Real-Time Weather Data on Terrain

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ABSTRACT

This paper describes the visualization of 3D Doppler radar with global, high-resolution terrain. This is the first time such data have been displayed together in a real-time environment. Associated data such as buildings and maps are displayed along with the weather data and the terrain. Requirements for effective 3D visualization for weather forecasting are identified. The application presented in this paper meets most of these requirements. In particular the application provides end-to-end real-time capability, integrated browsing and analysis, and integration of relevant data in a combined visualization. The last capability will grow in importance as researchers develop sophisticated models of storm development that yield rules for how storms behave in the presence of hills or mountains and other features.

Keywords: Real-time visualization, NEXRAD data, Doppler radar visualization, Global geospatial hierarchy, VGIS

1. INTRODUCTION

It has become clear that access to universal data (i.e., all data for a given field or set of tasks maintained as one readily accessible collection) makes possible faster and better analysis. In the context of weather analysis and prediction, high quality simulation and visualization facilities are vital, because these highly complex phenomena require human-in-the-loop analysis to interpret and understand evolving weather patterns. Since weather occurs in a comparatively thin volume of air over a large extent of the Earth's surface, we believe that current analytical practice can be sustained and improved by the ability of meteorological professionals to examine weather phenomena in the context of natural and human-made ground features.
Such visualizations can be used not only by weather forecasters but also by researchers to develop new knowledge about severe storm development and tracking, for the eventual purpose of predicting the track of severe storms that are destructive of life and property.

The goal of our geographic visualization work is to develop a system that allows the user to visualize in real time any area of the Earth at any resolution, with complete information about the natural and human features at any point on or near the surface. The modalities of viewable data are nominally any type of data that can be digitized in a form where each discrete data point corresponds to a location on the Earth. The usual examples of this are terrain elevation, aerial imagery of the Earth's surface, buildings, vehicles, and other mobile artifacts. The system we have been using to explore this vision is VGIS [Lin96, Dav98, Dav99, Fau00], the Virtual Geographic Information System, which uses a global hierarchical structure [Fau00] that effectively handles terrain [Dav98] and buildings [Dav99], providing a paging and caching structure that permits handling of scalably large data. This structure also offers view-dependent detail management so that objects in view are rendered with controls on the amount of individual and overall detail. VGIS has a structure for the dynamic acquisition, insertion, and use of global geospatial data. The acquired data could be in a variety of forms. For example, it could be aerial images to be used as terrain phototextures, new terrain elevation information, ground-level imagery to be put in a 3D context, positions and movement information for groups of people or vehicles, or time-dependent volumetric data. Our basic premise is that all these data will be fitted into a global geospatial structure based on a forest of quadtrees [Dav98, Dav99, Fau00]. Even the volumetric data will fit efficiently into this structure because they describe processes in the atmosphere, which is a thin layer with respect to the earth's surface extent.

This paper describes the visualization of 3D Doppler radar with global, high-resolution terrain. This is the first time such data have been displayed together in a real-time environment. Associated data such as buildings and maps are displayed along with the weather data and the terrain. The next section describes requirements for effective 3D visualization for weather forecasting. The following sections introduce data structures and algorithms used by our system to deliver on most of these requirements. We conclude with a brief review of results.

2. REQUIREMENTS

With the advent of nationwide meteorological networks such as NEXRAD Doppler radar, high resolution weather satellites, and automated surface sensors, operational weather forecasters have recently had access to much more observational data for making decisions in severe weather situations than ever before. These data sources provide higher spatial and temporal resolution than was previously available, but processing this vast amount of information in order to extract and display what is useful to the forecaster presents a formidable challenge. Even as the weather forecasting community struggles to take advantage of abundant observational data, the general public is expecting data that is both more precise and more highly customized to their particular geography and lifestyle. To meet this expectation, it is necessary to integrate very detailed thematic data (e.g., terrain, roadways, rivers/streams, political boundaries, landmarks) with the observational weather data. There will be significant advantages to combining these data into a new type of universal data set with significant limits on the times of access, display, and analysis. At present many of these weather and thematic data are not used efficiently because of a lack of real-time integration and visualization functionality.

This universal data set is a combination of global, regional, and local data -- they describe terrain, vegetation patterns, roads, urban patterns, and dynamic weather over the terrain. The slowly varying geographical elements must be combined with rapidly evolving observational data, such as weather data collected on the fly from overlapping, volumetric radars. There must be the capability to maintain and display high-resolution data, in context, wherever desired and to quickly drop in and display accurate elevation data, maps, GIS (Geographic Information System) layers of imagery, and time series of radar data as they are received.

To reach our goal of developing a 4D (3D + time) visualization system for viewing, interrogating, and analyzing large observational data sets, the user needs to be able to view data in real time and in an efficient and effective manner to assist operational weather forecasters in making decisions about severe weather situations. The system should bring together, for the purposes of analysis and forecast decision-making, 3D time-dependent volumes from multiple overlapping Doppler radars, and simultaneous satellite information for the same and wider coverage areas. These must be combined with accurate terrain elevations, multiple image layers, maps, and other geospatial thematic data. These observational data should be displayed on accurate 3D terrain so that the correlations of landscape and weather can be revealed in detail. This will enable predictions of flood extents, inclusion of the effects of mountains, rivers, or high-traffic roads on weather phenomena, and other capabilities. This universal data collection should be organized for integrated visual analysis and made available for interactive navigation, exploration, and discovery by weather forecasters, researchers, and other users.

A further requirement implied by the above requirements is the need for real-time interactive visualization of the data mentioned above. Without real-time graphics, users are required to understand the phenomena of interest by a series of still pictures, which would therefore prevent the use of the important depth cues of kinetic depth effect, motion parallax, and head-tracked (and therefore more accurate) stereopsis. Interactive visualization requires that the visual imagery react immediately to the commands of the user to navigate to the area of interest and investigate the features and objects of interest. This requires that lags between user input and corresponding system output be less than 100ms, because users start to notice sluggish performance with longer lags. At lags of 500ms or more, users abandon interaction altogether, and adopt a move-and-wait strategy that is functionally similar to issuing commands [She63].

Because the data sets of interest are on the order of gigabytes, and the size of main memory is usually somewhat smaller than the data set, the visualization system must support interactive paging of data from secondary (disk) storage. Also, such paging strategies help manage the small CPU data cache and graphics rendering caches that are available to speed up graphics rendering. To support fast, scalable visualization, level-of-detail (LOD) rendering must be employed so that only the visible data of interest are displayed at the right time. Without LOD rendering, terrain or surface texture features that are small or far away will be rendered, regardless of their contribution to the final scene. For example, if a user is viewing a section of the surface that covers 100 square kilometers on a 1000 x 1000 pixel display, then each pixel will correspond to 100 square meters, or 10 x 10 meters. Terrain elevation and imagery at finer resolution than 10M x 10M will simply be invisible, because all such details would resolve to a single pixel. Similarly, terrain elevation data and imagery outside the filed of view can be ignored because it cannot be seen.

In summary, requirements for real-time acquisition and effective visualization for decision-making such as weather forecasting are as follows:

- Real-time data acquisition and data communication. This requires that real-time acquired data should be organized, transferred to data analysis modules for analysis, and then displayed in an interactive environment.

- End-to-end real-time capability. This means not only real-time acquisition but also visualization and on-the-spot analysis in appropriate time budgets.
- Capabilities for both browsing (or exploring) and analyzing time-dependent 3D data, including historical data.
- Easy-to-use 3D navigation and manipulation.
- Details on demand, to eliminate clutter presenting the important details initially.
- Integration of relevant data in a combined scene (e.g., weather and terrain).
- Easy-to-use quantitative tools and information-retrieval tools to augment the qualitative visualizations.

Schneiderman and co-workers [Tan97] have shown that the details on demand strategy can be very effective when coupled with fast display updates and easy-to-use controls for adjusting the detail. Since the atmospheric visualization application presented here is coupled to our terrain navigation system, it naturally has a browsing capability.

3. RELATED WORK

Weather visualization has been a fairly popular topic over the years. We will not give here an exhaustive review of this work but will rather concentrate on representative work related to interactive visualization of weather data or simulations. In many cases these visualizations are intended for analysis of weather patterns and in a few cases for decision-making.

There are visualization/analysis tools developed on top of toolkits. For example, the Vis5D display and analysis tool [Hib96] and Display 3D (D3D94) developed by the National Oceanic and Atmospheric Administration (NOAA) Forecast Systems Laboratory have 3D display capability. However, these tools have been designed not as general 3D visualization interfaces, but rather to focus on numerical model output. In addition, these tools do not have an operational decision support focus (attained by supplying the most pertinent information for decision-makers). Finally they do not address the issues of scalably large data and integration of geospatial data. There are also tools developed on platforms such as AVS Express [Che96]. These tend to be for analysis of fixed data rather than real-time visualization of potentially large and constantly updated datasets.

There is also research that has combined visualization with the value-added of storm tracking analysis. Cheng et. al. [Che98] use fuzzy logic to develop a storm tracking algorithm that presents results that closely match an expert meteorologist's perception. This work is relevant to our approach of displaying results of automatic analysis to aid in decision-making. However, it does not address the issues of real-time 3D visualization and does not present weather along with other relevant data, such as terrain. So far, the major real-time acquisition and display system [NWS98] is the Advanced Weather Interactive Processing System (AWIPS). However, it only provides 2D visualization. The present paper provides the first example of real-time acquisition and interactive visualization of 3D weather data from multiple sources.

Treinish [Tre98] has considered the general issues of visualization design for weather forecasting, including 2D and 3D visualizations. The latter are classified as either 3D browsing or analysis tools. The perceptual issues in using color and the representations for quantities such as wind vectors are also considered. Our approach combines browsing and analysis in a coherent 3D setting. We also build on some of the design issues presented in [Tre98].

Djurcilov and Pang [Dju99] address the issue of missing data in Doppler radar and other gridded data. Because of the curvlinear nature of the radar scan (Fig. 1), the data are rather sparse when usual visualization techniques (i.e., isosurfaces and volumetric rendering), which use regular grids, are applied. To the extent that the pre-analysis tools in our approach take into account the data non-uniformity (and the possibility of false readings), some of this uncertainty is accounted for. However, it is still useful to show the locations and scan patterns (and location-dependent uncertainties) for the radars, especially since in the future overlapping radars will be used. In the future we also expect to apply more direct and detailed rendering of data; here the considerations in [Dju99] will be important.

4. DATA SOURCES

To accomplish our goal of real-time display of the most recent weather data, we developed a system to automatically gather the latest NEXRAD Doppler readings as they became available. NEXRAD Doppler radar takes a number of 360-degree azimuthal sweeps, collecting radar reflections from the atmosphere at ranges from 0 to 190 kilometers. The NEXRAD radar takes sweeps at 9 elevations: 0.5^o, 1.5^o, 2.4^o, 3.3^o, 4.3^o, 6.0^o, 9.9^o, 14.6^o, and 19.5^o. The lowest elevation of 0.5^o is designed to avoid any ground reflections, and covers the greatest ground distance. This set of elevation angles is intended to cover elevations up to 31000 feet, so the radar probe length for sweeps at higher elevation angles is somewhat shorter. The zone swept out by the radar is a series of cones with very wide apex angles. Fig 1 shows a side cut-away view of the sweeps. The sweeps closest to the ground are actually somewhat longer than shown in the diagram.

To collect data at each angle of azimuth, the radar antenna generates a pulse every 1.5 microseconds at .5 watts, and remains in position long enough to hear back from objects as far away as 190km. From the return stream, it takes up to 460 samples (from 0 meters to 190 km). The antenna then turns 1 degree to the next azimuth angle, and collects the next pulse train. When a sweep of 360 degrees is completed, the antenna rises to its next elevation. At higher elevations, fewer pulses are collected per azimuth angle, giving a shorter range of sensing in terms of straight-line distance. At 19.5^o, for example 70 pulses are collected, with the most distant pulse gathering data at an altitude of 31400 feet.

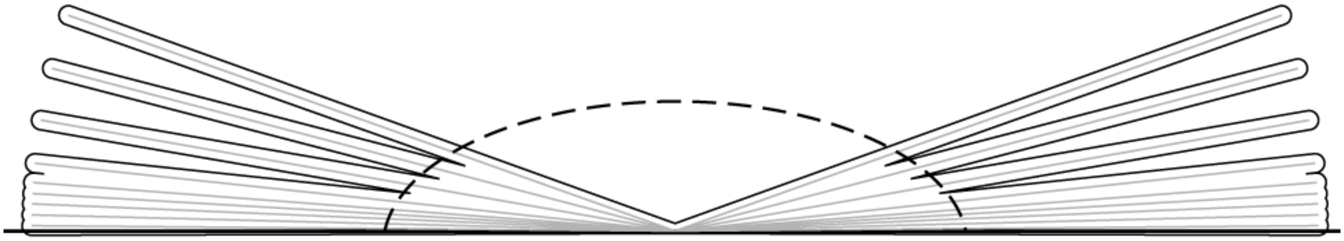

Fig.1 Side cut-away view of a single NEXRAD radar. The gray sweep lines are surrounded by regions of high confidence in the accuracy of the readings. At lower elevations, spacing between the sweeps is close enough to assume readings from a continuous medium. The dashed half-ellipse shows this high-density region. The sweeps closest to the ground are actually somewhat longer than shown in the diagram.

From the raw reflection data, the radar system analyzes the signal received at every sample point, and generates reflectivity, spectral width, and velocity information from the signal that was reflected at that location. The Reflectivity quantity is the amount of electromagnetic energy returned to the radar. For objects such as buildings or aircraft, the larger the object, the more energy it returns, and the greater its reflectivity value, on a logarithmic scale. For atmospheric measurements, higher reflectivities typically correspond to a higher density of water vapor or water droplets in the air at the sample location. Thus, instead of a single object, reflectivity measures density of a cloud of objects.

At each sample point, radial velocity is derived from the Doppler effect on the returned signal. A greater Doppler shift indicates greater velocity of the reflecting object as it either moves toward or away from the radar. Radar reads an object moving perpendicular to it as having velocity of 0. The velocity number is positive if the object is moving away, and negative if moving toward the radar. Analysis programs can use the vector field derived from the velocities collected at each point along a sweep to detect vortices, mesocyclones, and so forth.

The spectrum of the reflection signal is also analyzed at each sample point, which yields an indication of the range of velocities present in the sample location. A spectrum with close maximum and minimum values gives a narrow spectral width, indicating that the velocities of all the individual particles have similar radial velocities. A very wide spectrum indicates a wide spread of velocities of the objects within a cell. If the particles within a cell are highly agitated, they could be moving in random directions. The spectral width captures this randomness in velocities within a cell. If the number (spread) is high, that is considered an indication of interesting weather behavior.

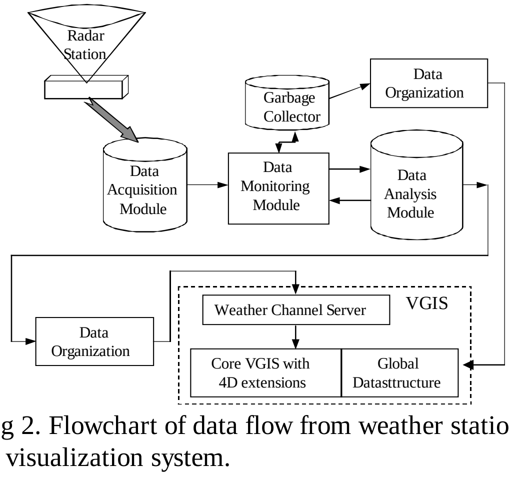

Fig 2. Flowchart of data flow from weather station to visualization system.

1. Data Transmission

Since velocity and spectral width are derived values from the “raw” radar readings, the National Weather Service does some post-processing before the derived products can be made available at their ftp site. Since the radar sweeps take about 5.75 minutes, new data is available every 6 minutes. The size of this data for a complete set of sweeps is 2.6MB, including the derived products.

To directly access the latest radar imagery, we created a daemon (the data-monitoring module in Fig.2) that wakes up every 6 minutes and checks their ftp site to see if the latest data is available. If the data is ready, we copy it over to our local disk for processing. At our option, if there is any data on the ftp site that we have missed on a previous pass, we copy that, as well. Because a full day's weather data for a single radar station is 620MB, we do not collect data at all times. When we anticipate that current visualization efforts will require new data, we turn on the data-copying service, and then start browsing the latest data.

Once the data is available at our site, the data acquisition module organizes the raw volumetric data into a form appropriate for the hierarchical global data structure [Fau00]. The data analysis module then applies a set of pre-analysis and modeling tools, using methods developed by the National Severe Storms Lab (NSSL) [Eil95, Joh98, Mit98]. The tools are embedded in the Warning Decision Support System (WDSS), used by weather forecasters to make severe storm and tornado warning decisions. The pre-analysis is described further in the results section below. Since it is made for operational weather forecasting, the WDSS can analyze 3D Doppler radar on the fly. An extension of the structure of our terrain visualization system [Fau00, Dav98, Dav99] permits immediate insertion of these data and the accompanying raw volumetric data as a time-stamped stream of objects for real-time display.

Typically it takes about 6 minutes to collect a set of volumetric data. In order to prevent the constant stream of networked data from overflowing the data analysis module, the data-monitoring module will deliver only the most recent data to the analyzer, skipping a 6-minute segment(s) for later analysis. After volumetric data is analyzed, the organized data (both raw and analyzed data) is sent in an efficient, compact form to the real-time server channel of VGIS. VGIS, which supports the interactive display part of our visual interface, then provides an updated visualization.

5. RESULTS

We have used our system on sequences of analyzed data from a Doppler radar located at the National Weather Service (NWS) facility in Peachtree City, GA. We visualize both raw data and analyzed results, using simple shapes for the latter. Our display meets the real-time requirement. The process of data acquisition, analysis, preparation for display, and display takes about 1 minute (Fig. 2). Most of this time is spent in the analysis step, which could be speeded up. This should be compared with the 6 minutes it takes to make the 3D Doppler radar scan, which involves a series of 2D scans at progressively larger angle with respect to the ground (Fig. 1). For a series of time steps, display is typically in the range of 5-15 updates per second. (The update rate depends on the amount of data displayed. It is 15 fps if only the analyzed shapes are shown.)

To show the capabilities of our methods in detail, we use some previously captured severe storm data. Forecasters will often look at histories as well as at current data. The data presented are from a series of severe storms that occurred over Georgia from 2 am till 10 pm on March 19, 1996. There are 72 time steps in these results, but the system could handle a much larger group of time steps. The analyzed data were in the form of mesocyclones and tornadic vorticity signatures. The mesocyclones are areas of large coherent rotation and are possible precursors to tornadoes. The tornadic signatures are obtained by looking for compactness, intensity, and shear in adjacent radar bins. At least some of these signatures were actual tornadoes. The heights and elevations off the ground (which can be seen clearly in fly mode) of the mesocyclones are indicators of their power and potential for damage. Both types of signatures were built from the stacked 2D scans using simple spatial correlation. The 3D view of the arrangement and time evolution of these structures can provide the forecaster with useful additional information.

We used semi-transparent cylinders and cones to represent the mesocyclones and tornadic signatures respectively. The rotation intensity was mapped to the color with the range of color chosen to be similar to the range employed in 2D visualizations used by forecasters. Icons similar to the ones used in the 2D visualizations were attached to the tops of the mesocyclones so that in orbital mode the 3D scene looks similar to the 2D scene. However, these features are also shown in correlation with the raw 3D radar scans (Fig. 3). The raw reflectivity data is shown as a false-color texture that is mapped onto the cone surface that represents each sweep. In addition, a lot more information is displayed showing correlation with terrain features, urban areas, roads, and rivers. Information like this has not been visualized in detail before with time-dependent 3D weather data. Although the correlation between analyzed storm cell features and underlying Doppler radar features is good in Fig. 3, these features can diverge over time—some of the divergence may be due to terrain features or even human activity. In addition, the integrated visualizations give ample, immediate information about what the storm cells are hitting or about to hit. We have added a grid that can be turned on and off through a menu option to show the coverage of the radar.

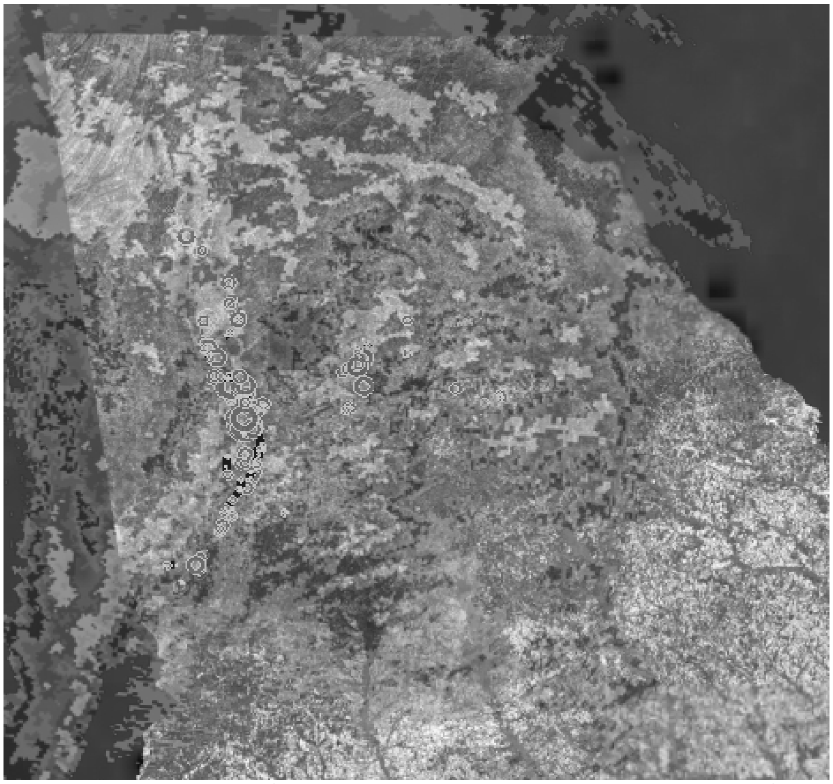

Fig. 3 Interactive view of North Georgia with Doppler radar shown as false-color texture plus mesocyclones shown as semitransparent cylinders.

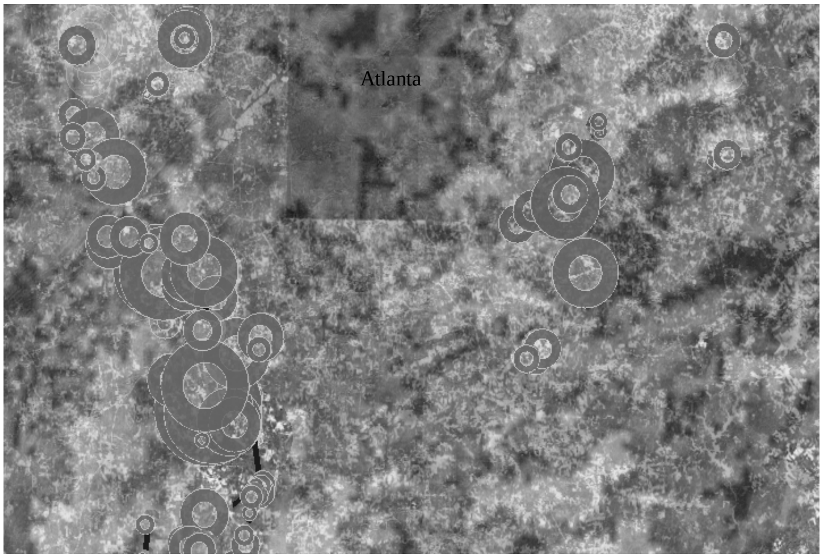

Fig 4. Close-up of South Atlanta area showing large mesocyclones in a curved line approaching the southern part of the city.

In overview, one can easily see the sweep of the storms as they progress from the Alabama border across North Georgia. (See, for example, Fig. 3.) Since the weather visualization is embedded in a global terrain framework, one does not have discontinuous or truncated views but can move smoothly to any view with higher resolution terrain and feature data coming in wherever they are available. For example, the visualization does not stop abruptly at the Georgia border. In the next generation of weather forecasting tools, data will be collected from overlapping Doppler radars and other sensors over a much larger area. The global terrain capability will be even more useful when this occurs.

The orbital and fly modes permit a continuous movement between browsing and more detailed analysis. For example, Fig. 4 shows an overview of storm cells as they increase in size and intensity over Atlanta. The forecaster can use the jump mode (and then can fly around) to see the relation of these features to urban areas and can also see the heights of these features and their relation to each other and to the ground (Fig 5).

We have found that terrain features, such as mountains or buildings, plus the 3D shapes of the storm signatures are especially prominent on the virtual workbench. Here the stereoscopic display makes the 3D structure “stand out” automatically, even without changes of view by the user. Further, the workbench provides a large work surface for analysis and collaboration among users. The navigation modes are also fast and intuitive.

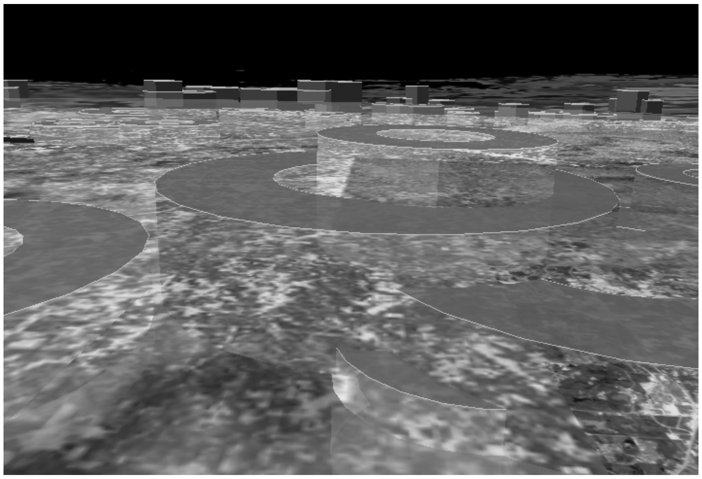

Fig 5. Closeup of some mesocyclones, allowing examination of their height.

6. CONCLUSIONS AND FUTURE WORK

We have presented methods and results for real-time acquisition, organization, and visualization of atmospheric data in a geospatial environment, emphasizing capabilities that will be of use to forecasters and other decision-makers. We expect these capabilities will also be useful to others concerned with the analysis of weather or other atmospheric data, such as researchers or planners. Our atmospheric visualization application meets most of the requirements listed at the beginning of section 2. In particular the application provides real-time acquisition, end-to-end real-time capability, integrated browsing and analysis, details on demand, and integration of relevant data in one visualization. This last capability will grow in importance as researchers develop better models of storm development, which will yield rules for how storms behave in the presence of hills or mountains and other features.

The results show how time-dependent atmospheric data in a geospatial environment can be effectively explored visually using appropriate interactive tools. These include direct manipulation tools for navigation and manipulation, and interface elements for controlling animation and scale. With these tools and with multiresolution global visualization the user is able to quickly get to features of interest and to gather more information than was available before for decision-making.

We have several avenues of future work. We expect to redesign our prototype application and bring more elements from the menus into an always-visible control panel for faster access. We are also exploring volume-rendered Doppler radar data as a supplementary mode to the present simple texture mapping. Once these features are in place, we will give the application to colleagues at the NSSL and to NWS forecasters for evaluation. We will develop new methods for detailed rendering of the 3D radar data. These data will be in the form of “hierarchical geospatial volumes” so that they have levels of detail that fit into our overall global data structure [Fau00, Dav99]. This will be a major step towards fully implementing the most detailed and accurate views of the evolving 3D weather patterns.

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