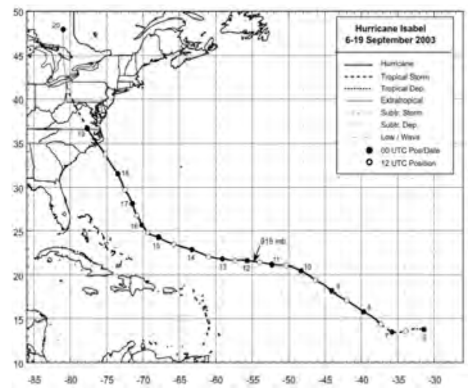

Figure 2: Hurricane Isabel's track

Hurricane Isabel formed on September 1, 2003 and became a category 5 hurricane on September 11th with sustained wind speeds of over 145 knots. These winds stayed in the 130-140 knot range until September 15th. During this time the eye exhibited a diameter of 35-45 nautical miles. Vertical wind shear caused Hurricane Isabel to gradually weaken and it made landfall near Drum Inlet, North Carolina, USA on September 18th as a category 2 storm. The track of Hurricane Isabel provided by the National Hurricane Center is in Figure 2.

The Hurricane Lili data came from the Four-Dimensional Variational Analysis (4DVAR) sensitivity run outputs of Zhang, Xiao, and Fitzpatrick [9]. They used the fifth generation Penn-State University – National Center for Atmospheric Research Mesoscale Model (MM5) [10] to simulate Hurricane Lili.

The Hurricane Isabel data came from the dataset provided for the 2004 IEEE Visualization Conference contest. [11]

B. *Ocean Data Set*

Barbara Reed, NAVOCEANO provided access to a dataset of ocean data. The data was generated by the Navy Coastal Ocean Model (NCOM) and includes temperature, salinity, eastward currents, northward currents, and surface elevation.

Sample images of temperature and salinity are in the following section.

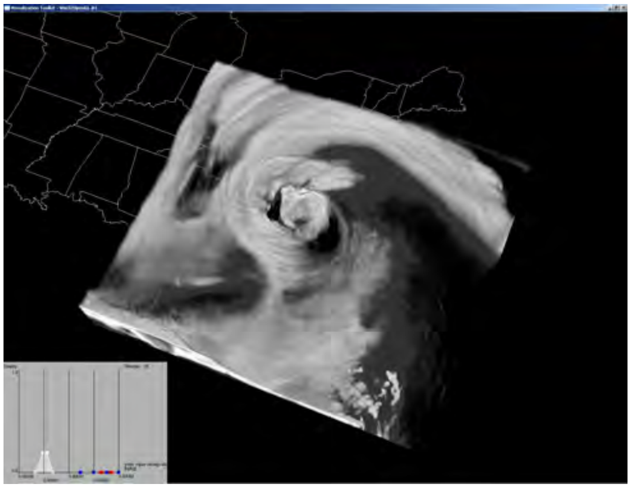

Figure 3: Hurricane Isabel, Q variable

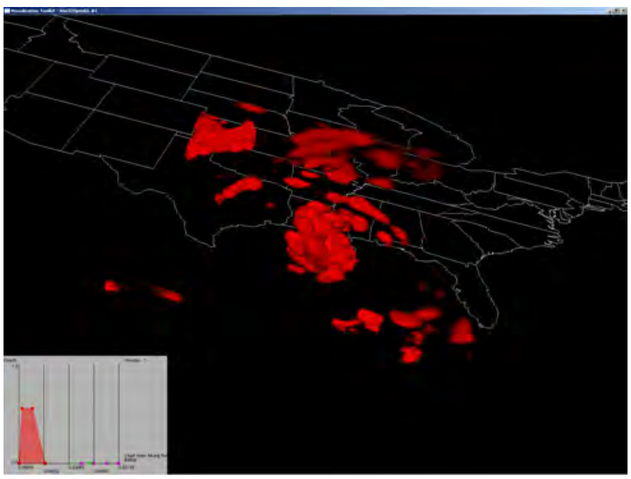

Figure 4: Hurricane Lili, Cloud-Water Mixing (CLW) variable

C. Sample Images from HurricaneVis

Figures 3 and 4 are screen shots from HurricaneVis on a desktop computer. Figure 3 is the scalar variable labeled Q (water-vapor mixing ratio). Figure 4 is the scalar variable labeled CLW (cloud water mixing ration). In the lower left-hand of each display is the area of the display where the user can interactively modify the transfer function. Figures 5 and 6 are screen shots of the NCOM ocean data set. Figure 7 is HurricaneVis in the MSU Virtual Environment for Realtime Exploration (VERTEX).

V. User Study

A. Study Goals

We conducted a user study to evaluate this statement: "Volume rendering and isosurface visualization can both be used to examine hurricane data, but volume rendering is more easily and effectively understood." [1,11] The comparison for this user study involved using HurricaneVis for the volume rendering and ParaView for the isosurface visualization. ParaView is an open source software tool, based on VTK, that has comprehensive capabilities for user interaction and is well documented. It was principally developed by Kitware.

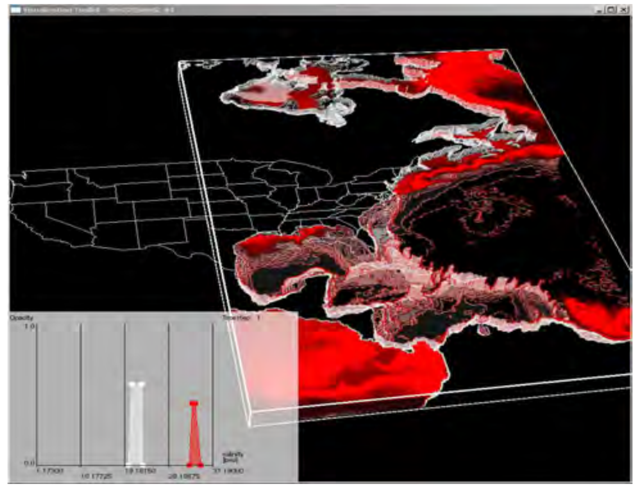

Figure 5: Salinity from NCOM Ocean data set

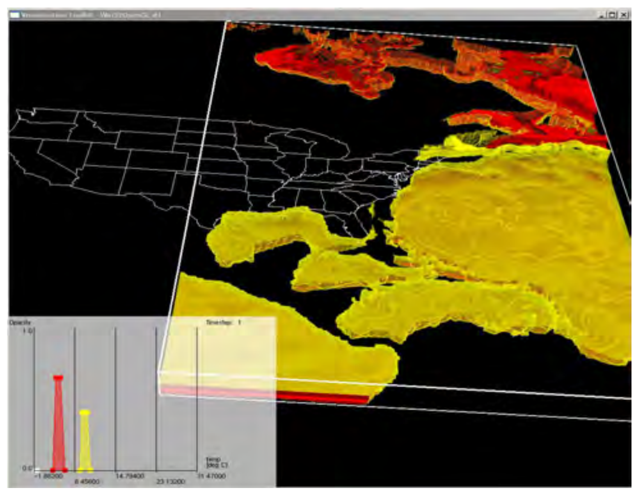

Figure 6: Temperature from NCOM Ocean data set

Figure 7: HurricaneVis in the MSU VERTEX

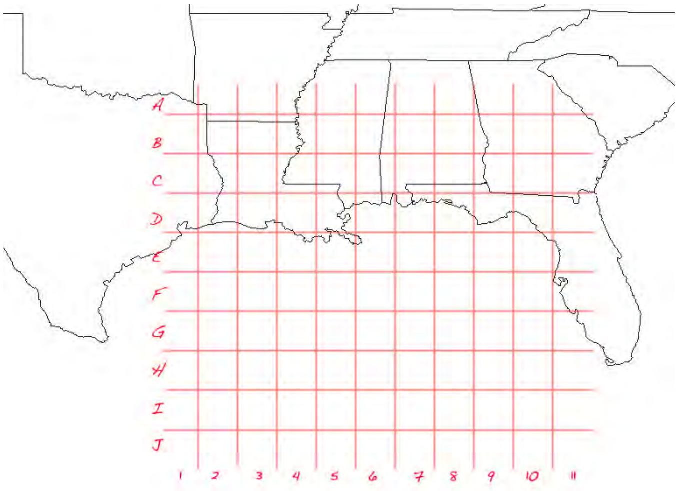

Figure 8: Map used for Hurricane Lili data

B. Subjects

Fifteen students at Mississippi State University served as the subjects for this user study. These students were from two classes *Dynamic Meteorology II* and *Physical Meteorology*. Seven subjects were senior undergraduate students and eight were graduate students.

C. Tests for subjects

Each of the subjects participated in an hour-long training session where they learned how to use both ParaView and HurricaneVis. Using the Hurricane Lili data, we conducted a pilot study to determine the usefulness of the questions. In the actual user study, we used the same questions but presented the Hurricane Isabel data.

Half of the subjects used HurricaneVis first, and the other half used ParaView first. Figure 8 is the map used for questions and answers about the Hurricane Lili data set. We also asked the subjects to record the amount of time they needed to answer each of the questions.

The five questions for Hurricane Lili were:

1. Where is the strongest moisture inflow into the eye of the storm in timestep 4? Mark **one quad** on the map.
2. What timestep (0 - 8) corresponds with the maximum vertical extent of the 300 Kelvin isotherm?
3. What region shows the strongest horizontal wind speeds in timestep 5? Mark **one quad** on the map.
4. What region shows the highest upward vertical wind speeds (updrafts) in timestep 0? Mark **one quad** on the map.
5. What region shows the highest downward vertical wind speeds (subsidence) in timestep 0? Mark **one quad** on the map.

D. Results

The analysis of the user study indicates that users of HurricaneVis are more accurate and/or faster than they are when using ParaView. Subjects may have been able to answer questions more quickly with HurricaneVis because the interface is easier to use. However, the results do indicate a significant advantage of direct volume rendering compared to the representation with isosurfaces.

Tables 1 and 2 below are a summary of the results from the user study. We used scatterplots, interval plot of means, and ANOVA to analyze the results of each question. "PV" represents ParaView and "HV" represents HurricaneVis. "w" indicates that the visualization technique is a significant winner.

Table 1: Accuracy results

	Accuracy				
	Q1	Q2	Q3	Q4	Q5
PV					
HV				w	w

Table 2: Timing results

	Time				
	Q1	Q2	Q3	Q4	Q5
PV					
HV	w	w	w		

VI. Conclusions and Future Work

HurricaneVis is a promising prototype that was successfully used by undergraduate and graduate students to evaluate and investigate numerical weather model data. The superior image quality from direct volume rendering presents a promising and user friendly way to evaluate extensive, 3D, time-dependent data. The interactive modification of transfer functions is very appealing to users.

The user study confirmed our expectations that both direct volume rendering and isosurface visualization are useful and effective as techniques for these large data sets. Users preferred direct volume rendering because of the higher image quality and the interactive frame rates made possible by shader programs running on the GPU.

We need to conduct additional user studies to quantify performance differences between using the traditional 2D methods and these 4D methods. While there is no doubt users enjoy the interactive 4D presentations, establishing the specific benefits to understanding and eventually performance when doing a task is imperative.

Acknowledgment

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