Exploring Geographic Data in a 3D Environment: 3D Visualization and Analysis of Severe Tropical Cyclone Larry

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ABSTRACT

Three-dimensional visualization of GIS data is emerging as a powerful tool through which to better understand severe weather events such as tropical storms and hurricanes. The integration of scientific data, satellite imagery, and GIS data in a 3D virtual environment provides scientists with a unique opportunity to explore hurricanes in a detailed and comprehensive way.

Currently, several initiatives are utilizing recent advances in computing technology to create 3D simulations of tropical storm events. Their efforts promise not only to improve the understanding of the science of storms but to advance the effective visualization of geographic data. Both are central to supporting risk management mitigation and reducing the huge economic costs associated with tropical cyclones and hurricanes.

Severe Tropical Cyclone Larry hit the north east coast of Australia in March, 2006, and took its place as one of the costliest natural disasters in Queensland's history [9]. Larry presents an excellent opportunity to apply 3D visualization techniques to help answer questions surrounding cyclone patterns and processes, like the budding of the cyclone's path, the influence of topography and westerly winds on the its track, and the pattern of vegetation destruction it produced. High-resolution remote-sensing technology and weather recording instruments make it possible to provide accurate data for wind velocity, atmospheric temperature, pressure, surge height and water flow direction. By combining these data with aerial photography, satellite images, and elevation maps to create a composite 3D visualization, this project aims to create an accurate visualization of Cyclone Larry, which in turn could help in the prediction, awareness, and management of future storms.

A similar challenge was posed by Hurricane Katrina's hitting New Orleans, Louisiana, and the northern coast of the Gulf of Mexico. Techniques for integrated visualization of observational and computational data from different sources have been created for this special case [6]. In this article we compare the data available for Hurricane Katrina with those for Cyclone Larry, and discuss how far the techniques used in the visualization of Katrina can be used in that of Larry.

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Categories and Subject Descriptors

J.2 [**Computer Applications**]: Physical Sciences and Engineering—*Earth and atmospheric sciences*; K.4.1 [**Computers and society**]: Public Policy Issues—*Human safety*; D.2.12 [**Software Engineering**]: Interoperability—*file formats, scientific data*; E.5 [**Data**]: Files—*Organization/structure*

Keywords

Atmospheric research, GIS, surge models, visualization, numerical simulation, data integration, file formats

1. INTRODUCTION

1.1 Motivation

Tropical cyclones and hurricanes play a major role in shaping coastal ecosystems and landscapes. The force, speed, and duration of their winds alter canopy topography and wildlife habitat and determine species structure and composition. As coastal populations increase worldwide, the risk to human life also becomes a serious issue. Given these facts, the ability of scientists to predict tropical storm intensity, frequency, and geographic distribution becomes vital. Besides saving lives, accurate predictions are crucial to forest and wildlife management; ecological restoration; conservation of fish, wildlife, plants and their habitats; and conservation of natural resources and watershed management–all vital areas of concern to conservation professionals.

Recently new technologies and satellites have enabled the collection of a rich variety of highly precise data. Concurrently, advances in computing power and improvements in software have combined to give Geographic Information Systems (GIS) the ability to integrate various forms of geo-spatial data and perform complex analyses. These developments have brought GIS to the forefront of landscape analysis, assessment, design, and planning. Today, sophisticated 2D and 3D visualizations of geographic and atmospheric data are able to describe, with increasing accuracy, the complex atmospheric characteristics of hurricanes and tropical cyclones, as well as the effects produced on ecosystems, infrastructure, and coastal communities [10]. The latest experiments in 3D scientific visualizations of geographic data explore using supercomputing to create immersive, interactive virtual worlds in which, for example, a person can access and query numerical data related to the geo-spatial areas displayed. Such visualizations provide a tool to gain insight into relationships among multiple data sets [7, 2, 10]. Supercomputing is also used in the atmospheric sciences to generate highly accurate 2D and 3D models of meteorological phenomenon. However, the temporal and spatial scales used in atmospheric data vary considerably from those used in GIS data. This fact, combined with the large file size and incompatible file formats, often prevents the integration of model outputs [12, 6, 17].

1.2 Hurricane Katrina

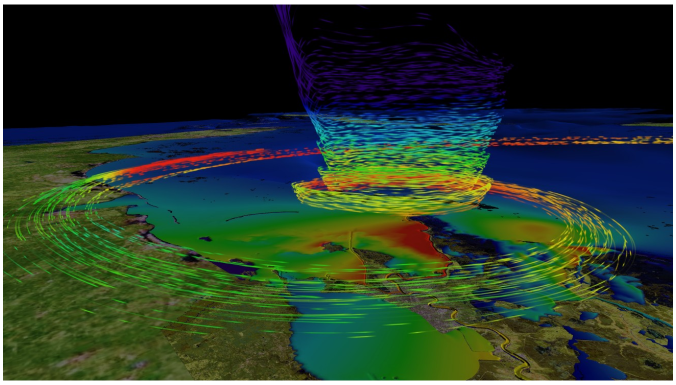

Figure 1: Depiction of the wind flow of Hurricane Katrina and its accompanied surge when approaching New Orleans, Louisiana, image from [6].

What is needed is a way to integrate scientific data, satellite imagery, and GIS data in a virtual 3D environment. Numerous pioneering initiatives are underway in this area, one of which is at Louisiana State University's Center for Computation & Technology (CCT). In 2006, the CCT, an interdisciplinary research center funded by the Louisiana Legislature and staffed by an international team of experts in various fields, used its computational facilities to create a data-driven visualization of Hurricane Katrina called Katrina Revealed[1]. The visualization focuses on the events on and around August 28, 2005, when Hurricane Katrina made landfall at New Orleans and caused a surge that ultimately lead to the flooding of the city. The following data sets are available for this visualization:

1. The atmospheric conditions (wind velocity, pressure, and temperature) as obtained from an atmospheric model known as "MM5[2]"; each time-step is a regular grid with dimensions 150x140x48, given hourly.

2. The clouds imagery utilizing the infra-red channel of the GOES-12 geostationary weather satellite[3], given every 15 min. on a 4km resolution grid.

3. Terrain elevation data of New Orleans obtained from LIDAR[4] with a uniform resolution of 5m.

4. Satellite imagery of the land surface from the MODIS and LANDSAT instruments at 500m and 250m resolution respectively.

5. Time-evolving water elevation and wind and water flow directions on an adaptively refined triangular mesh connecting ca. 600,000 vertices, as provided by an ADCIRC simulation [1].

There is no unique way to represent all these data sets at once, so specific visualizations are better suited to depict the relationships among each of these data sets. For instance, fig. 1 utilizes streamlines computed from the 3D atmospheric data set to visualize the instantaneous wind velocities. These lines are colored with the air temperature to show the loss of atmospheric energy over land masses. Surge heights of the ocean and Lake Ponchartrain (the large freshwater lake that actually flooded the city) are depicted in colors, with red indicating dangerously high surge levels. Coloring the water red, however, troubled many viewers of the visualization. Fig. 2 depicts an alternative approach using different shades of blue representing the surge, plus using the standard approach of utilizing vector arrows to indicate wind velocities. While using vector arrows does not

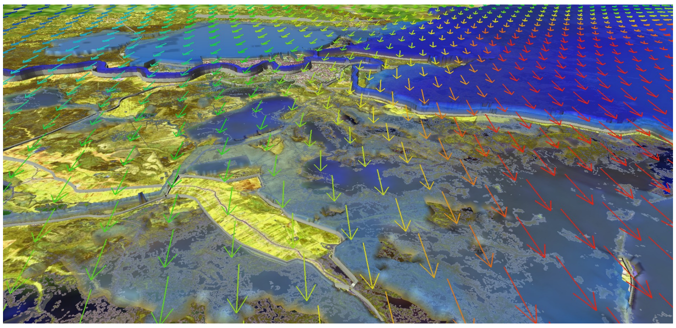

Figure 2: Detail of the Louisiana coast depicting the hurricane's wind velocities and the surge, as obtained from two different simulations (MM5 vs. ADCIRC).

[1] `http://www.lsu.edu/highlights/062/cctkatrina.html`

[2] `http://www.mmm.ucar.edu/mm5/`

[3] `http://www.nnvl.noaa.gov/`

[4] LIght Detection And Ranging `http://www.lidarmapping.com`

allow the depiction of the full 3D structure of the entire atmosphere,for some viewers it is more intuitive and easier to grasp when first seen.

The effort of visualizing Hurricane Katrina using a variety of different data sources improves the communication of the chain of events that caused the flooding to a non-scientific audience in the aftermath of the catastrophe. The same techniques applied to future cases may well support planning and management decisions that could reduce devastating economic, ecological, and human costs.

1.3 Cyclone Larry

In March, 2006, Australia suffered its own Hurricane Katrina when Severe Tropical Cyclone Larry struck the state of Queensland on its northeast coast. Packing winds of 140mph, Larry caused damage estimated at $1 billion to homes, buildings, roads, bridges, beaches, farmland, and rain forests, ranking it as one of the costliest natural disasters in Queensland history. But despite the high economic losses it caused, Larry also presents an opportunity to apply 3D visualization techniques to gain insight into cyclone processes and the damage they cause to landscapes and infrastructures. In particular, researchers' preliminary studies of Larry have revealed an intriguing fact: the local terrain appears to have affected the direction and force of cyclone winds [14, 9]. Not only was this dynamic apparently responsible for the unusual pattern of vegetation damage, but it poses a significant future threat to population and urban infrastructure. Naturally, this latter fact much concerns the Cairns (Australia) City Council, which is already struggling with rapid regional population growth. This growth is spurring urban and residential development, which has now extended onto sensitive rangeland slopes. In these regions, the risk to population and infrastructure is intensified due to the way local terrain accelerates downslope winds. Cyclone Larry made these risks starkly evident, with structures unprotected from westerly down slope winds suffering the most damage. Conservation professionals responsible for devising effective strategies to manage these risks are eager for information from researchers. These in turn, from organizations like the Australian Bureau of Meteorology, Geoscience Australia, CSIRO Tropical Forest Research Center, and JCUs Center for Disaster Studies, are working overtime to understand the cyclones effect of on wildlife, vegetation, and urban infrastructure. To help these many researchers better study this situation, this research aims to build on the work of integrating geo-spatial and atmospheric data done at CCT [6] and to create an interactive 3D visualization of Cyclone Larry. The overall goal of the visualization is to reveal the interaction between the cyclone and the land masses it encountered, and their effects on each other.

2. METHODS AND DATA

2.1 Study area

The Atherton Tablelands is located west of Cairns between the Bellenden Ker Range and the Great Dividing Range. The area boasts a unique combination of natural attractions, including World Heritage-listed rain forests, vibrant arts and crafts communities, and rich agricultural lands. While the central Atherton Tablelands escaped the brunt of the force, eye of the cyclone passed 30-40km to the north. The area was affected by wind gusts of up to 230km/h [14], resulting in significant damage to rain forest vegetation. According to on-ground observations, vegetation exhibited similar patterns of damage when Cyclone Winifred, a Category 3 storm, swept through the Innisvale area on February 1, 1986. Winifred followed a similar trajectory to Cyclone Larry's, with maximum wind gusts recorded at approximately 137mph. While the extent of damage was less severe from Winifred than from Larry, similar patterns of damage suggest a relationship between local terrain and wind direction. Remote sensing data sets (Landsat TM, Spot XS, and Aster) are available for Atherton Tablelands.

2.2 Field data

To gather field data, the study area was divided into four sectors, each of which was assigned to a team of students. Each team drove through the assigned area and stopped every 5km to record GPS locations and fill out damage assessment forms. The categories used to assess damage were developed by Unwin et al. [16].

I. Slight canopy disturbance: foliage loss, occasional stem or branch breakage.

II. Moderate canopy disturbance, structural loss mostly branch and foliage, some tree-falls and most stems erect.

III. Severe canopy damage, boles or crowns of most trees broken, smashed or wind-thrown. Contains both windward and multidirectional impacts.

The GPS points were entered as point data into a GIS with the following attributes: damage category, vegetation type, canopy height, geology, and aspect. Accuracy of point data was checked against on-ground observations and true color satellite image. Due to error in GPS locations, some points did not align to corresponding land cover type. When this occurred, hand editing was used to reposition points.

2.3 Meteorological data

ADCIRC (The Advanced CIRCulation model [1]) is a framework for computing flow and transport in coastal water bodies. For hurricane visualization, it is used to model wind-driven storm surge. Bathymetric data are used to build an underlying computational mesh. Each vertex of the mesh contains numerical simulation outputs of water elevation, wind, and water-flow direction. A finite element grid, consisting of a series of triangles which vary in size according to sea level, is used to provide detail in coastal areas where water is shallow. The Adcirc grid was provided by the National Tidal Center (NTC) part of the Australian Bureau of Meteorology and covers the Australian coastal region. It is an experimental grid that was developed to model seasonal tidal flows, and as such is incomplete (no wind data). However, the model provides enough information to develop rudimentary tidal flow visualization for the study area. The data set includes the following files:

- Grid and Boundary Information File (`fort.14`);
- Model Parameter and Periodic Boundary Condition File (`fort.15 nowetdry` and `wetdry`);
- General Diagnostic Output file (`fort.16`);
- Elevation Harmonic Constituents at Specified Elevation Recording Stations file (`fort.51`);

- Elevation Harmonic Constituents at All Nodes in the Model Grid file (`fort.53`);
- Depth-averaged Velocity Harmonic Constituents at All Nodes in the Model Grid file (`fort.54`).

Instead of dealing with these huge complex ASCII files, we convert them into HDF5 [13] using the F5 [4] approach. This not only reduces the file size by a factor of 20, but allows the interpretation of the highly ADCIRC-specific meanings in the data file to be outsourced to a stand-alone program independent from a complex visualization application. Currently not all of these files are handled,but just a subset. The organization details will be described in section 3.1.

2.4 Atmospheric Data (WRF - Weather Research and Forecasting Model)

WRF is a mesoscale weather prediction system capable of a wide range of applications, including numerical modeling of climate simulations. WRF is being used in the re-analysis of Tropical Cyclone Larry. For the purpose of hurricane visualization, past research [6] suggests that streamlines are a very user-intuitive way to communicate complex wind-field data to both public and scientific audiences (see also fig. 1). For streamlines to display hurricane/cyclone vortices effectively, they may be related to atmospheric pressure. The streamlines are made transparent over this area and clipped to show wind field values only around the eye of the hurricane. Coloring the streamlines by the temperature of the atmosphere additionally depicts the effect of energy gain and loss over sea areas and land masses. This approach allows the simultaneous visualization of five independent quantities—temperature, pressure, and three quantities of wind velocity—on the three-dimensional volume of the atmosphere. Thus it is suitable for targeted analysis of atmospheric properties as the hurricane makes landfall.

2.5 Remotely sensed data

2.5.1 *Aster*

ASTER level 1B (Advanced Spaceborne Thermal Emission and Reflection Radiometer) hyperspectral satellite imagery is available from September 25, 2006, and ASTER level 3, from June 5, 2006. The resolutions are 15m, 30m, and 90m for the visible-near-infrared, shortwave infrared, and thermal infrared, respectively. Height information derived from the shortwave infrared was used to create a digital terrain model. An existing 20m DEM of Cairns area filled in data gaps apparent in the ASTER coverage.

2.5.2 *Spot panchromatic and multispectral data*

Spot panchromatic and multispectral data from June 4 , 2006. The resolution for these data is 2.5m and 10m. The time lapse between the cyclone event and acquisition of satellite imagery was longer than desired because cloud coverage obscured the area up to three months after the cyclone struck. But post-cyclone, on-ground field observations made during this time noted vigorous re-growth in areas which suffered severe canopy damage. Satellite images taken after cloud clearing will be used to identify these areas and confirm the re-growth.

2.5.3 *Radarsat*

Radarsat is a remote sensing satellite that uses microwave-based sensors to provide information about the earth's surface under all weather conditions [11]. The satellite records radar backscatter, which is influenced by underlying geology, vegetation type, and soil moisture content. It is well suited to mapping vegetation type, moisture content, and surface roughness. Radarsat imagery taken immediately after Cyclone Larry hit is available for the central Atherton Tablelands area and provides a good indication of patterns of vegetation damage caused by the cyclone's path.

2.6 Pre- processing

2.6.1 *Aster Digital Elevation Model (DEM)*

The elevation data, derived from level 3 Aster satellite imagery, are available in 15m, 30m, and 90m resolutions. For the purpose of the animation, 15m resolution is used. Four individual scenes were tiled together in ER Mapper to provide maximum coverage of the region effected by Cyclone Larry. The resulting image had data voids, which were filled using a SRTM 90m digital elevation model of the Cairns region. The final image was saved as a geotiff and converted into HDF5 format for further processing. The integrated visualization of the water surge, the atmospheric properties, and the terrain elevation provides valuable insight into the interaction of these components. Fig. 3 demonstrates these elements in the visualization of Hurricane Katrina. The application of these techniques to Cyclone Larry awaits the completion of the Larry visualization.

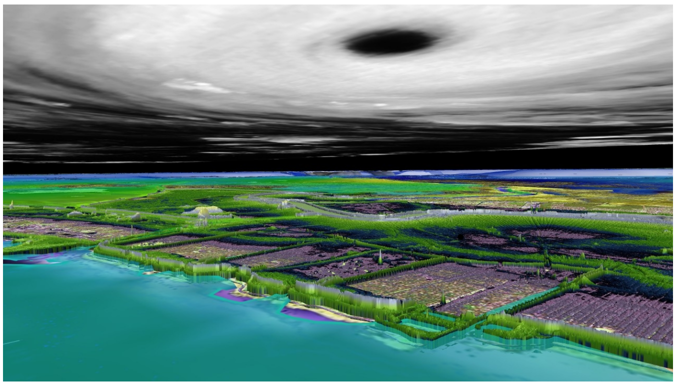

Figure 3: Rendering of the high-resolution of the terrain elevation model from the city of New Orleans, as obtained by LIDAR measurements, overlaid with ADCIRC surge data and GOES-12 satellite imagery, from [17].

2.6.2 *Radarsat*

A smoothing filter and texture analysis filter was applied to the Radarsat image to highlight areas of damage.

3. DATA MANAGEMENT CHALLENGES

A first hurdle in combining data from various sources is finding a file format to function as a common denominator. This is essential to cut down on processing time and allow seamless integration of all data sets into the visualization software. To accomplish this objective, the "F5" file format [3] is used. This approach builds upon the Hierarchical Data Format V.5 (HDF5) [13]. HDF5 maximizes storage and I/O (input/output) efficiency by organizing multidimensional data into a hierarchical structure. As part of the Hurricane Katrina visualization project, the F5 library was extended by customized file converters to transform surge surfaces, wind, pressure, and temperature volumes into this F5 format. The use of HDF5 accelerates initial loading time of all data sets and makes it easier to load subsections of large, dynamic files on demand.

The GeoTIFF library is built on top of the TIFF (Tagged Image File Format) 6.0 specifications. It adds a set of tags to define cartographic features of the data and to allow georeferenced raster imagery. This file format was used for storing the ortho-rectified SPOT images for the Innisfail region at a height of 2.5 m. A GeoTIFF file starts with a Header; it goes on with one or more directories called IFDs (Image File Directories), usually containing tagged pointers to the data; and finally contains the data. This format tries to encompass many kinds of data storage, which makes it very flexible and simple. However, this means that there are many cases to cover during work on a converter from/to GeoTIFF. HDF5 is a more powerful file format for which we already had a working infrastructure in a more general context, so we converted the GeoTIFF files into this format. The files to deal with in the context of Cyclone Larry have 4 samples/pixel corresponding to the RGBA channels, with a resolution of roughly 34000X15000 pixels. Moreover, the data is organized in strips (as opposed to tiles), with 16 rows/strip. Every sample takes one byte of memory storage. We mapped these four channels of data to four scalar fields in HDF5, then stored all the information from the six GeoTIFF files in one HDF5 file, and reconstructed the ground image. Each GeoTIFF file stores one piece of the ground image.

3.1 F5

The F5 structure listing of the currently available Australian ADCIRC data mesh consists of 80935 triangles made from 45180 vertices. In contrast, the ADCIRC mesh used for Hurricane Katrina was build from 1190404 triangles with 598240 vertices. Using "h5ls", a tool that comes with the HDF5 library to display the contents of an HDF5 file like a file system structure (a "Group" corresponds to a directory, a "Dataset" to a file), the Australian mesh appears as:

```
/t=000000000.0000000000 Group
/t=000000000.0000000000/surface Group
/t=000000000.0000000000/surface/Charts Group
/t=000000000.0000000000/surface/Charts/Points Group
/t=000000000.0000000000/surface/Charts/StandardCartesianChart3D Group
/t=000000000.0000000000/surface/Connectivity Group
/t=000000000.0000000000/surface/Connectivity/Points Group
/t=000000000.0000000000/surface/Connectivity/Points/Positions Dataset {80935}
/t=000000000.0000000000/surface/Points Group
/t=000000000.0000000000/surface/Points/StandardCartesianChart3D Group
/t=000000000.0000000000/surface/Points/StandardCartesianChart3D/Positions Dataset {45180}
```

This file listing depicts the 5-level hierarchy of the F5 data layout [3]. The HDF5 listing is still quite low-level, as compared with the information required by an entire mesh: HDF5 knows only about simple datasets, but an entire grid is created by multiple datasets. The F5 library deals with such multiple datasets and their relationships in order to define a grid and the fields defined on it. So in order to also display this information conveniently, a tool called "F5ls" is provided with the library that lists the same HDF5 file on a higher semantic level:

```
******* Timeslice for t=0 *******
Grid ‘surface’ (no timestep information)
  <<< Points >>>
  Positions :  Contiguous <0.1.3> Size:  45180 cartesian coordinates (no range)
  [[[ Connectivity ]]]
  Positions :  Contiguous <0.1.3> Size:  80935 triangles
```

While this tool cannot work with generic HDF5 files but only those in the F5 layout, it now shows that there is a "Grid" object, constructed from triangles and vertices (points) in Cartesian coordinates.

Data are ordered by time slices in F5 because this is the natural output of a dynamic simulation. In case some properties remain constant over time, such as the connectivity and vertex information of an ADCIRC mesh (in contrast to the time-dependent surge elevation and wind velocity), symbolic links among datasets can be well utilized. Symbolic links are a core feature of HDF5, and F5 supports their use for such a purpose [6]. Therefore, an application can read in every time step as if it were a new grid, but also time-independence can be detected by exploring these symbolic links. As these symbolic links can be made among any datasets or groups, this approach is very flexible and allows one to specify certain selected properties of a grid to be constant, for the entire time period or just subsets.

While working with these issues, there was a need for stringently and properly defining time semantics attached to every dataset. When combining datasets coming from different sources, it is crucial that the time information is synchronized among all of them to one common set of semantics. For example, the time scale for each dataset is specific to each simulation, but we need a common time unit. This reason, as well as avoiding loss of accuracy for time values, has been a good motivation for enhancing the F5 library with a set of functions meant to store, delete, and manipulate time values and all the information available about them. [8]

3.2 Amira

The Amira visualization program [15] is utilized as a possible framework to display the 3D datasets and render animations. This program was originally developed for use in the fields of medicine, biology, and engineering, but has been successfully used also in other domains such as astrophysics. It was the basis of the Hurricane Katrina visualization. However, it is designed to handle static geometries and does not support time-dependent objects well. To overcome this problem, Benger et al. developed extensions that allow time-dependent variables (e.g. wind-speed, surge elevation) and dynamic objects to be displayed. Thus, interactivity is maximized and the user can explore data that cover the entire time-range of the cyclone, data restricted to a specific period, or data expressing events that recur intermittently[6]
.

3.3 VISH

VISH ("visualization shell" in a broad sense) is a novel approach to provide a common infrastructure for visualization and data management algorithms [5]. It is yet in a very preliminary phase, but first results of a rendering of the Australian ADCIRC grid can be seen in fig. 4 and fig. 5. VISH is not an application by itself, but a library providing an API that allows development of algorithms independent from a specific visualization software. It comes with a standalone front end, but VISH modules can be used as part of Amira or another visualization program that is equipped

Figure 4: Preliminary visualization of the bathymetry grid from the ADCIRC grid used to run Cyclone Larry.

with the VISH API. A typical visualization module utilizing the VISH API requires about 200-300 lines of C++ source code to enable it to be shared in binary form as a plugin to various front ends.

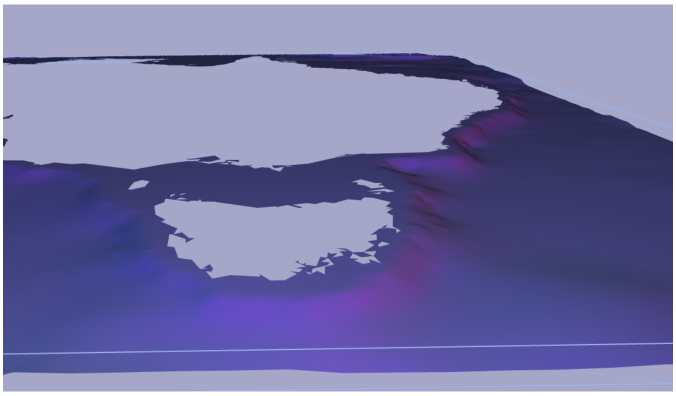

Figure 5: Zoom into Tasmania region of the australian ADCIRC grid, depicting 3D rendering of the coastline.

4. CONCLUSIONS

This article compared data available for Hurricane Katrina with those for Cyclone Larry and discussed how specific techniques developed for the Katrina simulation supports the management and integration of geo-spatial and atmospheric data for cyclone Larry. This research builds on previous work in hurricane visualization[6] to effectively visualize diverse data types and manage complex data sets. The resulting visualization aims to highlight interactions between topographical and storm surge data, provide researchers with a tool to examine interaction between atmospheric and geo-spatial data, and stimulate further research in techniques for integrated visualization of observational and computational data.

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