2006

The Virtual Storm: an exploratory virtual environment of a supercell tornadic thunderstorm for meteorological education

Galen William Faidley
Iowa State University

The Virtual Storm: An exploratory virtual environment of a supercell tornadic thunderstorm for meteorological education

by

Galen William Faidley

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Computer Engineering

Program of Study Committee:
James Oliver, Major Professor
William Gallus Jr.
Diane Rover

Iowa State University

Ames, Iowa

2006

UMI Number: 1439864

UMI Microform 1439864

ProQuest Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346

Chapter 1 Introduction

1.1 Motivation

It is widely believed that hands-on experience is the most effective means to learn scientific and other technical subjects. The National Research Council[15] and the National Science Foundation[16] have urged that "All students have access to supportive, excellent undergraduate education in science, mathematics, engineering, and technology, and all students learn these subjects by direct experience with the methods and processes of inquiry." Laboratory work has proven to be a popular means of providing hands-on experience. However, there are some areas of study where it is not feasible to conduct laboratory experiments. Meteorology is one such area. The systems involved in meteorology have a level of complexity that does not lend itself to the simplification necessary for demonstration in a laboratory setting. Therefore, educators in meteorology have turned to other means to provide students with direct experience. Out of class exercises, such as forecasting activities[28] and web-based simulations[27], are examples of some techniques used by meteorology educators to enhance students' learning. However, all areas of metrology are not equally suited for such activities. In particular, these activities are not ideal when dealing with severe weather. There are at least three, almost self-evident, reasons for this. First and foremost, severe weather is dangerous and allowing students to have first hand experience with the phenomena would be irresponsible. Secondly, severe weather phenomena are rare enough that there are no guarantees they will develop during the term of the course. Finally, these phenomena are difficult to predict, so even if they do occur during a course, it is unlikely that an instructor would receive a prediction accurate enough on which to plan a course activity. The research presented here endeavors to provide a safe and controlled environment, which will give students hands-on experience with a severe weather phenomenon.

Its location in the midst of Tornado Alley contributes to a large popular and research interest in tornadic thunderstorms in the Iowa State University's (ISU) community. Of course, popular interest spreads much further than just the ISU community and encompasses not only the people in tornado prone areas, but also, thanks to intense media coverage, many people not directly affected by tornadic activity. In short, a large percentage of the population is interested in tornados. This general appeal of tornados, plus the local researchers' expertise, led to the selection of a tornadic thunderstorm as the severe weather phenomenon that would be the focal point of a hands-on teaching tool. If successful, the tool would find an audience not only in higher education, but also in middle and high school science courses, science museums, and through proliferation on the information super highway to anyone with an interest in tornados. The tool will be referred to as the Virtual Storm from now on.

1.2 Statement of Purpose

The purpose of the research presented here is to explore the feasibility of using Virtual Reality and computer graphics technologies to provide a means for hands-on experience when learning about severe thunderstorms and tornados.

1.3 Project Scope

The work to achieve the goal set forth in the statement of purpose can be divided into three components:

1.3.1 Design and Implementation of the Virtual Storm Application

The Virtual Storm application needed to be created. This interactive 3D application, coupled with a data visualization component, provides the user with the hands-on experience necessary to learn about tornadic thunderstorms. The selection of the data presented to the users, and how they interact with that data, was inferred through an iterative design process that used the results from the two evaluation components of the research.

1.3.2 Pedagogic Evaluation of the Effectiveness of the Virtual Storm

Formal user studies were conducted to evaluate the teaching qualities of the Virtual Storm. This evaluation was used to both determine if the tool was an adequate teaching aid, and refine the next iteration of the tool. Specifically, this evaluation was used to determine if additional information needed to be conveyed to the user.

1.3.3 Usability Evaluation of the Virtual Storm

The usability of a piece of software can often be detrimental to its effectiveness. Ideally, the software would purely act as an enabler to access the knowledge. Therefore, the Virtual Storm was evaluated with regards to usability. The results from this evaluation were used in the iterative design process to improve each successive version of the software.

1.4 Thesis Organization

This document explicitly focuses on the final implementation of the Virtual Storm application and the pedagogic evaluations of that tool. The usability evaluations are implicitly covered throughout the document as their effect on the tool itself or the pedagogic results are discussed. The thesis is laid out as follows:

- Chapter 1 provides the motivation, goal statement, and scope of the research presented through out the rest of the document.
- Chapter 2 presents research related to the Virtual Storm. Specifically, the work of three other groups using virtual reality or computer graphics for education is presented. The tool itself is presented first, followed by a description of the user test set up, and concluding with the results of those user tests and any insight the researchers presented.
- Chapter 3 provides a detailed overview of the functionality provided in the Virtual Storm. The interface and interaction techniques are described.
- Chapter 4 dives into the details of how particular features were implemented and describes why certain choices were made.

- Chapter 5 presents the formal user studies conducted on the Virtual Storm. The test methodology and five years of results are presented.
- Chapter 6 highlights some of the limitations in the current implementation of the Virtual Storm, and provides insight on what can be done to improve upon the tool in the future.
- Chapter 7 draws the thesis to a close with a summary of what was accomplished.

Chapter 2 Related Research

Since the mid-1990's Virtual Reality (VR) systems and, more recently, desktop based real-time computer graphics systems have been employed in the education arena. These technologies have allowed for innovative means of presenting information to students, and have allowed for hands-on learning with subject matters that previously could only be taught from a textbook. A sample of these tools is presented here, along with the results from the pedagogical evaluations conducted on them.

2.1 ScienceSpace

Some of the first to apply Virtual Reality technologies to education were Dede, Salzman, and Loftin with the ScienceSpace suite of applications[8]. ScienceSpace consists of three unique applications, each targeted at a different physical phenomenon. The first application is NewtonWorld, which provides a means to explore the kinematics and dynamics of one dimensional motion. The second application is MaxwellWorld, which allows users to experiment with electrostatics. The final application is PaulingWorld, which allows users to study molecular structure. ScienceSpace leverages many of the strengths of virtual environments to enable learning. Its tools leverage virtual reality's ability to visualize abstract concepts. By mapping these abstract properties to visual cues, students form a mental image of what is taking place. ScienceSpace also heavily relies on multiple representations of the same data, both by mapping the same information to different cues, and by providing multiple reference frames to choose from when observing the same event or phenomenon. The multiple simultaneous representation of the information is not limited to visual cues, but is truly multi-sensory and incorporates the visual, auditory, and tactile senses.

User studies were conducted on both NewtonWorld and MaxwellWorld. An iterative design process was employed in the creation of ScienceSpace, and the data gathered in each user study was used to further refine the applications.

NewtonWorld underwent two preliminary studies before a formative pedagogic evaluation was performed. The first study used nine high school students as test subjects. Each student used the application for a little over one hour. 107 physics educators, who experienced the tool for a brief demonstration during a conference, were test subjects for the second evaluation. The results from these preliminary studies were used to refine the application. This revised version was then tested with 30 high school students. Each student was instructed to perform certain experiments and think aloud as they worked. The tests lasted between two and a half and three hours. From a pedagogic point of view, the results of this user study showed that a single session in NewtonWorld did not significantly improve the users' understanding of the subject matter. Students did, however, enjoy their experience and felt it was a good way to explore scientific concepts. Furthermore, the researchers noticed that care must be taken when using multi-sensory cues, as they may have the effect of merely changing a users' focus rather than improving his or her over all understanding of the information. Specifically, the researchers discovered that mapping vibrations in a haptic vest to kinetic energy and momentum led students to have a better understanding of the collisions of particles; however, these same students were less likely to predict how the system as a whole would behave. The results from these user tests have led the researchers to undergo a redesign of NewtonWorld, through which the focus has been changed to exclusively concentrating on conservation of momentum, and the target users are now fifth through seventh graders rather than high school students. Results from user studies of the revised application have not been published.

MaxwellWorld underwent two distinct user evaluations. The first was a formative evaluation that saw 14 high school and four college students use the application three times over a two week period. The students were engaged by the application and felt that it was a better way to learn about the subject matter. It was observed that the students' ability to interact in the 3D environment varied widely. Finally, from a pedagogic standpoint, pre and post evaluations determined that by using MaxwellWorld students gained an in depth understanding of the subject matter. After the promising results found in the formative evaluation, a comparative evaluation was conducted to determine to what extent (if any) the unique multi-sensory immersive properties of the MaxwellWorld contributed to the learning experience. This test was conducted in two stages. The first stage compared a two dimensional electromagnetic educational software (EM Field) to a version of MaxwellWorld with the multi-sensory features disabled. The second stage, conducted five month after the first, evaluated the MaxwellWorld with all features enabled. 14 high school students took part in the first phase of the study and either used EM Field or MaxwellWorld. The results of pre and post tests show that those students using MaxwellWorld gained a better understanding of the concepts and were better able to describe an electric field in 3D than the students who used EM Field. The two groups had an equivalent performance when performing 2D sketches. Seven of the original 14 students returned for the second phase of the evaluation five months after the first. The pre test of stage two was compared with the post test of stage one to analyze the students' retention of what was learned in stage one. This comparison showed that there were no significant differences in the retention between the students who used MaxwellWorld and those who used EM Field. In stage two all the students used a full version of MaxwellWorld. When comparing the post test results from stage two with the post test results from stage one for the EM Field users, the stage two results were significantly better for all areas. Though not presented in the research, it would have been interesting to analyze how much of this improvement was due to MaxwellWorld, and how much could be attributed to a second lesson on the subject matter.

Through the implementation and testing of ScienceSpace, the researchers gained valuable insight into using VR for education. They found an iterative design process that focused on learner-centered development to be helpful in making the most meaningful learning tools. They discovered unique challenges when working with VR environments. Many of these challenges revolve around the limitations in VR hardware that cause user discomfort. Proper set up and continuing monitoring of user discomfort can mitigate these limitations. Another challenge discovered was that there is a high degree of variability between different users' abilities to interact with 3D worlds. Finally, the researchers identified aspects of VR that aid in the learning experience. Among these are the use of multi-sensory cues to direct the learner's attention to important features, and the ability to provide students with a visual mapping of a phenomenon that they can then use to construct a mental model.

2.2 Virtual-SAP

A more recent example of Virtual Reality used for educational purposes is the Virtual Structural Analysis Program (Virtual-SAP) developed by Bowman, et al at Virginia Tech.[2][3] Virtual-SAP is a tool for visualizing environmental impact on building structure. The current implementation focuses exclusively on earthquakes; however, this could be extended to simulate other environmental conditions. The use of Virtual-SAP is divided into three phases referred to as "build-simulate-animate." In the build phase users create the structures they wish to analyze. Virtual-SAP incorporates 3D modeling capabilities so that it is possible to create the structure in an immersive environment. Virtual-SAP also has the ability to import structures built with an external package. These structures may then be further refined with Virtual-SAP modeling capability. Once the users are content with their structures they instruct Virtual-SAP to run a simulation. Virtual-SAP submits the structure to a pre-selected earthquake. The data used for the earthquake simulations are based on actual data recorded from various earthquakes over the years. The earthquake simulation is not real-time; however, the user is free to move about the virtual world while Virtual-SAP waits for the results of the simulation. Once the simulation is complete, Virtual-SAP allows the users to visualize the results as a 3D animation. The users study the results and then further refine their structure, thus starting another "build-simulate-animate" cycle.

As an educational tool Virtual-SAP is used in both graduate and undergraduate building structure courses at Virginia Tech.[17]. The application is integrated into the curriculum and classroom lecture through the use of a mobile VR system[2]. This portable system consists of an inexpensive head mounted display (HMD), a head tracker, projector and PC. One student is immersed in Virtual-SAP using the HMD while the rest of the class views the immersed student's same view on the projection screen. The class is presented with five different scenarios. In each scenario a predefined structure is loaded into Virtual-SAP and submitted to an earthquake. The class observes the effect of the earthquake on the structure and has a class discussion to decide what modifications should be made to the structure so that it could withstand the seismic event. The immersed student then modifies the structure based on the class's suggestions and the simulation is rerun. The class observes the new results and, where necessary makes further refinements.

A Subjective evaluation of Virtual-SAP was conducted through observation, student interviews and surveys. The intent was to capture the effectiveness of Virtual-SAP in the classroom. The tool was used in two classroom settings; a small class of eight students and a large class of 50 students. The students in both classes where Virtual-SAP was used felt it was effective to switch between the instructors' lectures and the Virtual-SAP exercises that highlighted what they had just learned. 74% of the students found the use of Virtual-SAP to be worthwhile. High levels of engagement were reported in the small class: 7.0/7.0 for the users of the HMD and 5.5/7.0 for the other students. In the large class the reported levels of engagement were 3.5/7.0 with no distinction between the HMD users and observers. 84% of students felt that the use of Virtual-SAP improved their understanding of the subject matter. The most effective use of the tool appeared to be achieved by prodding users for their expectations before running the simulation and having them comment on the results with regards to their hypotheses. When asked if the tool improved their understanding users reported very high scores: 7.0/7.0 for the HMD users and 5.25/7.0 for observers. Finally, the spatial layout of the virtual world was well understood by all students and received a 6.25/7.0 on the survey. The difference in results between the users of the HMD and the observers was studied. The researchers determined that the increased effectiveness of the HMD was due to interaction, not immersion. This suggests that a desktop (non-immersive) tool may be better suited for this application, as it would allow more students to interact with the system. However, it was suggested (but not verified) that a desktop tool would see lower scores on user engagement and efficiency.

2.3 eCigro

Over the past decade high performance computer graphics have become ever more accessible. What started off as being possible only with dedicated visualization centers migrated to scientific and engineering workstations, then further expanded to high end gaming machines, and finally became possible on commodity hardware. The industry is now at the point where every PC sold has hardware accelerated 3D graphics. With this capability available on the desktop, more and more applications are harnessing this power, including educational software. One example of an educational software package designed to run on the desktop is eCigro. [5]

As engineering design has moved from two-dimensional sketches to 3D CAD models, it has become ever more important to develop students' spatial reasoning and the ability to understand different views (or projections) of a model. eCigro is a tool designed to aid this process. Using a graphics tablet (or other drawing based input device) students create "sketches of pseudoaxonmetric representations of rectangular polyhedral shapes," or more simply, shapes with edges and faces that converge at 90-degree angles. Sketches the students draw on the tablet are interpreted in real time and eCigro extracts a 3D model based on the user's 2D input. The interface is simple, containing only three drawing commands: add edge, remove edge, and add auxiliary line (a line used to help define the shape, but not actually in the final geometry). The view of the component is dynamic and can be rotated at will. Sketching can occur with the shape positioned in any rotation, and eCigro uses parallel line recognition and edge intersection recognition to generate the 3D representation. The instantaneous feedback from sketch to 3D representation allows for students to check design intent as they work.

A pilot study to evaluate the effectiveness of the eCigro application was conducted at La Laguna University. The evaluation criteria were the Mental Rotation Test (MRT) and the Differential Aptitude Test Spatial Relations subsection (DAT-SR). All 461 students in a freshman-engineering course were pre-tested. The 78 students with the lowest scores were given the opportunity to take a remedial course to improve their spatial understanding. Three different remedial courses were designed. Each course was composed of three 2-hour sessions that were conducted over the first week of the semester. The first course used a traditional pencil and paper approach, and covered topics including face identification in different views and drawing different views of an object. The second course was built around web-based exercises from the University of Burgos. The content mostly consisted of using VRML models to complete visualization exercises. The final course was built around the eCigro application. All the students that completed the remedial course were post tested with MRT and DAT-SR. Statistical analysis was preformed on the data. The null hypothesis that the course had no effect upon the scores was evaluated with a paired test. The results of the tests and the statistical probability that the hypothesis is correct (p value) are presented in Table 1. As can be seen from the table the null hypothesis is rejected in all cases, with a certainty of greater than 99% in all but one instance. Thus, it can be said that all three remedial courses had a measurable positive effect on students' scores on both MRT and DAT-SR. Furthermore, the students using Ecirgo demonstrated a higher level of engagement, which may lead to a higher likelihood of students completing the remedial course.

Table 1. Results from Engineering Remedial Courses

Learning technique (Number of students)	MRT			DAT-SR		
	Pre	Post	p	Pre	Post	p
Traditional (17)	8.18	13.53	1.15E-4	28.47	39.35	4E-7
Web (15)	9.60	13.27	0.043	30.53	35.67	0.002
eCirgo (20)	7.85	12.95	5.05E-4	33.00	40.40	2.18E-5

Chapter 3 Virtual Storm: Overview

The Virtual Storm application is a computer-generated tornadic super cell thunderstorm designed to be explored by its users. The Virtual Storm can be used either in an immersive environment[6], as seen in Figure 1, or as a desktop application, as seen in Figure 2. Users are able to explore the storm from both the ground and air. There are no restrictions placed on exploration of the storm. Users can fly into the funnel cloud or look down at the storm from 10,000 meters. The visual representation of the storm is enhanced with auditory cues. To complement the exploration of the storm the users are given scientific instrumentation in the form of a data-gathering interface, as seen in the right side of Figure 2. This instrumentation allows users to take readings of meteorological information, such as temperature, relative humidity, wind speed, and pressure. Furthermore, a map-like chart is displayed to plot these readings and to aid in navigation of the storm.

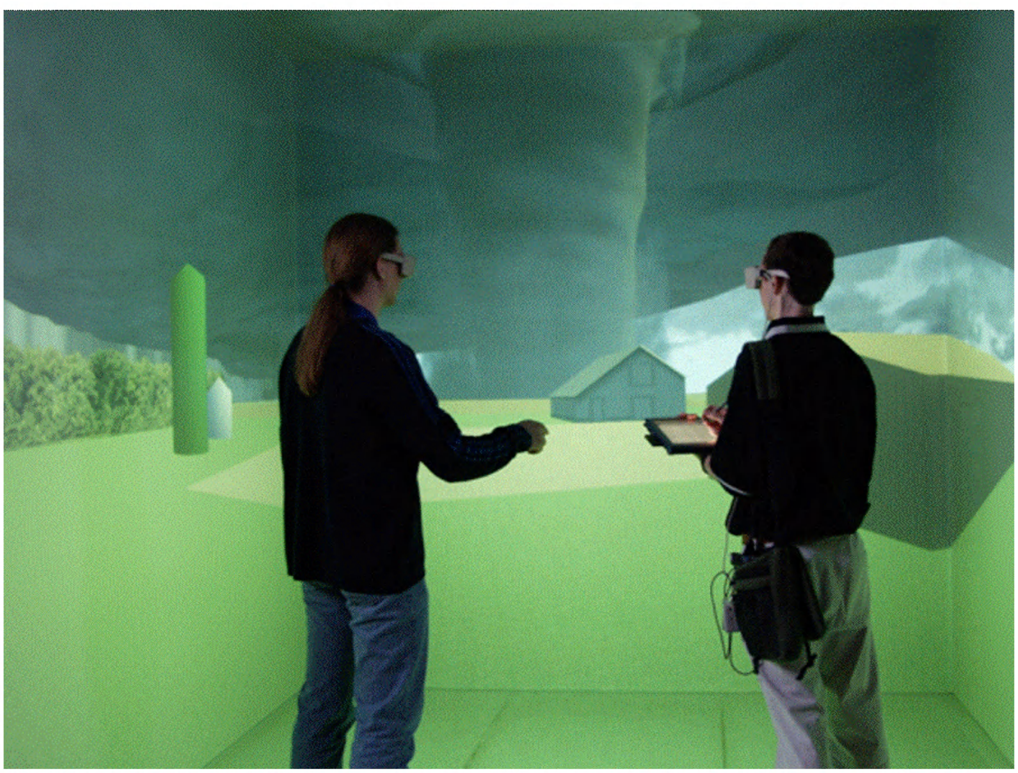

Figure 1: Two students use the Virtual Storm in an immersive environment.

The Virtual Storm can be subdivided into two components, which are represented by the two windows presented to the user (Figure 2). The two components are the Storm Visuals component and the Data Gathering component. The Storm Visuals component provides a view into the storm while the Data Gathering component allows users to acquire meteorological information regarding the storm. The two components communicate with one another, and together are the Virtual Storm. Each component has its own interface and interaction technique. Furthermore, these interaction techniques vary depending on whether the Virtual Storm is used on a desktop machine or in an immersive environment. The rest of this chapter describes the functionality provided and the interaction technique of the Storm Visuals and Data Gathering components in both an immersive and non-immersive configuration.

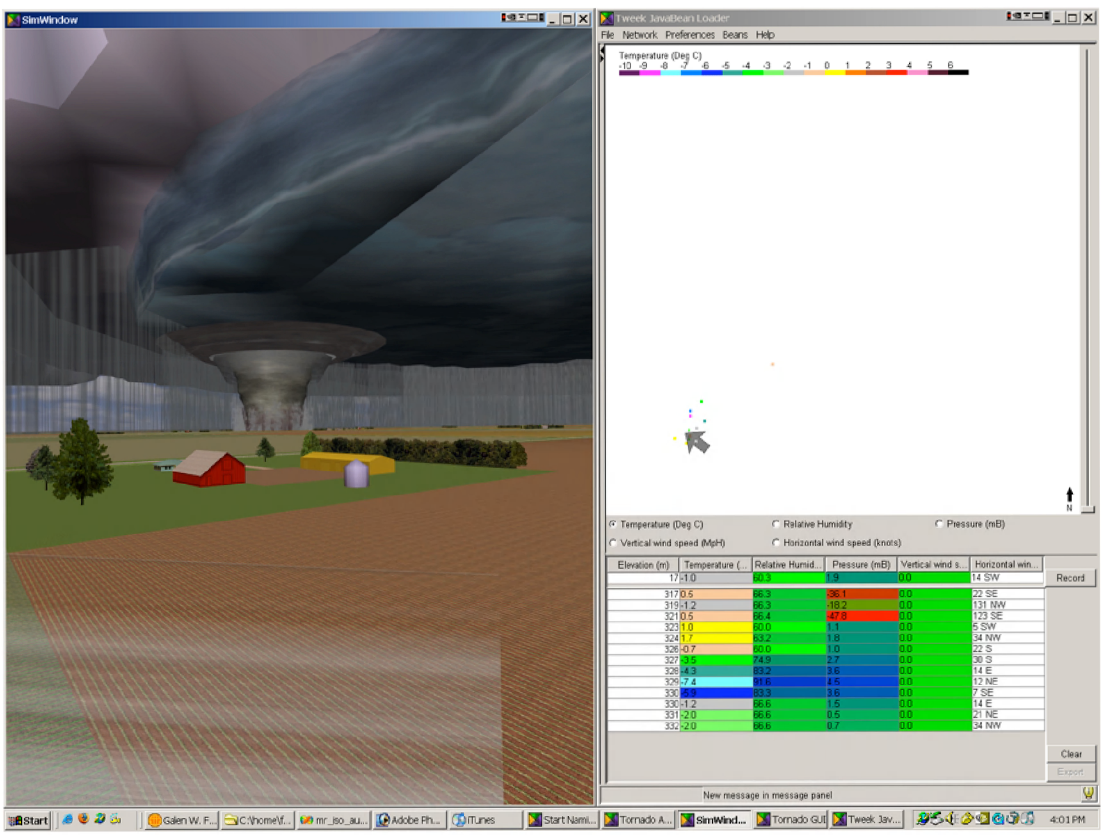

Figure 2 The Virtual Storm in use on a desktop system. The Storm Visuals component is on the left and the Data Gathering component is on the right.

3.1 Storm Visuals

The purpose of the Storm Visuals component is to provide a view into the storm. This view of the virtual world is meant to mimic the real world. Computer graphics and audio effects make the users feel as if they are standing in an Iowa cornfield as a storm is approaching. Emphasis is placed on reproducing the features and the behaviors of the storm with the most pedagogic value. A natural and intuitive navigation technique is also employed so that the storm can be explored with ease.

3.1.1 Visual Storm Features

The Storm Visuals component of the Virtual Storm is a recreation of a 120 mile by 80 mile area of rural country side. Lingering over the area is a full supercell tornadic thunderstorm. Special care was taken to include the visual features of this storm that convey important meteorological information. Figure 3 through Figure 7 illustrate these features.

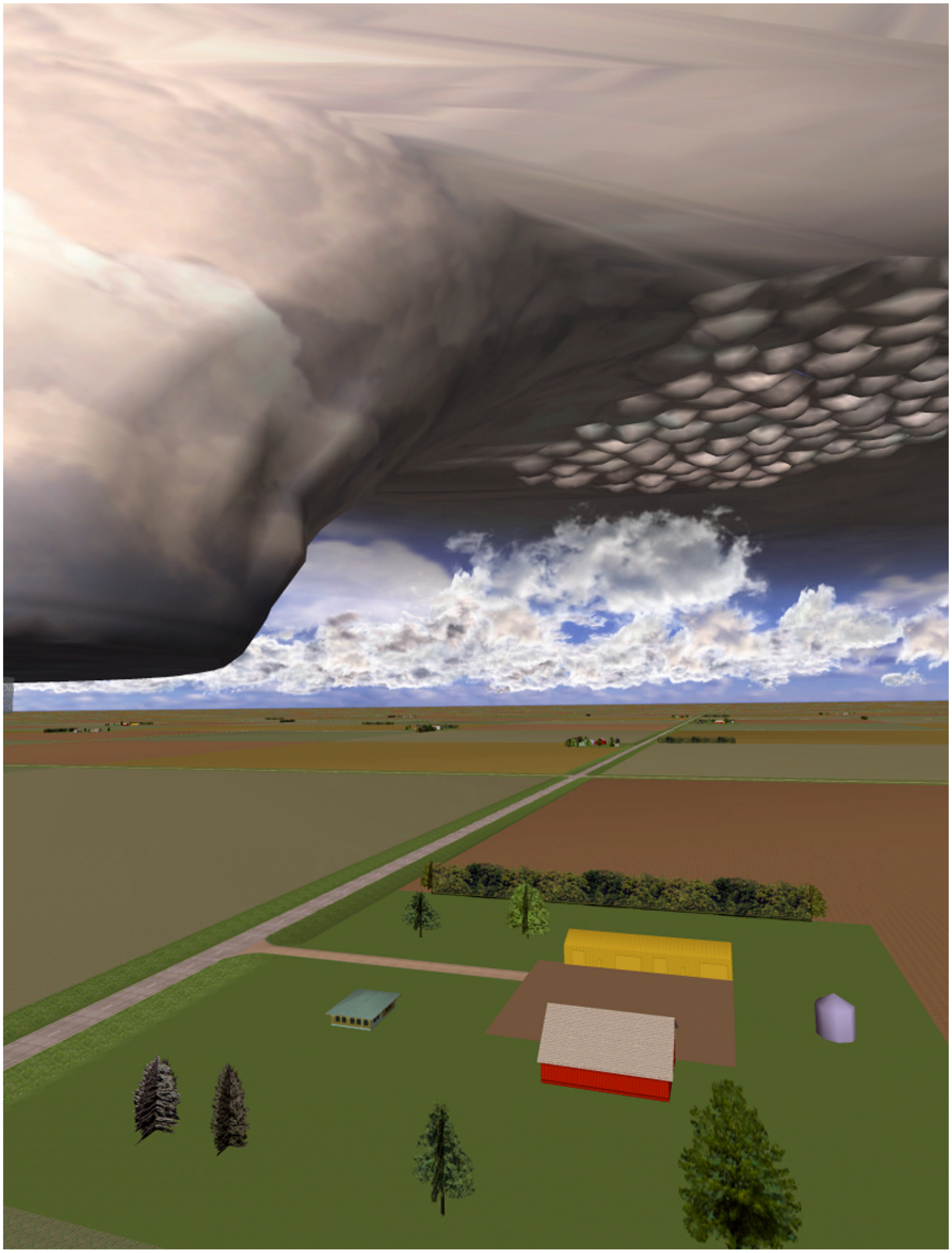

Figure 3: A view of the anvil cloud and mammatus clouds. The anvil cloud is the flat widespread top of the storm showing that rising air in the storm has reached the stratosphere. Mammatus clouds are downward hanging smooth protuberances on the underside of the anvil cloud.

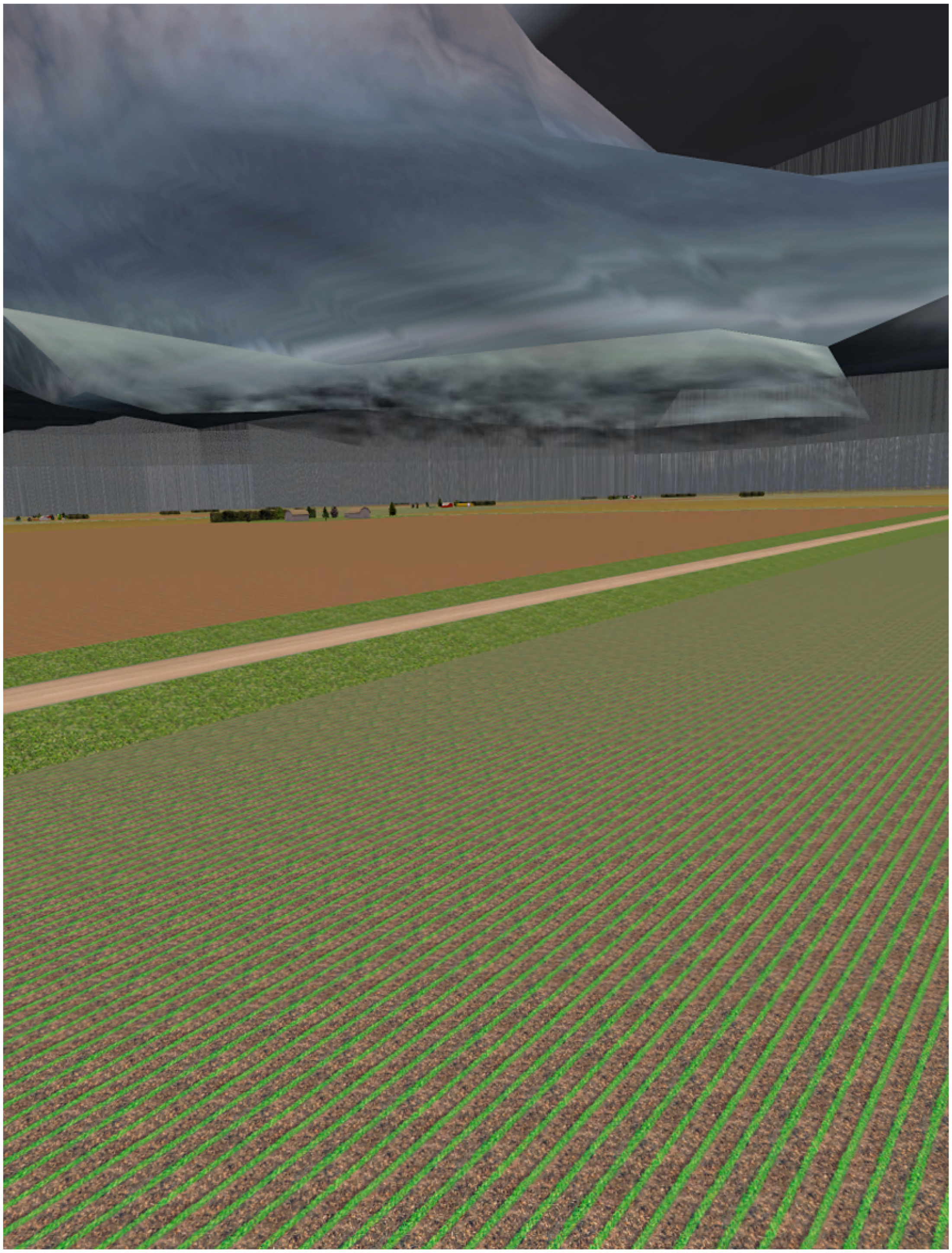

Figure 4: A view of the shelf cloud; a smooth sheet of cloud that often occurs just ahead of the main rain region.

Figure 5: A view of the wall cloud and tornado. The wall cloud is a lowered area of cloud base from which tornados usually descend. The tornado is the rapidly rotating column of wind usually visible due to debris or condensation within it.

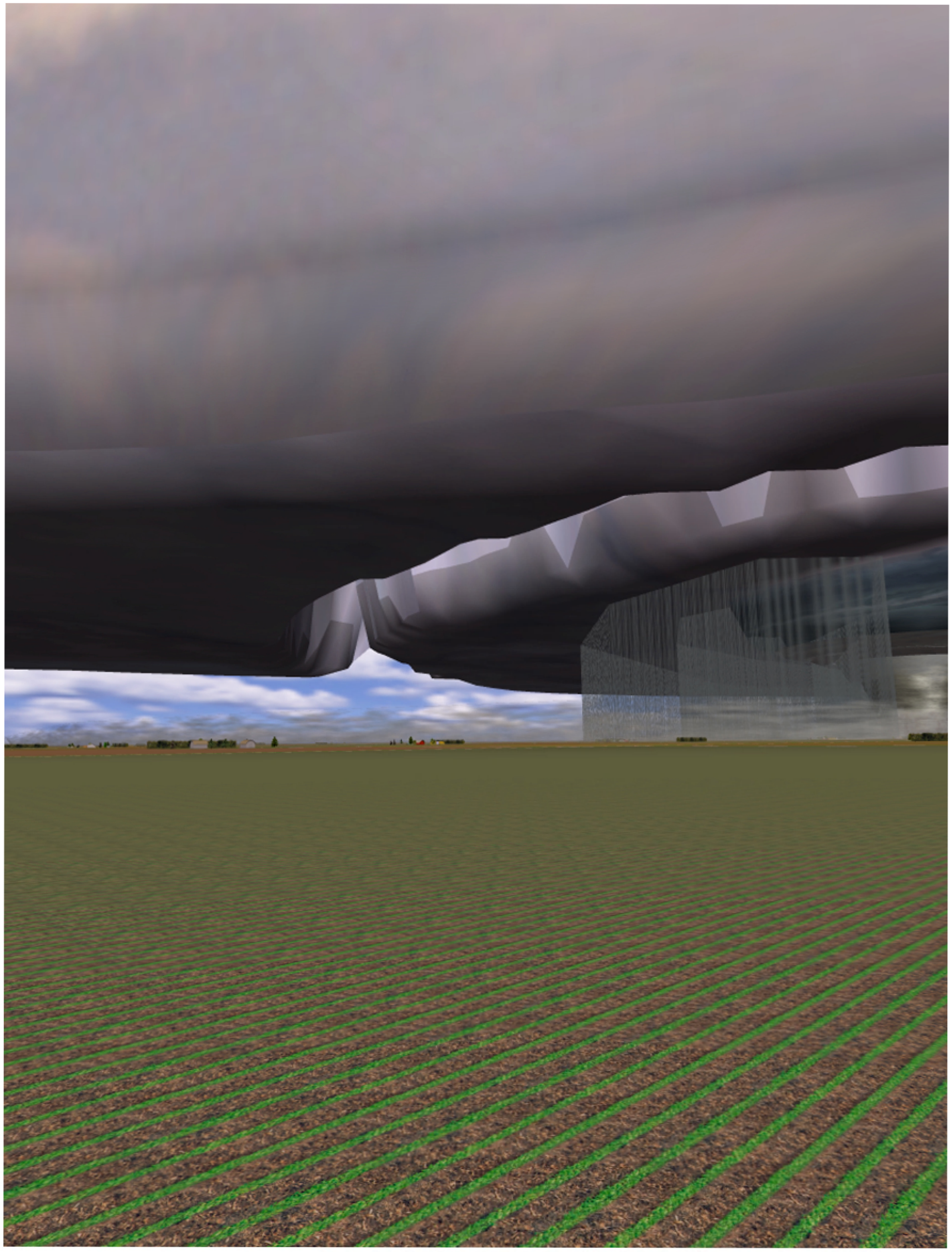

Figure 6: A view of the rear-flank downdraft, an arc-shaped zone of sinking air that tries to circle around the tornado, often producing sheets of blowing dust at the ground and partial clearing of cloud base aloft.

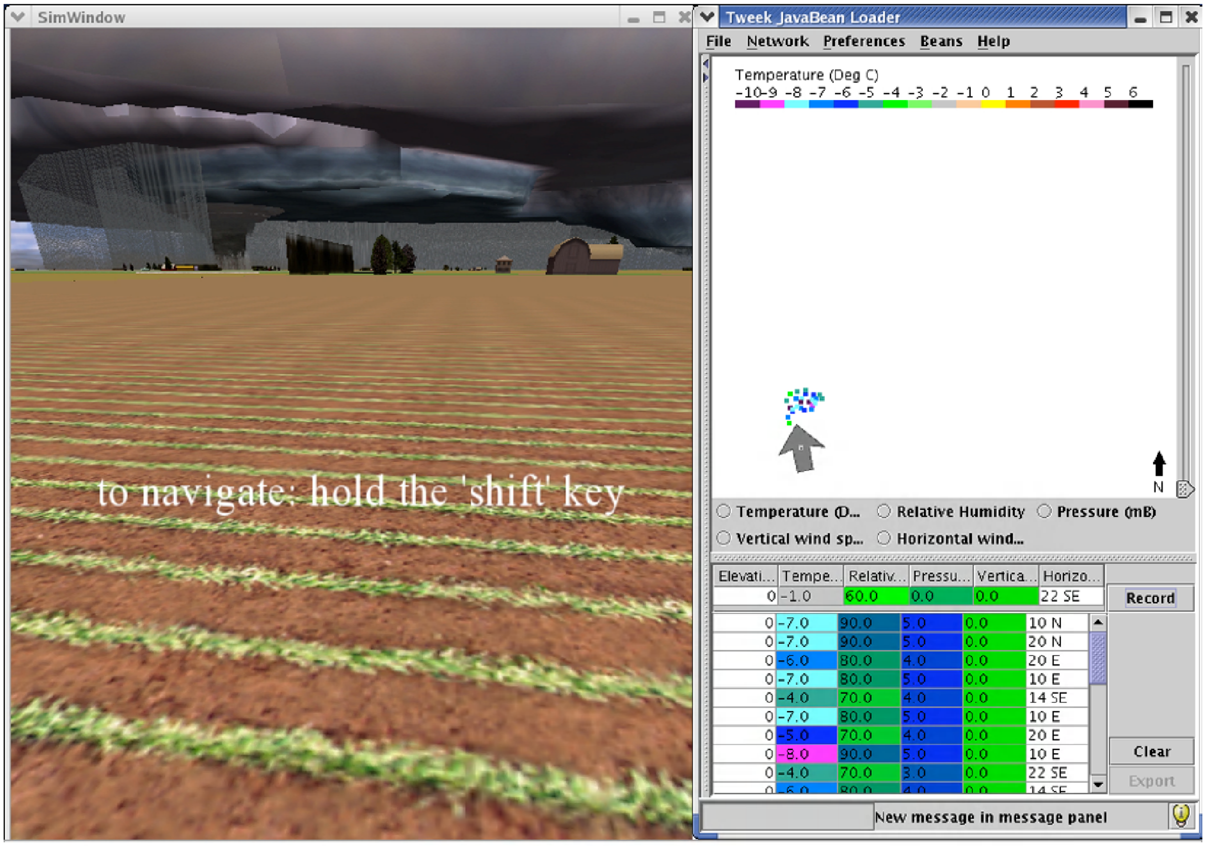

Figure 7: A view of the comma-shaped rain region. The shape is related to the dynamics of the storm. A top-down view from the Data Gathering component showing the temperature variance in the rain region is also present.

The visual references to salient features allow students to explore key concepts of supercell tornadic thunder storms. Users are able to explore storm-scale dynamics, such as updrafts, downdrafts, and wind shear. The microphysical effects, such as the evaporation-driven cold pool, can also be studied. Finally, as will be discussed in further detail below, the issues of perspective and visibility can be assessed.

3.1.2 Behaviors

An interactive 3D world allows for not only visual realism but also behavioral realism. With the Virtual Storm the capability of computer graphics were leveraged to produce a learning tool that both looks real and behaves realistically. Behaviors were applied predominantly to produce auditory effects and to provide life-like precipitation (rain and hail). These behaviors were implemented with the hope that the users' experience in the Virtual Storm be as natural as possible, and that when finished using the application they are left with the impression of having been through a real storm.

3.1.2.1 Audio Cues

In the natural world sound and vision go hand in hand to convey information to a human observer. The auditory cues placed in the Virtual Storm are not only used to enhance the realism of the experience but also used as an alternate means to convey information. Such multiple representations of the same information are seen as one of the strengths of using virtual reality in education.[25]

Four sound effects are used throughout the Virtual Storm. Figure 8 illustrates the regions where these effects are put to use. Throughout the entire virtual world background audio is present. This audio consists of sound samples of things that are typically heard on a farm: the sound of livestock, the wind blowing, etc. This background noise is used mostly to provide increased realism, while the remaining three sounds are used to also convey information regarding the storm.

The second two sound effects enhance the visual representation of precipitation in the Virtual Storm. When users are in a region of light rain they will hear the patter of raindrops. As they move into heavier rain the intensity and frequency of the patter increases. Finally, as the users venture into a region of hail the sound of the rain is now complimented with the sound of falling hail. Much information can be gathered through the precipitation audio cues. Users can judge whether they are moving towards a more violent region of the storm, or away from the heart of the storm based on the intensity of the sound. In the case of rain, this same information can be gathered by visually judging the intensity of the rain. However, in the case of the hail, the auditory cues provide information that cannot be conveyed visually. As will be covered in the next section, the hail is also presented visually; however, limitations in human visual perception cause these visual cues to break down. In the real world, two of the perceptual features of hail that differentiate it from rain are the sound it makes when it hits something and the fact that it bounces on the ground. As mentioned earlier, the Virtual Storm allows users to fly through the storm. While navigating off the ground the user will not be able to see the hail bounce. As in the real world, hail streaming by visually is almost indistinguishable from heavy rain. However, the sound of hail is indisputable, and by including such a sound effect in the Virtual Storm users immediately know when they are in a region of hail even without being able to see the hail stones.

The final auditory cue provided in the Virtual Storm is the tornado itself. As the user approaches the funnel the roaring sound of the tornado steadily increases. The sound can be used to locate the tornado even when it is not in sight. Furthermore, as with the rain, the change in intensity informs the user of whether they are approaching or retracting from the funnel. With regards to realism, the deafening sound of the tornado helps to instill feelings of urgency and panic into the user. This helps convey the utter destruction that can be caused by such a storm.

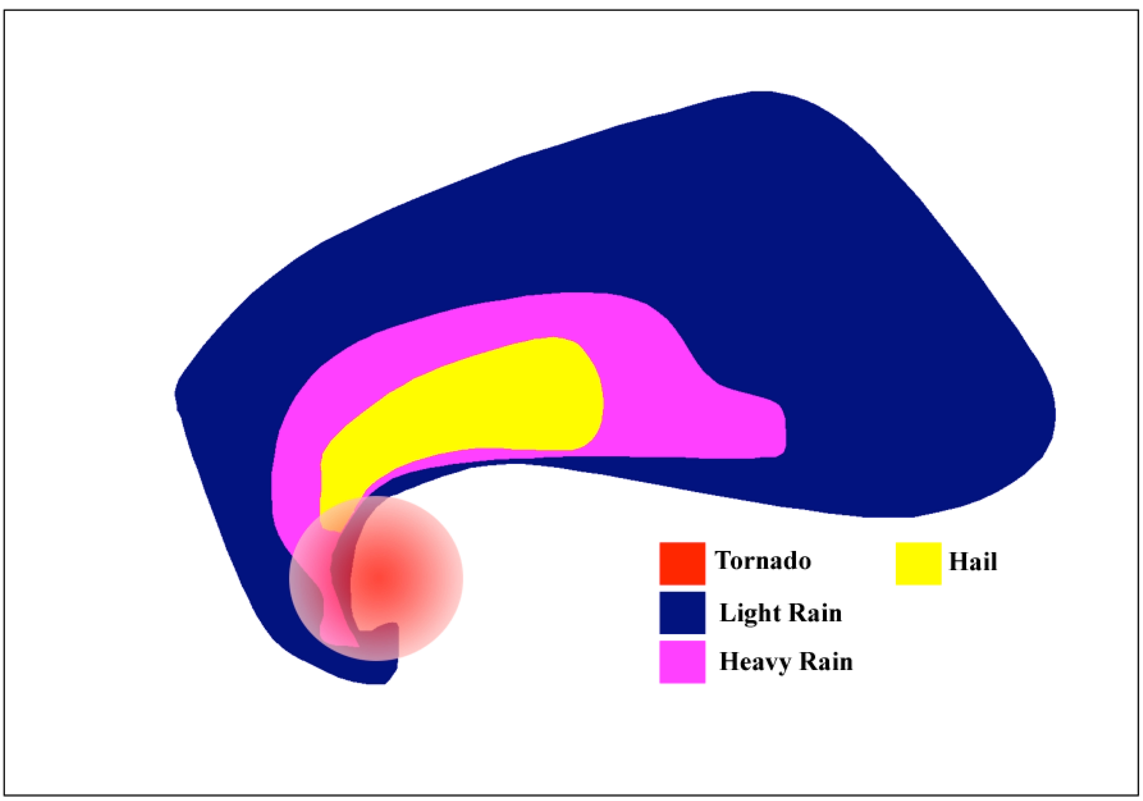

Figure 8: Regions within the Virtual Storm.

3.1.2.2 Precipitation

The second application of behaviors in the Virtual Storm is to precipitation. There are three distinct areas of precipitation incorporated into the storm. These are a region of light rain, a region of heavy rain, and a region of hail. Each of these areas behaves realistically. When approaching an area of light rain the user will first see a few drops of rain that will increase to steady drizzle. The user will also experience a loss of visibility due to the rain itself and the mist in the air. As the user moves further into the storm he or she will encounter a region with much heavier rainfall. While in the heavier region of rain many more raindrops are present and the visibility drops even further. As the user ventures into the most violent region of the precipitation hail starts to fall. The hail behaves realistically as it falls past the user and when it strikes the ground it bounces before settling. The hailstones will then start to melt on the ground, and after a short period of time they will completely disappear. The visibility in the region of hail is also further reduced from that in the two regions of rain.

As with the auditory cues, the behavior of the precipitation allows the user of the Virtual Storm to infer information about the storm system. By helping users identify the severity of the precipitation, the behaviors enable users to build geographic relations between storm features and rainfall. For example, students will hopefully notice that the temperature is lower in the regions of rain due to cloud coverage and water evaporation. To teach about the danger of tornados, the reduced visibility is of prominent importance. A common misconception about tornados is that people can see them coming and can seek shelter once they spot one. Because of the reduced visibility, even with a relatively slowly moving tornado the funnel can creep up on an unsuspecting victim. By the time it becomes visible it is often too late to seek shelter. Figure 9 shows a screen shot looking at the tornado from within a region of heavy rain. The tornado is less than a mile away, yet is barely visible.

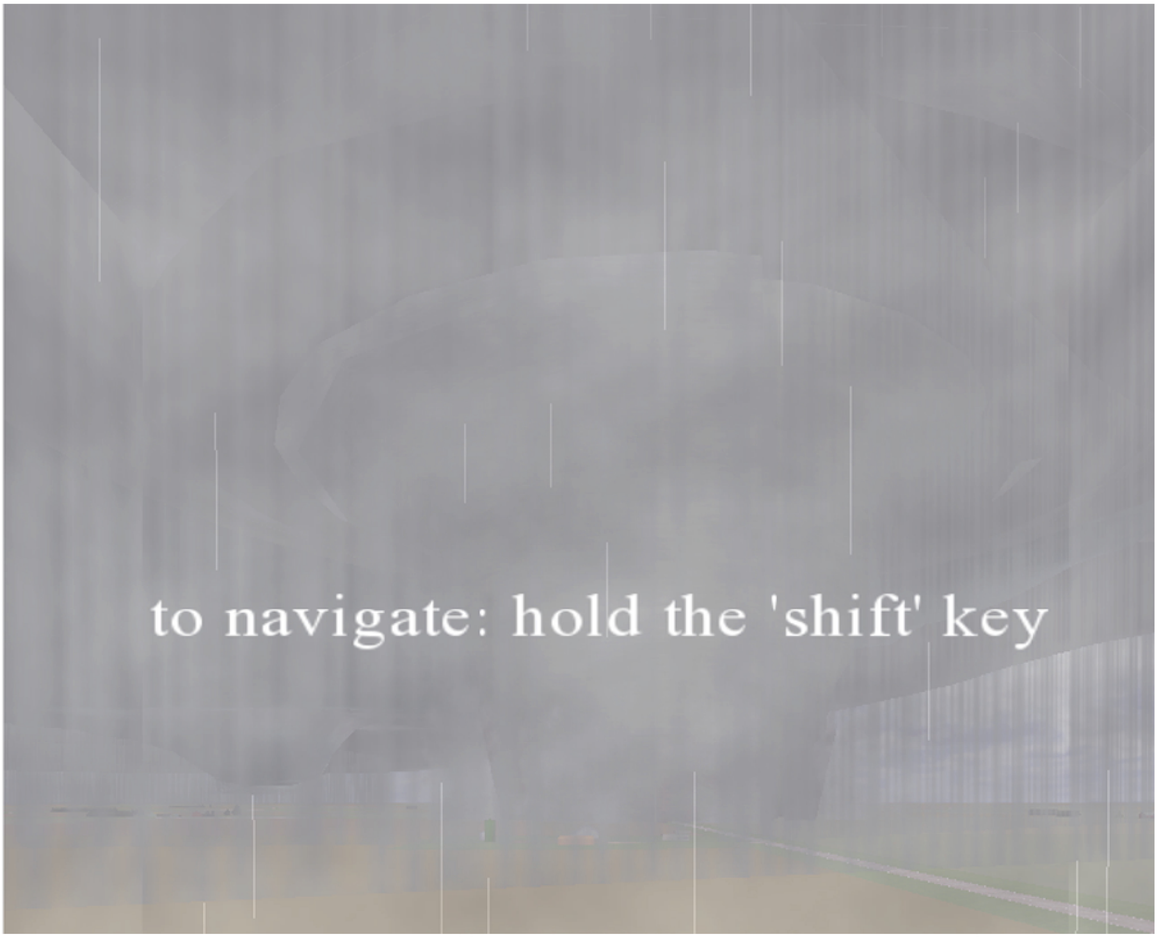

Figure 9: View of the tornado, highlighting the poor visibility, from within the heavy rain.

3.1.3 Navigation

The Virtual Storm can be experienced either as a desktop application or in an immersive virtual reality system. The visual representation and the behaviors of the Storm Visuals component are consistent between immersive and desktop use, even though the presentation of this information is tailored to the different display systems. Navigation techniques depend heavily on the interaction methodology unique to the two display systems, and, thus, differ significantly.

3.1.3.1 Desktop

When the Storm Visuals component is used on a desktop platform the user is presented with a view of the world through a window, as seen in the left side of Figure 2 on page 12. This view can be thought of as a virtual periscope: at any one instance the users' field of view is limited to what is in front of them. However, they are able to experience the full 360 degrees field of view by rotating their view, just as rotating a periscope makes a full horizon visible. Furthermore, users can also rotate their view vertically so it is possible to gaze in all directions.

Mouse input is used to manipulate the view. Moving the mouse away from the user causes the view to rotate up, while moving the mouse toward the user causes the view to rotate down. Moving the mouse left causes the view to rotate to the left, and similarly, moving the mouse to the right causes the view to rotate to the right. This viewing technique and the means to interact with it are similar to the standard keyboard and mouse navigation technique used for first person shooter (FPS) video games. The primary distinction is that an FPS game relys on two-handed navigation. The view is manipulated exactly as it is in the Virtual Storm. The second hand on the arrow keys is used to control motion within an FPS game and the mouse buttons are used for primary and secondary triggers. Of course, the Virtual Storm has no need for trigger function, so it was possible to make a single-handed navigation technique by placing the motion controls on the mouse.

On the desktop the Virtual Storm's navigation technique is based on heading and speed. The heading is always determined by the view: the user moves either towards or away from what he or she is looking at. The speed is changed via the mouse buttons. The left button causes acceleration in the forward direction, the right button causes acceleration in the backward direction, and the middle button causes the user to instantaneously come to rest. When neither mouse button is pressed there is no change of speed and the user travels at a constant rate. A summary of the mouse input to the Storm Visuals is presented in Figure 10.

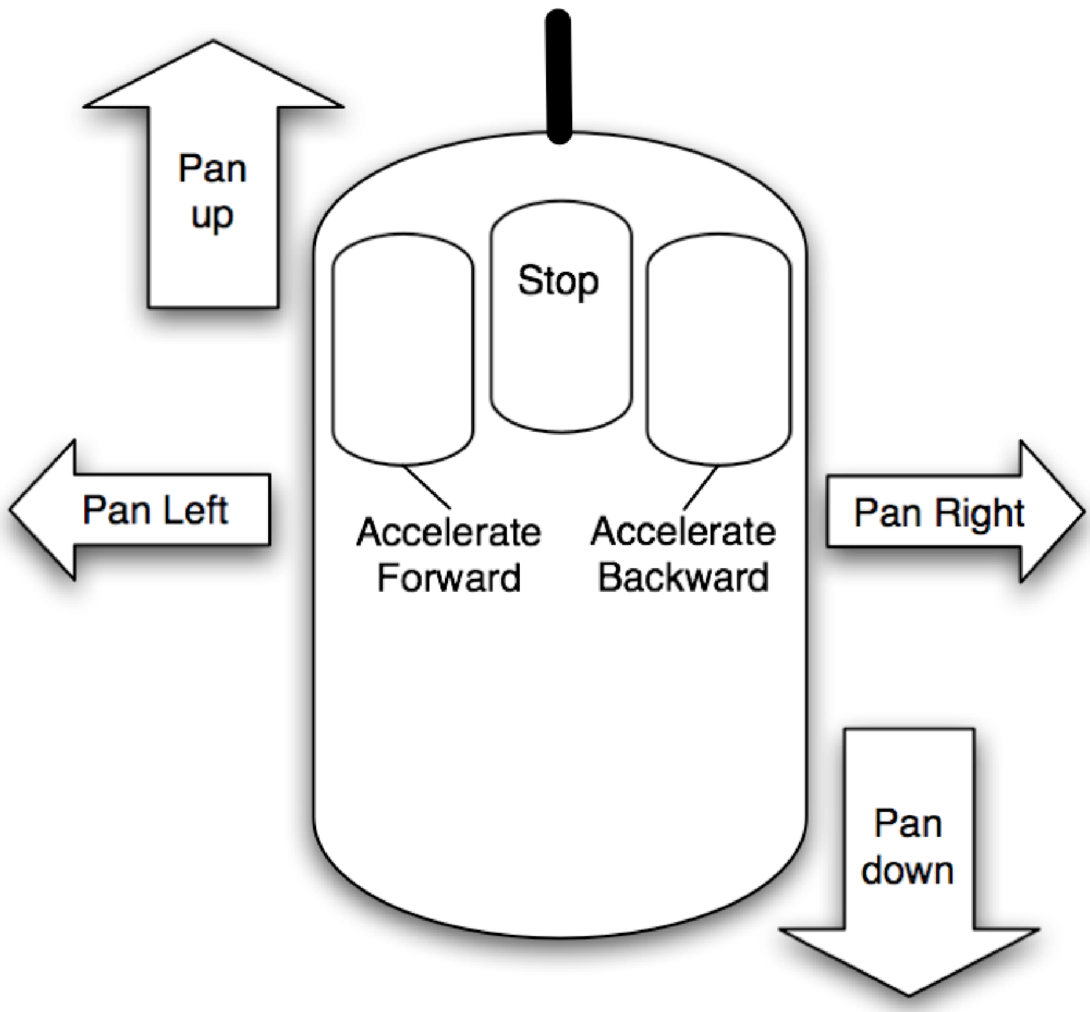

Figure 10: Mapping from mouse movement to control of the Storm Visuals.

Perhaps the best way to explain the Virtual Storm's navigation technique is through an example, illustrated in Figure 11. Let us assume that Alice has just started the Virtual Storm application and is standing still facing north. She moves the mouse to the right, which causes the view to rotate toward the east (Figure 11-A). When she is facing due east she stops moving the mouse. She now clicks and holds the left mouse button and begins to move toward east, the direction she is facing (Figure 11-B). Alice releases the mouse button after about ten seconds, which causes her to stop accelerating and she continues to travel toward the east at a constant speed (Figure 11-C). She determines that she is traveling too fast and holds down the right mouse button (Figure 11-D). This causes her to accelerate in the backward (westerly) direction, thus slowing her down. She holds the button for five seconds (half the time she held the left button) and her speed is now half of what it was. Alice soon moves the mouse to the right and her view begins to rotate towards the south (Figure 11-E). When facing due south, she stops moving the mouse and is now moving south at the same speed she had been moving east moments before (Figure 11-F). Alice passes an interesting feature in the virtual world and decides to return to it. She holds the right mouse button down and again beings to accelerate in the backward direction, which is now northward (Figure 11-G). Alice's speed slows until she is no longer moving. She continues to hold the right mouse button and begins to move backwards toward the north. After passing the point of interest she presses the middle mouse button and is immediately brought to stop (Figure 11-H). Alice then moves the mouse left and right to get a better view of the point of interest and surroundings.

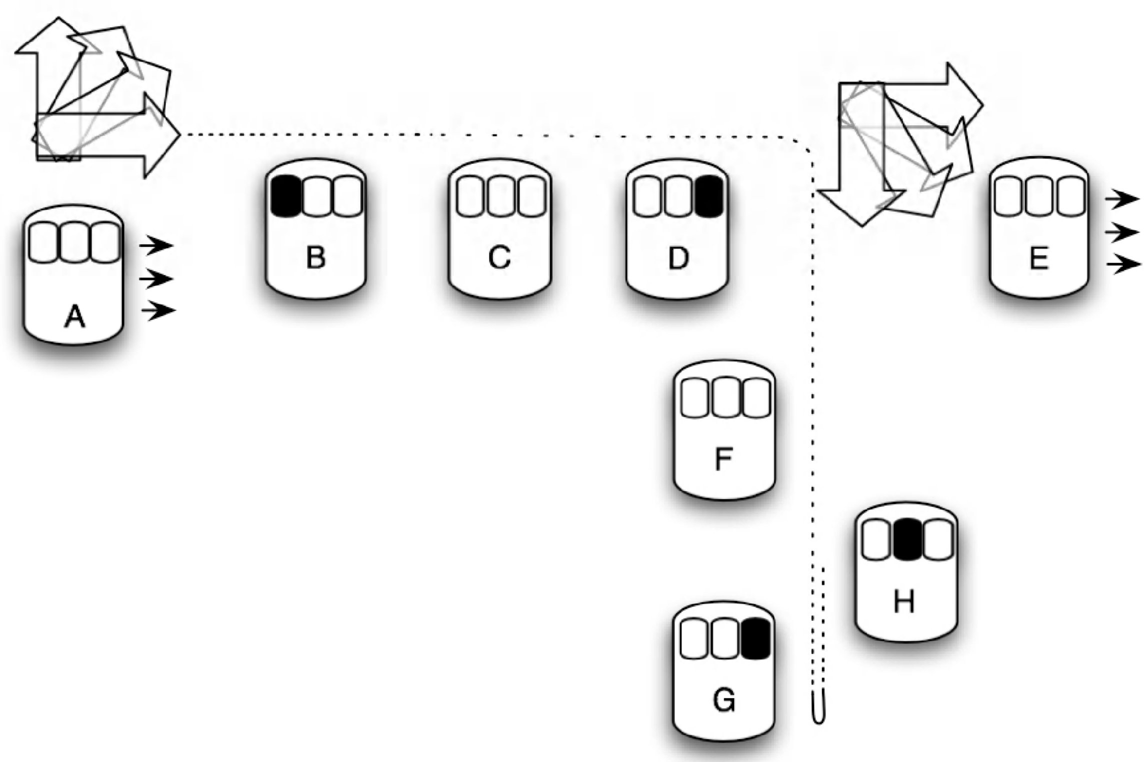

Figure 11 An example of navigation within the Virtual Storm.

The above example presents a simplified two-dimensional navigation case. In reality the navigation is not limited to two dimensions. If a user is moving and looks toward the sky, he or she will leave the ground and fly in that direction. If the user looks downward, he or she will move in that direction. The only constraint placed on the navigation is that it is not possible to burrow underground. The application places a boundary on the ground plane that users may not travel through.

3.1.3.2 Immersive Systems

By displaying the Virtual Storm in an immersive virtual environment the user can view and interact with the application in a much more natural way. The view is presented in one to one scale where objects and features in the virtual world are correctly sized with regards to the user. If the Virtual Storm is used in a fully immersive system, such as Iowa State's C6 or a Head Mounted Display (HMD), changing view is completely natural. The directions are absolute, just as in the real world. If a user is facing north and she wants to look to the west, she rotates her head to the left; or if she want to look up, she tilts her head back. A fully immersive system will faithfully reproduce the effects of such movement and provide the correct view into the virtual world.

When displayed in an immersive system, navigation within the Virtual Storm uses a common interaction technique know as point-to-fly [14]. A user holds a directional pointing device known as a wand. Three buttons on the device are used the same way the mouse buttons are used with the desktop Virtual Storm: specifically, to accelerate forward, to accelerate backwards, and to stop. The direction of travel is no longer determined by where the user is looking, but rather by where the user is pointing the wand. Just as with the desktop, motion is possible in all three dimensions and again only bound by the ground plane. By separating the navigation direction from the gaze direction, it is possible to be moving in one direction and looking in another. This is analogous to looking out the side window of a bus as it travels down the road. The point-to-fly technique has been shown to be a good interaction metaphor for exploratory virtual worlds [14].

3.2 Data Gathering

The Data Gathering component of the Virtual Storm provides functionality to support three different interaction scenarios. First, the tool aids in the exploration of the virtual world by presenting the user with metrological data to supplement the visual data provided in the Storm Visuals component. Secondly, this same data is also used in building a history of the information to better users' understanding of the storm as a whole. Finally, the component provides a convenient way to navigate large distances. These interaction scenarios are accessed through a two dimensional GUI that relies on standard GUI widgets. Unlike the Storm Visual component, the Data Gathering component is identical between immersive and desktop application, differing only in the hardware it is presented on. On the desktop, the Data Gathering component resides within its own window adjacent to the Storm Visual component (see Figure 2 on page 13). In an immersive environment, the Data Gathering component is presented on a tablet PC that users carry with them into the system, as seen in both Figure 1on page 12 and in.

Figure 12: View of the Data Gathering component on a tablet computer for use in immersive environments.

3.2.1 Exploration

As discussed earlier in this chapter, the Storm Visuals component allows users to explore a virtual storm. The extent of that exploration is limited to the audio and visual representation of the storm. The Data Gathering component supplements this exploration with meteorological information. In the real world, this data cannot be gathered by merely observing the storm; it would require some sort of instrumentation or equipment to capture. The data gathering component should be thought of as this piece of equipment.

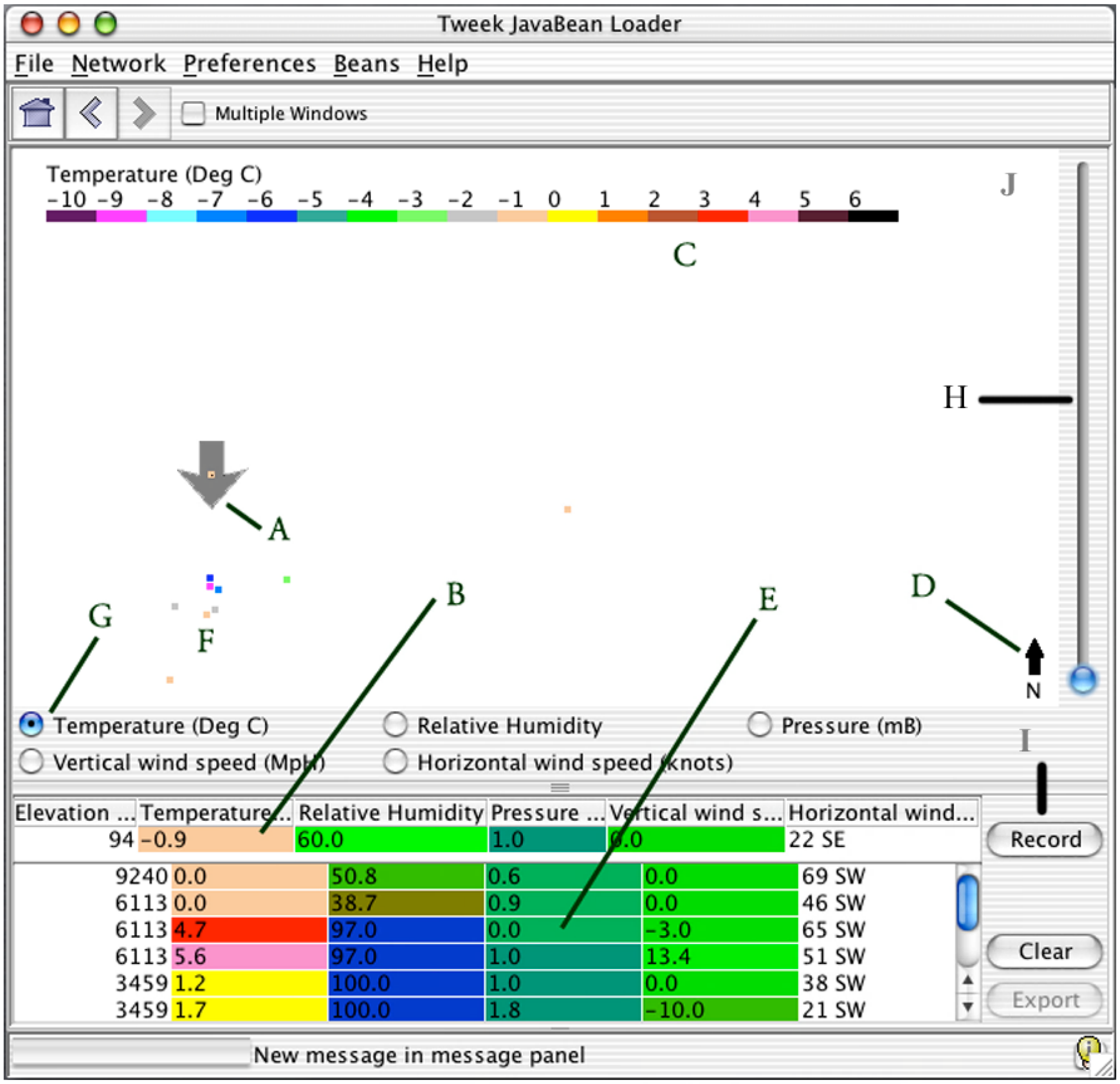

Figure 13: Data Gathering GUI (A) 'You are here' locator with color coded data. (B) Display of meteorological information for current location. (C) Key for data displayed on the chart. (D) The northwards Cardinal point. (E) A tabular history of points the user has recorded. (F) A visual history of points the user has recorded. (G) Selection of the active chart. (H) Slider used to change elevation. (I) Button used to record a point of interest. (J) The data chart.

Exploration revolves around the link between the Storm Visuals and Data Gathering components. This link shares the user's position and orientation information. To continue the metaphor of a piece of equipment, it is as if the user is carrying a handheld instrument that can probe for meteorological information. The probing occurs at the user's current location in the storm. This information is presented to the user is two distinct ways. The first is a graphical representation of the data. This is presented to the user in the form of a chart (Figure 13-J). The chart represents a horizontal slice of the exportable world. The left side of the chart represents the west side of the world, the right side the east, the bottom side the south, and the top side the north. A slider (Figure 13-H) on the far right hand side of the interface represents the elevation of this slice. The arrow (Figure 13-A) represents the user's current location and orientation in the storm. If the user is to the west of the storm looking south, the arrow will be to the left side of the chart pointing down. The center of the arrow conveys graphic meteorological information. The information matches the chart's key (Figure 13-C). The user is able to select between five chart types representing different information (Figure 13-G). Specifically, the different charts available are temperature, pressure, relative humidity, vertical wind speed, and horizontal wind speed. The graphic representation on all charts, except the horizontal wind speed, is color-coded. The horizontal wind speed is presented as a vector, as seen in Figure 14. Only one chart can be displayed at a time. A table is provided to allow users to simultaneously view all the data for a particular location. This table (Figure 13-B) concurrently presents both the numerical value and associated color-coding for all five types of meteorological data. Users can use this simultaneous representation of the data to determine correlation between different data types.

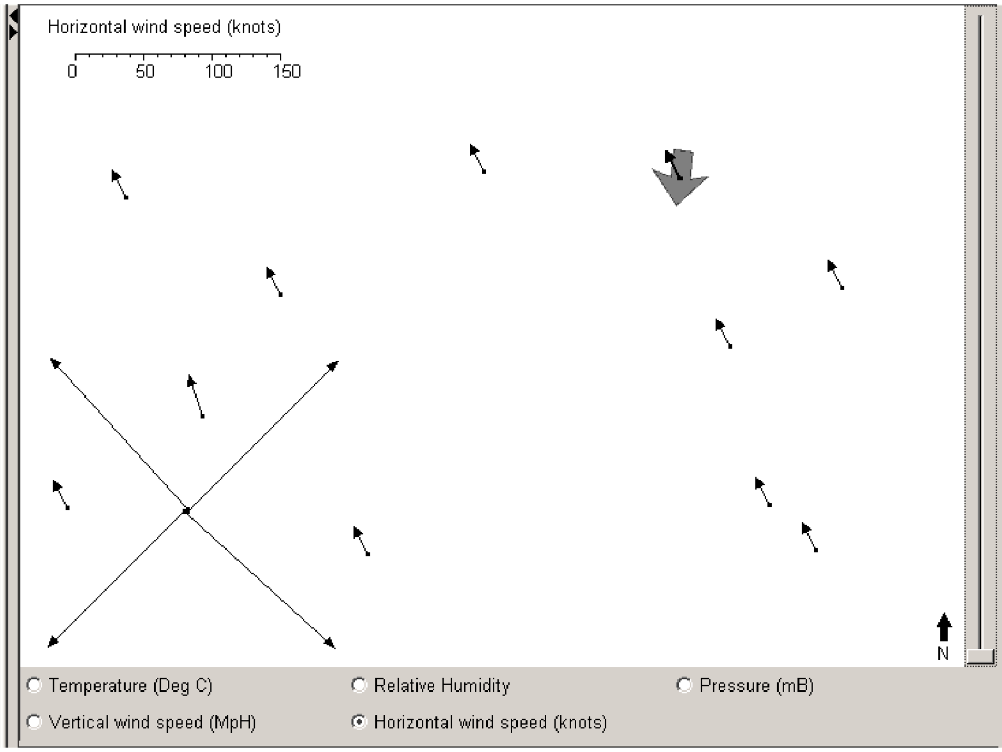

Figure 14: Data Component showing the horizontal wind speed chart. Vectors represent the wind speed. The long vectors in the lower left are data points recorded within the tornado.

3.2.2 Recording

The Data Gathering component also allows for the recording of data throughout the Virtual Storm. This can be thought of as placing remote sensors in the world that continuously feed back information regarding the position in which they were left. A sensor is placed in the world by pressing the record button (Figure 13-I). This sensor is positioned at the user's current location. The sensor returns data in the same format as described in the exploration section. Specifically, a graphic representation of the sensor data is placed on the chart (Figure 13-F) and a tabular representation is provided below (Figure 13-E). A row is added to the recorded value table for each sensor placed in the environment. These table entries also serve as spatial bookmarks in the Virtual Storm. If a user selects a table row with the cursor he or she will automatically be transported back to that location in the virtual storm. Both the graphics in the Storm Visuals component and the "you are here" arrow in the Data Gathering component's chart will be updated. Users are encouraged to leave large numbers of sensors. As they cover the virtual storm area with sensors they begin to gather a complete understanding of the storm.

3.2.3 Navigation

The final function of the Data Gathering component is to provide a convenient means to navigate large distances within the storm. This navigation supplements the point-to-fly and desktop navigation techniques described earlier in this chapter. The navigation technique revolves around the chart view presented in the Data Gathering component (Figure 13-J). As previously mentioned, the chart is a top-down view of the storm. This chart is an active GUI component. The user may click anywhere on the chart to be instantaneously transported to that location in the virtual storm. For example, if the user is in the south-west corner of the storm (bottom left of the chart) and clicks on the top-right corner of the chart, the user will now be in the north-east corner of the storm. This position is updated both on the chart an in the Storm Visuals component. Furthermore, it is also possible for the user to travel at a high rate of speed rather than being instantaneously transported. Clicking on the directional arrow and dragging it around the chart accomplishes this. As the user drags the arrow, the view in the Storm Visuals component will update in real-time. When the mouse button is released the user will stay positioned at the point dragged to.

Chapter 4 Virtual Storm: Implementation Details

The previous chapter discussed the high level functionality provided by the Virtual Storm. Some of this functionality is quite common, and its application and implementation are known in the field of human computer interaction. However, some particular features of the virtual storm deserve further note. This chapter parallels the previous one in organization. The implementation details of the Storm Visuals component are discussed first, and then the Data Gathering component is covered. This chapter details the techniques required to achieve the desired level of realism, the rationale behind the desktop interaction methodology, and the selection and implementation of the data-gathering component.

4.1 Storm Visuals Component

The Storm Visuals component of the virtual storm was designed to be cross-platform and portable. The application leverages a number of open source libraries, so that more effort could be spent concentrating on the peculiarities of the Virtual Storm rather than solving problems with known solutions. The Virtual Storm relies on VR Juggler [1] to provide abstraction over input device, display technology, and interaction methodology. The graphics in the virtual storm are rendered and manipulated with the Open Scene Graph [4], which provides a high level graphics API. The reliance on cross platform tools allows the Virtual Storm to be used on numerous platforms without requiring any change in the source code. In fact, the Virtual Storm has been used on Irix, Linux, Solaris, Windows, and Mac OS X. A binary release of the Virtual Storm is available to the general public for Windows and Linux [21].

By some measures the Storm Visuals component of the virtual storm is very similar to other exploratory virtual reality applications. However, the area where the tool differs the most is in the realism provided by both the graphics and behaviors of the storm system, and the emphasis placed on usability for desktop VR applications.

4.1.1 Realism

As discussed in the previous chapter, the Virtual Storm provides a photo realistic representation of a tornadic thunderstorm. This representation models the mature, almost steady state, stage of the storm. The characteristics and behaviors of the storm are based on Wakimoto, et al's, findings in [22]. The graphics are inspired by photographs and video footage of actual tornados captured by storm chasers. An artist created these graphics in Multigen Creator, a premium real-time modeling package. The artist worked in conjunction with meteorologists and education experts to make sure that his rendering of the storm was scientifically correct and that it conveyed the correct information to the users.

One important lesson that the educators wanted the users of the Virtual Storm to learn was that it is possible for a person to be near the tornado, yet not realize that he or she is in danger. This is because visibility is very poor within the rain and hail regions. Therefore, the visibility in the Virtual Storm should also reflect this reduced visibility. A common way to reduce visibility in computer graphics is through the use of OpenGL fog. However, because of the way VRJuggler handles views on multiple screens, the use of OpenGL fog is not possible. Instead, the notion of a fog-box was created. The fog-box is a cube that is attached to the user's location. An outside view of this is presented in Figure 15. The cube is textured with a fog like image (created using Adobe Photoshop's cloud filter). The cube is placed in the scene graph so that it is drawn on top of all other objects and blends with the rest of the scene. From the point of view of the user, the visibly in the world is reduced. The state of the fog-box, whether it is visible or not, and how transparent it is can be controlled programmatically. This allows for an arbitrary degree of visibility to be set and provides the means to convey the danger associated with reduced visibility in a storm

A similar concept of localizing the graphics around the user was utilized for the rain and hail. Just as if a watering can is poured over the user's head a localized particle system is attached to the user. This particle system emits a particle at a random rate at a random position on a circle 20 feet above the user's position. The rate of release is fast enough for the user's field of view to be filled with rain. Yet, as seen from the outside view presented in Figure 15, only a small cylinder needs to be rendered to achieve this effect. This provides a realistic sense of rain without the complexities of having regions filled with animated rain. The hail behaves much in the same way except additional intelligence was added so that it bounces when it hits the ground and then melts. This localized generation of graphics allows the storm to provide very realistic visuals but still render in real-time on modest computing hardware.

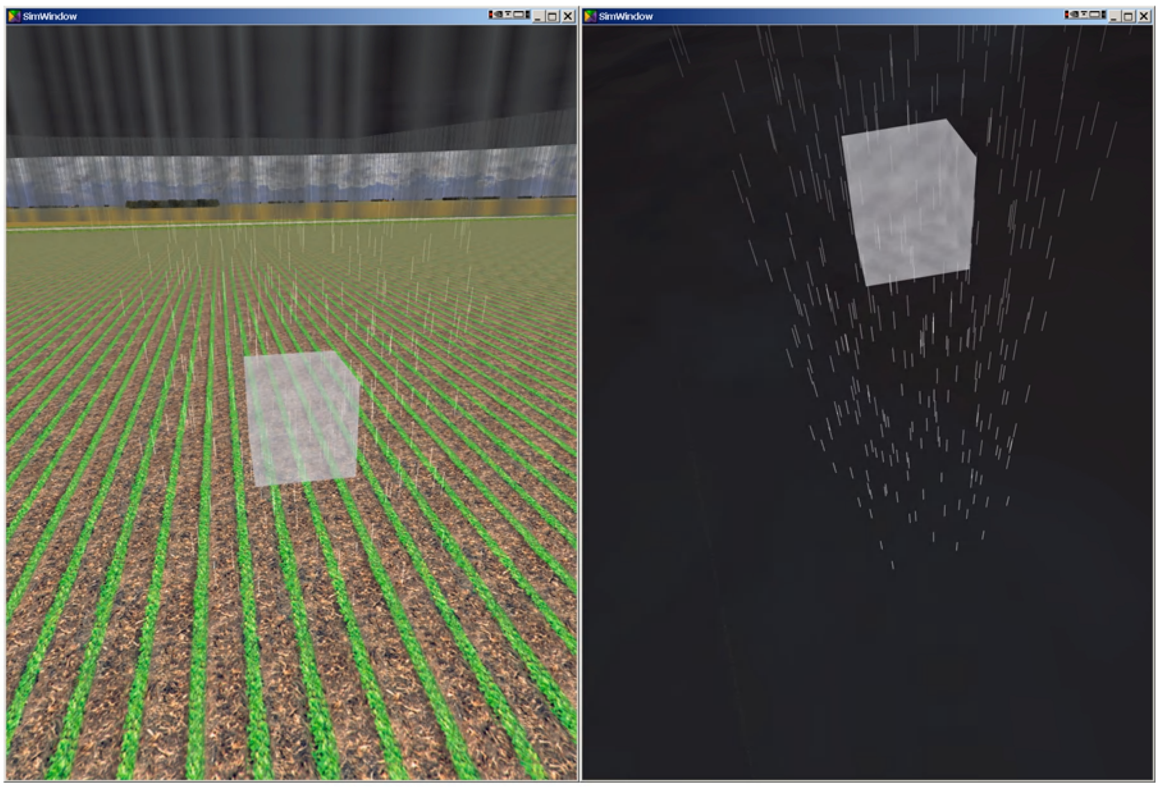

Figure 15 Two views of the cylinder of rain and the fog box

As described in the previous chapter, the audio sound effects were important to the user's experience in the Virtual Storm. There was a desire to provide as realistic a sound behavior as possible. Since it was unlikely that a spatial sound system would be available on the desktop systems some alternate means of providing spatial audio queues was necessary. Therefore, a method was implemented that revolved around volume adjustment. Sounds for the tornado, the rain, and the hail were placed in the Virtual Storm. All three sounds were played on a continuous loop, but their volume levels muted. When the user entered the region of rain the rain sound was un-muted. The volume was increased as the user ventured into heavier rain. The same was done for the hail. The sound for the tornado was attenuated as the inverse square of the user's distance to the funnel (the same function a point source of sound dissipates at). As the user approaches the funnel, the sound levels increases. The maximum level is obtained whilst inside the funnel. The regions of sound are shown in Figure 8 on page 21.

The techniques described in this section all require that the application determine if the user is within some region. The simplest means of determining if a point is within a region is to use a bounding object. A bounding object, however, introduces false positives where locations that are not in the region behave as if they are. A number of fast algorithms exist that assume convex regions; but as seen in Figure 8 the regions of rain in the Virtual Storm are concave. Instead, the crossing number[19], or Jordan curve[18], method was implemented. This method allows for convex polygons to define the region and can still be computed relatively efficiently. The algorithm is designed to solve a two dimensional point inside a polygon problem. Even though the regions in the Virtual Storm are three dimensional in nature, the 2D solution was not a limitation, since the region can be thought of as a linear extrusion of a 2D polygon. Once the algorithm determines if a point is within the 2D region, then a simple comparison based on elevation is used to determine if the point is within the volume extruded from that region.

4.1.2 Desktop VR

Much work was put toward making the Virtual Storm usable as a desktop application. The vast majority of users' experience with the Virtual Storm is on the desktop so it was important it be as user friendly and intuitive as possible. All VRJuggler applications designed for immersive environments can be used as desktop applications through the use of the simulator. The VRJuggler simulator reproduces hardware used for interaction in immersive systems that is not typically found on the desktop, such as head trackers and wands. The simulator was designed for testing immersive applications and not for extended use. Interaction with the simulator is known to be troublesome[9]. The limitations of the simulator meant that it could not be used for the Virtual Storm; therefore, a specific desktop

VR configuration and interaction technique for VRJuggler was created, based on keyboard and mouse controls.

One of the main differences between a desktop system and an immersive VR system is that the desktop system does not have positional tracking hardware. In an immersive environment, the tracking system is used to both calculate the user's view, and function as an input device in combination with the wand. However, knowing the exact head location is less important with a desktop system, since a user will typically be seated in a stationery position. Therefore, it is possible to approximate the position of the head and its relation to the display surface.

The functionality of the keyboard and mouse interaction was presented in the pervious chapter. In order to implement this technique, the yaw and pitch, as well as the position of the user, are maintained by the navigation system. The system calculates the user's next position based on the speed the user is traveling and the direction the user is looking. A vector is created based on this information, with orientation set by look-at direction and magnitude set by speed. This vector is then added to the current position and results in the new position. The yaw and pitch are manipulated based on user mouse interaction. The rotation and translation information is used to transform the view into the scene. The implementation was designed so that it would be scene graph independent. In fact, it has been used with the Open Scene Graph, OpenGL Performer, and pure OpenGL.

The usability results of such a system have been promising, based on user feedback. This form of Desktop VR navigation is not restricted to use with the Virtual Storm. It is applicable to any application, and can provide a better means of navigating a VRJuggler application on the desktop than the VRJuggler simulator can.

4.2 Data Gathering Component

Early versions of the Virtual Storm did not include the Data Gathering component. They were comprised solely of the Storm Visuals component. User tests with this graphics-only version of the virtual storm indicated that additional meteorological data would be useful in understanding the thunderstorm. The data deemed necessary was temperature, pressure, relative humidity, vertical wind speed, and horizontal wind speed. Devising a means to present this information to the user posed interesting challenges, and drove an innovative approach to solve them. The data gathering component was also used to improve on the navigation through the virtual world.

4.2.1 Presentation of the Meteorological Information

The first challenge was to determine the best way to present the meteorological data to the user. A proven means to present abstract information in virtual reality applications is data overlay. This is the method of choice for computational fluid dynamics visualization [23][24]. For example, the airflow inside a furnace can be shown[13]. The physical walls of the furnace, as well as a color-coded representation of the airflow, are shown at the same time so a user can understand what physical characteristics are influencing the abstract data. Data overlay takes advantage of VR's ability to show abstract quantities visually.

The initial inclination was to use data overlay to place the meteorological information inside the Storm Visuals. However, some of the Virtual Storm's characteristics do not align with data overlay's strengths. One such example is the sheer size of the virtual world. For pedagogic reasons, it is important to understand the storm system as a whole. Thus, it is desirable to see the data for the whole storm at one time. The only means to do this with data overlay is to also see the whole storm. This is, indeed, possible by flying above the storm and looking down. However, the user is now removed from the system, so it is difficult to understand how a particular location in the storm exists in context with the storm as a whole. Furthermore, data overlay does not lend itself for use in the Virtual Storm because of visual obstruction. Unlike the furnace example, in which all the abstract data is being displayed in the void of the furnace, in the Virtual Storm the meteorological data needs to be displayed everywhere in the world. So the geometry for the data and the geometry representing the physical world would collide. For example, one would not be able to see the data inside a cloud because the cloud itself would occlude it.

Once the predominant way (data overlay) for displaying abstract data in virtual worlds was excluded alternatives were sought. The choice that emerged as a front runner was displaying the meteorological data on a two dimensional chart. Charts have the advantage of being a common way to convey information both in meteorological textbooks and in the field. Through their use in the Virtual Storm, trained meteorologists can leverage this known format, and meteorologists in training can gain familiarity with charts similar to what they will find once they are in the field. Using maps and chart or worlds in miniature (their three-dimensional counterparts) in conjunction with virtual worlds is not entirely new in Virtual Reality[10][7]. However, this approach is typically used for navigational purposes and not for the presentation of abstract information.

4.2.2 Presenting 2D Data in a 3D Environment

The selection of a two dimensional chart for the presentation of meteorological data presented a technical challenge in itself: what is the best way to display two-dimensional information in an immersive virtual environment? There are three primary ways to do so. The three correspond to what can be thought of as the three spaces associated with a virtual display system: the virtual space, the display space, and the physical space.

The first option is to place the chart inside the virtual world or space. A higher dimensional system can always display a lower dimensional component. In this case, the chart would behave like any other geometric object in the scene. To increase manipulability, the 2D plane should be attached to a three dimensional frame. Interaction with the chart would occur via the virtual environments interface, most likely a wand. The user could manipulate the chart like any other object in the scene, or the developer could add specialized functionality for the chart. The benefit to this methodology is that it is easy to implement and is consistent for the users, since all information is coming from the virtual space.

Imbedding the 2D object in the 3D scene does pose a few problems, however. A major concern is limited resolution. This is an inherent problem in most current projection-based immersive environments. Quite simply, a projector with a limited resolution is being displayed on a large surface. For example, Iowa State's original C6[20] has projectors that use a resolution of 1024 pixels by 1024 pixels. This image is projected on to a 10' by 10' screen. This gives a pixel density of 8.5 dots per inch (dpi). That is an order of magnitude less than a desktop monitor's pixel density, which typically falls in the 72 to 96 dpi range. If detailed information is displayed on a screen with limited pixel density, information will be lost. Interacting with the embedded data can also be problematic. This is mostly due to the phenomenon of jitter, where instability in the tracking system causes both the view and the wand to not stay still. This impedes the use of the wand to point at objects for selection purposes. In this instance this problem is slightly reduced by the fact that the chart will typically be close to the user, so the error is not as severe as it would be if the user were interacting with a distant object. However, this closeness to the user exacerbates another limitation of projection-based virtual environments: specifically, that the perspective is being drawn correctly only for the single head tracked user's view. For distant objects, a few feet of separation between the tracked user and an observer will not be significant; however, for near objects the observer's view will start to become skewed. A final issue is the focal accommodation vs. convergence problem suffered in projection-based VR systems, where the stereo-graphics cause a user's eyes to converge at different distances, yet the eyes are always focused on the screen. There was concern that interacting with an embedded 2D element could cause eye fatigue over extensive use.

A second option is to place the GUI in the display space. The display space is perhaps the hardest to conceptualize. When projecting stereo-graphics, individual images for the left and right eye are generated from the three dimensional scene and displayed on a screen. It is also possible to display non-stereo information on the screen at the same time. This approach is often used to display text, and is sometimes referred to as a heads-up display (HUD), since it behaves similarly to how a HUD behaves in the real world by always being on top of the view. This solution eliminates two of the issues associated with embedding the 2D element in the 3D scene. Specifically, all users will see a non-distorted view of the 2D element; and there is no concern with focal accommodation vs. convergence, since the GUI is actually located on the focal plane (the screen). But the problems of limited resolution and tracker jitter still remain. Furthermore, this solution presents additional challenges. Most notably, the 2D element placed in the display space will conflict with objects in the virtual space. A user will be looking at the storm in the distance, glance down to the horizon, and see the chart rather than the farm he expected to see. More problematic is the case where the user is observing a close object. For example, if a user is standing in the middle of the C6, she is five feet from any wall. The 2D element is displayed on the wall and will appear to be five feet away. However, if the user is observing an object that is only two feet away, the 2D element will obstruct her view even though it is further away. This conflicts with how we know the world to behave and will shatter the user's willing suspense of disbelief.

The final way to display the 2D object is to place it in the physical space. Conceptually, this is equivalent to users taking a paper map of the virtual world into the immersive environment with them. To have a dynamic 2D object, a second display, such as a tablet computer, can be carried by the user. None of the issues associated with the other two methods manifest themselves when placing the 2D element in the physical space. Tablet computers typically have higher pixel densities than desktop monitors and a tracker is not used for interaction. Furthermore, the display will be equally legible for all users, and if desired, each user can have a dedicated display. An additional benefit is that standard interaction techniques can be used with the tablet computer. This is especially important when presenting users with familiar GUI elements, as they will already know how to interact with them.

The separate display option does have issues of its own. It is not possible to use such a device with a head-mounted display, since the user sees only the virtual world. There can also be a polarization problem when used with projection-based systems. Most tablet or palm top computers use LCD screens that inherently polarize light. If the user's polarized glasses (either passive or shutter glasses) line up with the display's polarization, the screen becomes difficult to read. The application also must be more complex, since it now must handle communication between the two display devices. Finally, the size and weight of the device may make it awkward to use. This becomes even more problematic when coupled with standard immersive interactive devices, such as the wand.

4.2.3 Selecting a Technique

As the choice to present the metrological data as a chart had been made, the three possible ways of doing so were evaluated. The three primary considerations that went into selecting one of the display techniques were the need for a high-resolution display, the need to display text, and considerations for using the same technique with a desktop VR setting.

To allow students to understand the storm system as a whole there was a desire to display the meteorological data for the entire storm at one time. The storm covers an area of 120 by 80 miles, or 9,600 square miles. Assuming that a quarter of the immersive display's screen can be used to display the GUI, and that the chart consumes half of that, would yield a total of 1024 x 1024 / 4 / 2 = 131,072 pixels resulting in about 14 pixels per square mile. On the other hand, using a tablet computer would equal: 1024 x 768 / 2 = 393,216, or 41 pixels per square mile. Thus the tablet computer allows for three times more information to be concurrently displayed. The GUI also contains a fair amount of text, and, as described in the pervious section, the physical space technique also has advantages in displaying text.

The final and most compelling reason to select the tablet computer solution actually had less to do with the physical characteristics of the device and information to be displayed, and more to do with the implementation. As mentioned earlier, with the desire to reach the largest possible audience it was determined that the Virtual Storm should also work as a desktop application. It is advantageous to have the chart and associated GUI behave as any other interface on the desktop using standard GUI interaction techniques. Had the chart been embedded in the scene, this would not have been possible. Had the chart be placed in the display space this would have been possible, but would have required separate interaction techniques for immersive and desktop use. The interface that was designed for the separate display in the immersive system could easily be displayed on the desktop machine and behave identically.

By selecting the dedicated display in the physical space, it was possible to provide the highest resolution, accommodate the displaying of text, and use identical interfaces and interaction techniques on the desktop and immersive systems. These benefits more than over came the complications necessary to implement such a solution.

4.2.4 Generation of Data

Large amounts of data were necessary to provide information about the whole storm. Entering the data by hand would have been a very tedious task. Even if only one data point was used per square mile that would still result in 180 x 120 = 21,600 data points per vertical plain. Considering the six different types of data, temperature, pressure, relative humidity, and the three wind components, that results in 129,600 data points per horizontal plain. To add the third dimension, a number of such plains would have to be added. So, even with a very coarse data set, more than half a million data points would have to be entered. This enormous number of data points meant that manual entry of the data was not feasible.

To overcome this obstacle an image processing solution was devised. High-resolution images were created and the data encoded in the color information. To generate the images a meteorologist worked closely with a graphic artist. The data portrayed in the images was again patterned after Wakimoto, et al's, findings in [22], the same source for the visuals of the Virtual Storm. Images were created for different elevations; in total, 28 images were created, yielding over 20 million data points.

When used in the Virtual Storm, these images are loaded at runtime when the Data-Gathering component is launched. The color information is read out of the image file and stored as an indexed eight-bit value in a look up table. When the data is needed, either to be displayed on the chart (Figure 13-J) or in the table (Figure 13-B), a search is performed to find the data set with higher and lower elevation than the location of interest. The horizontal coordinates are then used to access the values for that position on the two planes stored in the lookup table. Finally, a linear interpolation is used to calculate the value for the position in three-dimensional space.

This approach allowed for a high number of data points to be used, and for a more efficient means of data entry. The approach also has the side effect of generating data charts that can be used independently from the application. A sample of these charts is shown in Figure 16.

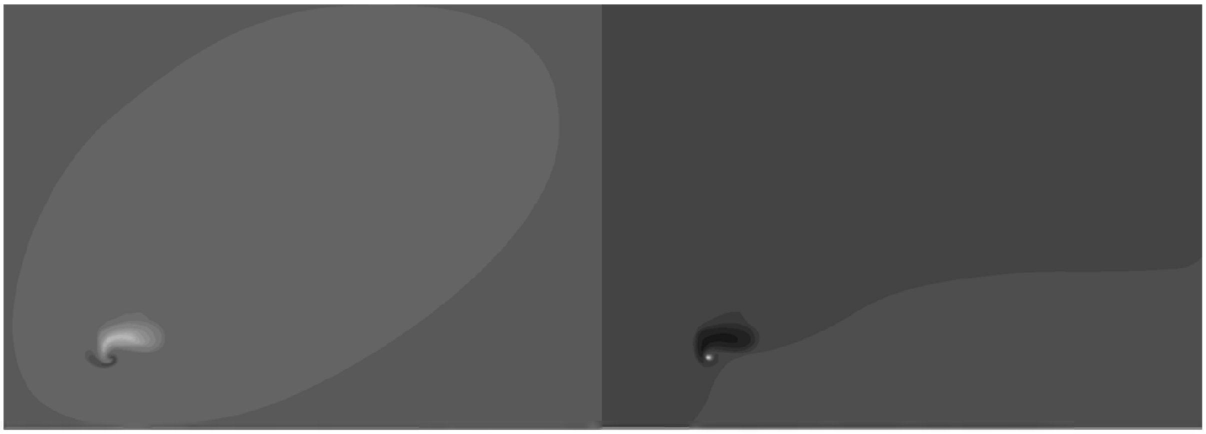

Figure 16 A sample of the charts used to store the metrological information in the Data Gathering component. The left chart is temperature and the right is pressure both at ground level.

4.2.5 Navigation and Orientation

Results from the first user test of the Virtual Storm indicated that users found it difficult to stay oriented and hard to navigate the world. The size of the Virtual Storm was the root cause for the navigation difficulties. The first issue encountered was that users were missing important features in the storm. This was due to the high rates of speed the users would travel at. The virtual world is 180 miles by 120 miles, so when users want to go from one part of the world to another they choose to travel very quickly so it does not take much time. Users travel so fast that important features may only be on the screen for a few seconds and it is easy to miss them. The second problem with navigation, also associated with speed, was a side effect of the control mechanism. The first version of the Virtual Storm used a terrain-following navigation mechanism. The user was attached to the ground and could drive about the virtual space. However, because of the high speed, ditches in the virtual world became lunching pads. If the user hit a ditch at high speed, the ditch behaved like a ramp, catapulting the user into the air. A few of the users discovered that it was even possible to land on the clouds. These large jumps confused the users and again made it possible to miss important features.

Orientation in the virtual world was also difficult. There was no visual indication on the orientation the user was heading. When the application started, the users were told they were facing north. The only way to stay oriented was to keep track of the changes in direction that had been made since the exercise started. As can be imagined, this is a difficult task, and indeed received poor feedback from the users.

The Data Gathering component addresses both the navigation and orientation issues. As described in Chapter 3, the chart in the Data Gathering component acts as a navigation device, allowing users to teletransport or to travel large distances in small amounts of time. These large-scale navigation techniques supplement the fly technique, and allow users to quickly jump to points of interest and then explore them more thoroughly. The "you are here" arrow can be thought of as a compass needle, which always gives the user's orientation information. After this chart was introduced, the users feedback on both navigation and orientation drastically improved.

Chapter 5 Evaluation of the Pedagogic Value of the Virtual Storm

To both quantify the effects of using the Virtual Storm on students' learning and to gather data to be used to improve the application, formal user studies were conducted over a five year period (2002-2006). Student volunteers were recruited from a large enrollment Introduction to Meteorology course at Iowa State University. For the first two years the data gathered was used to modify the Virtual Storm for the next version. During the latter three years the same version of the application was tested. The details regarding the user tests and the results of the evaluations are presented here.

5.1 Test Subjects

In order to find test subjects that represented the target audience of the Virtual Storm volunteers were solicited from an introductory meteorology course. Meteorology 206, Introduction to Meteorology, proved to be an ideal class for this purpose, offering both test subjects seeking degrees in meteorology and those simply interested in weather. The course is offered every spring semester at Iowa State University. The course covers such topics as atmospheric measurements, radiation, stability, precipitation, winds, fronts, forecasting, and severe weather. Meteorology 206 is required for students seeking a degree in Meteorology, but is also popular with others, since it fulfills a general science requirement. Because the Meteorology program is rather small, the vast majority of the students are not meteorology majors.

Each year all students in Meteorology 206 were given the opportunity to participate in the user study. In an effort to have as many volunteers as possible, the students participating in the study were given extra credit. A summary of the number of students in Meteorology 206 and those who volunteered is presented in Table 2.

Table 2 Students Who Took the Lecture Quiz and Those Who Volunteered by Year.

Year	Students in Met. 206 Lecture	Number of Volunteers (Took both quizzes)
2002	257	16(14)
2003	234	10(8)
2004	238	24
2005	176	23(20)
2006	115	29(17)

5.2 Equipment

For the first two years, a small computer laboratory owned by the meteorology department was used to test the Virtual Storm. A total of a dozen machines were used, all having different hardware configurations.

ISU's college of engineering provided the computing equipment for the remaining three years. A medium sized (roughly 30 machines) computer lab was used. The lab was closed to the public for the duration of the user study. The computers were Dell Dimensions powered by dual Intel xeon processors running at 2.66 GHz with two gigabytes of memory. Each computer had an ATI FireGL x1/128 graphics card using ATI's graphics drivers. They were connected to 19 inch LCD monitors. A Linux based operating system was installed on all the computers. The students were asked to bring headphones, so that the sounds in the application would not confuse other users performing the test. Even though each of the computers supported more than one set of headphones, most pairs of students chose to share a set.

5.3 Test Procedure

Each user study started with an orientation. This was mostly comprised of an instructor demonstrating the capabilities of the Virtual Storm application. A projector hooked up to a computer that was identical to the ones the students would be using was used for the demonstration. The orientation was given immediately before the students started the exercise, so they all received the same instruction. Careful consideration was used while conducting the orientation. It was important to demonstrate the capabilities of the Virtual Storm, but not to provide any education about tornadic thunderstorms. To do so, the capabilities were demonstrated at a position in the Virtual Storm world that was not affected by the storm itself. The southwest corner of the world was perfect for this since it was well outside of the storm area.

Students were given complete freedom to roam throughout the virtual world after the orientation. However, a worksheet was provided for them to work through (this worksheet can in found as Appendix A). The questions on the worksheet were such that in order to answer them, the students would have to experience aspects of the storm, that were deemed to be particularly important. The worksheet was also designed so that students would take their time and not rush through the exercise. The worksheet allowed each individual or pair to work at their own pace.

As each student or pair finished the worksheet they were given an 11-question multiple-choice quiz with questions about tornadic thunderstorms. This quiz can be found as Appendix B. The answers for some of the questions on the quiz were provided directly from the Virtual Storm application, while others required the students to process information provided in the application and information presented previously in the course. This same quiz was also given to the whole class (including the volunteers) immediately following a lecture on severe weather later in the semester. By comparing the scores on the two quizzes, the effect the Virtual Storm experience had on student learning could be quantified. For clarity when discussing the results, the quiz the volunteers took after the Virtual Storm exercise will be referred to as 'Virtual Storm Quiz', and the quiz after the lecture as 'Lecture Quiz'. Students taking the Lecture Quiz can be further partitioned into those who used the

Virtual Storm (termed 'Volunteer') and those who did not (termed 'Non-Volunteer'). The last part of the user study asked the volunteers to fill out a subjective questionnaire about their experiences using the Virtual Storm. These results highlighted aspects of the tool itself that the students liked or disliked.

5.4 Results and Discussion

The quiz results were analyzed in two ways. The volunteer's mean score on the Virtual Storm Quiz and the Lecture Quiz were compared. This analysis provides information about how the lecture supplements the Virtual Storm exercise. The second analysis performed was to compare the Volunteer's Lecture Quiz mean score with the Non-Volunteer's Lecture Quiz scores. This analysis provides insight into any effect the Virtual Storm exercise may have had on score results.

Table 3: Results of a Paired T-test comparing the Virtual Storm Quiz and the Lecture Quiz

Year	Mean Score		95% CI for mean difference	P-Value
	Virtual Storm	Lecture		
2002	4.28571	8.14286	(-5.47218, -2.24210)	0.000
2003	4.12500	7.62500	(-4.91313, -2.08687	0.001
2004	4.45833	7.37500	(-3.95037, -1.88296)	0.000
2005	4.05000	7.25000	(-4.14339, -2.25661)	0.000
2006*	7.41176	6.82353	(-0.357352, 1.533822)	0.206

The results comparing the Virtual Storm Quiz to the Volunteer Lecture Quiz are presented in Table 3. The mean scores were compared using a t-paired test. The null hypothesis was that there was no difference in scores between the user's two tests. As can be

* The quizzes were conducted in reverse order in 2006, with the lecture coming before the Virtual Storm Exercise.

seen in the table (p values approaching zero), that hypothesis is rejected in years 2002-2005. This indicates that attending the lecture has a statistically significant positive effect on quiz scores. This result was expected, as the lecture specifically addresses topics on the quiz and the intent of the virtual storm is to supplement the lecture. The quizzes in the year 2006 were conducted differently than those in pervious years. Specifically, the lecture on severe weather was given prior to the Virtual Storm exercise, thus allowing insight to be gained on how the Virtual Storm supplements the lecture, rather than vice versa. In this case, the mean scores were higher on the Virtual Storm Quiz; however, the relatively high p-score and the fact that zero falls into the confidence interval does not allow the null hypothesis to be rejected. This indicates that there may be no statistically significant difference in mean score between the quizzes.

Table 4 Results of a T-test Comparing Lecture Quiz between Volunteer and Non-Volunteer

Year	Mean Lecture Score		95% CI for difference	P-Value
	Volunteer	Non-Volunteer		
2002	8.14	7.77	(-0.545131, 1.299981)	0.397
2003	7.63	6.82	(-0.763375, 2.367357)	0.265
2004	7.38	7.68	(-1.174944, 0.560458)	0.473
2005	7.25	6.88	(-0.813431, 1.557021)	0.521
2006*	6.82	6.57	(-1.105616, 1.609818)	0.703

The results for the comparison between the Volunteer's Lecture Quiz mean score with the Non-Volunteer's Lecture Quiz scores is presented in Table 4. This comparison was conducted using a two-sample-T test. As can be seen from the table, the volunteers' mean score was higher in all years but 2003. However, the high p-scores indicate that there is no statistically significant difference between the Volunteer and Non-Volunteer scores. For the year 2006 the extremely high p-score was expected, since the volunteers had yet to use the

* The quizzes were conducted in reverse order in 2006, with the lecture coming before the Virtual Storm Exercise.

Virtual Storm. The results from 2002-2005 indicate that there is no statistically significant improvement in quiz score for those who used the Virtual Storm.

One might have expected the Virtual Storm to improve quiz scores. The reason that the user test shows no apparent benefit in using the Virtual Storm may have more to do with how the test itself was conducted, rather than the educational merits of the application. The Lecture Quiz was administered immediately after the lecture on severe weather, within the same class period. The proximity in time between when the information was presented and tested essentially equated to testing short-term recall. Hands-on experiences, such as the Virtual Storm have generally been shown to benefit long-term retention. [11] The effects of having just learned the material may have over-shadowed the benefits of having had a hands-on experience with the subject matter. Conducting a longitudinal study, in which users' retention is tested over a much longer period of time, may have been a more appropriate means to assess the educational merit of the Virtual Storm.

The students who volunteered indicated that they enjoyed using the virtual storm. On the subjective survey, when asked if they thought the application was realistic (on a scale of 1 to 5) they rated it 4/5. When asked if they liked the graphic display, they rated the application 4.2/5. Students also provided such comments as "Good simulation, just really hard questions," and "Very interesting to see the data from inside the tornado."

Finally, some comments need to be made about the fact that volunteers were used for the formal user study. The statistical analysis performed on the data requires a random sample. The reasons for this are obvious. For example, with the Virtual Storm extra credit was given to the participants, which opens up the possibility that only those students needing extra credit volunteered. Therefore, the sample may end up with no 'A' students volunteering and it would not necessarily represent the class. Unfortunately, there was no good way to get a random sample since the exercise had to be voluntary. To estimate the impact of the use of a non-random sample on results, the scores were adjusted based on final course grade, and the analysis performed again. The results were indistinguishable from the ones not taking grade into account, thus, indicating that the volunteer sample was a good representative sample of the class.

Chapter 6 Limitations and Future Work

Future work will continue, both on the Virtual Storm application itself and by using the Virtual Storm as a foundation for other educational applications.

The major limitation with the Virtual Storm is that it models only a single instant in time of a tornadic thunderstorm. If it was possible to incorporate changes over time, the capabilities of the Virtual Storm would be expanded so that it could be used to help students understand the creation, dissipation, and path of a storm. The most promising way to incorporate changes in time would be to generate the Virtual Storm visuals from a mathematical model or simulation of a storm. With a numerical model, time is a variable and the whole system would update to reflect a change in time. Early in the development of the Virtual Storm there was hope that a numerical model could be used. R. Wilhelmson at the National Center for Supercomputing Applications (NCSA) created a numerical model of a tornadic supercell storm in the 1990s [26]. Visualization techniques were used to provide a view into this model. Unfortunately, the results were not a visually realistic view of the storm because the simulation was too coarse. However, as computational power increases and the fidelity of the models is improved, there will come a time when their use for photo realistic visualization will be possible. In fact, at the recent 22nd Severe Local Storms Conference of the American Meteorological Society, extremely fine resolution simulations (50 m grid spacing) of a tornadic storm were shown by M. Xue. This high-resolution output suggests that reasonable photo realistic visualization of numerical models for supercell tornadic thunderstorms will likely be possible within just a few years. When this becomes a reality the Virtual Storm application should be updated to incorporate these simulations, and, thus, provide the capability of exploring the storm over time.

In the short term, binary distributions of the Virtual Storm can be created for a greater number of platforms. This should expand the dissemination of the software. The iterative design cycle used to develop the Virtual Storm should be continued. Feedback from more recent formal user studies and from the comments on the downloadable version should be used to improve the tool. Furthermore, the tool could be more tightly integrated into meteorology courses so that it becomes an integral part of the curriculum. The tools should also be useful to students with more meteorology experience. It would be interesting to discover how best to use the Virtual Storm in senior or graduate level courses. Students should be provided with access to the Virtual Storm in an immersive environment. A study could then be conducted to see what additional benefits using the application in such an environment would bring.

Another limitation in the Virtual Storm that may not have been completely addressed is that of orientation and navigation. A conscious choice was made not to illustrate storm features on the Data Gathering Component's chart. This decision was made so that users would have to explore the world to discover the storm's features. Only the data the student has recorded is present on the chart. This makes it more difficult for the users to use the chart as a navigation tool, since there is not an obvious link to a place on the chart and a place in the virtual world. By placing non-storm related landmarks in both the virtual world and on the chart, it should be possible to establish the relationship between the two and still encourage the users to explore. For example, if a water tower and grain silo were placed in the virtual world and on the chart, users could use them as reference points.

Chapter 7 Conclusions

The Virtual Storm application demonstrates that it is possible to create a photo realistic hands-on exercise to teach about severe weather using virtual reality. This research will hopefully pave the way for creating additional teaching tools for geosciences. The methods used in creating the Virtual Storm are applicable to a broad range of applications and are not restricted to uses only in education. Adopting these techniques and improving upon them could produce a new generation of highly effective and disseminated applications.

The driving motivation behind the Virtual Storm was to provide students with a hands-on means to learning about severe weather. In the past, providing students with a hands-on experience with tornadic thunderstorms was difficult due to the complexity of the systems, the lack of predictability, and the danger associated with the storms. However, hands-on experiences are considered an important teaching method. The Virtual Storm addresses the lack of hands-on experience through the use of computer graphics and virtual reality technology. The Virtual Storm functions both on high-end virtual reality systems for a greater level of immersion, and on desktop computers for accessibility and greater dissemination.

Formal user studies were used to determine the effectiveness of the Virtual Storm as a teaching tool. The user tests consisted of comparing the results from a quiz taken after using the virtual storm with the same quiz taken after a lecture on severe weather. There was no measurable benefit of using the Virtual Storm on the quiz results. However, the user tests may not have captured the true value of the Virtual Storm since they focused on short-term retention, and the strengths of hands-on experience are generally thought to improve long-term retention rather than short-term recall. Finally, the level of engagement demonstrated by the participants suggests that the tool is still a useful compliment to the lecture.

References

[1] Bierbaum, A, D., 2000: VR Juggler: a virtual platform for virtual reality application development. Master's Thesis, Iowa State University.

[2] Bowman, D., Gracey, M., and Lucas, J. Efficient, "Intuitive User Interfaces for Classroom-Based Immersive Virtual Environments". Poster abstract in Proceedings of IEEE Virtual Reality, 2004, pp. 219-220.

[3] Bowman, D., Setareh, M., Pinho, M., Ali, N., Kalita, A., Lee, Y., Lucas, J., Gracey, M., Kothapalli, M., Zhu, Q., Datey, A., and Tumati, P. "Virtual-SAP: An Immersive Tool for Visualizing the Response of Building Structures to Environmental Conditions." Proceedings of IEEE Virtual Reality, 2003, pp. 243-250.

[4] Burns, D and Osfield R, "Open Scene Graph - An Open Source Solution for Real Time Image Generation", Image 2003.

[5] Contero, M., Naya, F., Company, P., Saorin, J. L., and Conesa, J. 2005. "Improving Visualization Skills in Engineering Education." *IEEE Comput. Graph. Appl.* 25, 5 (Sep. 2005), 24-31

[6] Cruz-Neira, C., D. Sandin, and T. DeFanti, 1993: "Surround-screen Projection-based Virtual Reality: the Design and Implementation of the CAVE." SIGGRAPH 93 Conference Proceedings, 27, 135-142.

[7] D.A. Bowman, D.B. Johnson, and L.F. Hodges, "Test bed Evaluation of Virtual eEvironment Iteraction tTchniques", Presence: Teleoperators and Virtual Environments, 2001, vol. 10, pp. 75-95.

[8] Dede, C., Salzman, M. C., & Loftin, R. B. (1996). "The Development of a Virtual World for Learning Newtonian mechanics." In P. Brusilovsky, P. Kommers, & N. Streitz, (Eds.). Multimedia, Hypermedia, and Virtual Reality, (pp. 87-106). Berlin: Springer/Verlag.

[9] Hartling P., Scott B., Brown J., Bierbaum A., Cruz-Neira C., "Avatar Manipulation as a Metaphor for Virtual Reality System Simulator Interaction", IPT 2004. May 2004, Ames, Iowa, USA.

[10] J. S. Pierce and R. Pausch. "Navigation with place representations and visible landmarks". In Proc. IEEE VR, 2004.

[11] Lehrer, R., 1993: "Computers as Cognitive Tools." Authors of Knowledge: Patterns of Hypermedia design. S. P. Lajoe and S. J. Derry, Eds., Lawrence Erlbaum Press, 197-227.

[12] Mackinaly, J. D., Card, S. K., and Robertson, G. C., 1990, "Rapid Controlled Movement Through a Virtual 3D Workspace," SIGGRAPH Computer Graphics, Vol 24, # 4, pp 171-176, Dallas, Texas.

[13] McCorkle, D.S., Bryden, K.M., and Kirstukas, S.J., (2003), "Building a Foundation for Power Plant Virtual Engineering," Proceedings of the 28th International Technical Conference on Coal Utilization and Fuel Systems, pp.118-127, Clearwater, FL.

[14] Mine, M., "Virtual Environment Interaction Techniques. Technical Report TR95-018", 1995, UNC Chapel Hill CS Dept, Chapel Hill, North Carolina, USA.

[15] National Research Council, (1996) National Science Education Standards, National Academy Press, Washington, D.C.

[16] National Science Foundation, (1996) Shaping the Future: New Expectations for Undergraduate Education in Science, Mathematics, Engineering, and Technology, (NSF 96-139) Washington D.C.

[17] Setareh, M., Bowman, D., and Kalita, "A. Development of a Virtual Reality Structural Analysis System". Journal of Architectural Engineering, vol. 11, no. 4, 2005, pp. 156-164.

[18] Shimrat, M., 1962 August, "Algorithm 112, Position of Point Relative to Polygon," CACM, p. 434

[19] Sunday, D, 2001, March 2001 Algorithm: Fast Winding Number Inclusion of Point in a Polygon [Online] Available: http://softsurfer.com/Archive/algorithm_0103/algorithm_0103.htm.

[20] Virtual Reality Applications Center, Major Facilities (21 October 21, 2006) [Online] available: http://www.vrac.iastate.edu/facilities.php.

[21] Virtual Reality Applications Center, Virtual Storm (21 October 21, 2006), [Online] Available: http://www.vrac.iastate.edu/research/sites/tornado/.

[22] Wakimoto, R. M., C. Liu, and H. Cai, 1998: "The Garden City, Kansas Storm During VORTEX 95." Part I: Overview of the Storm's Life Cycle and Mesocycl1 26, 372-392.

[23] Wasfy, T.M. and Noor, A.K., (2001), "Visualization of CFD Results in Immersive Virtual Environments," Advances in Engineering Software, 32, 9, pp.717-730.

[24] Wasfy, T.M. and Wasfy, A.M., (2003), "Strategy for Effective Visualization of CFD Datasets in Virtual Environments," Proceedings of ASME Design Engineering Technical, Computers and Information in Engineering Conference, Chicago, IL.

[25] Wickens, C. D., "Virtual Reality and Education". In Proceedings of the 1992 IEEE International Conference on Systems, Man and Cybernetics, vol. 1, 842-847.

[26] Wilhelmson et al. 1990 (in Intl J. of Supercomputing Applications).

[27] Yarger, D. N., J. P. Boysen, W. A. Gallus, Jr., and R. A. Thomas, 1997: "Weather Forecasting: an Authentic Situated Learning Environment." Computer Assisted Learning in Meteorology Biannual Conference, Melbourne, Australia, July 1-9, 1997.

[28] Yarger, D.N., J.P. Boysen and R. Thomas, 1999. "Effective Teaching and Learning – Implementing Constructivist Learning Theory in a Meteorology Course". 8th Symposium on Education, Amer. Meteor. Soc., extended abstract.

Appendix A. Virtual Storm Work Sheet

Take a Ride Through a Virtual Tornadic Supercell Thunderstorm

NAME:

This exercise will place you in a virtual environment where you will experience a severe thunderstorm similar to those occurring in nature. Before beginning, think about the severe storms you may have experienced in your lifetime or heard about, and storms that produce tornadoes. What are some questions you have about these types of storms, and features you don't fully understand about them?

At the computers where the virtual storm resides, all necessary windows should be set up already. You will experience the storm visually in one window (graphics window), and have the ability to collect weather data (what has the storm done to various weather parameters such as temperature and pressure, and what are the current winds and humidities) while moving into a second "data" window. In the data window, you can select the weather parameter you would like to see plotted on the screeen. When you find a point where you want to take a measurement of that parameter, click on the ``Record" button at the lower right. A color-coded dot (or an arrow showing wind) will appear and you can determine the approximate value by using the color scale. (Wind arrows are drawn so that the stronger the wind, the longer the arrow.) The precise value will appear on the top line in the table below the map. The two windows are linked, so when you move in one window, you will be moved to the same spot in the other window. Keep in mind that the data window will always show you the data on a horizontal slice (a flat plane at a certain height).

Think about the questions you wrote down earlier. What data do you think you will have to record to try to answer your questions? In what areas/locations do you think you would need to collect these data?

To navigate in the graphics window, be sure to click once in that window, and then hold down the shift button and use the mouse. The left mouse button accelerates, the right decelerates, and the middle stops you. The mouse also controls which direction you are looking. Moving the mouse to the left or right causes you to turn to the left or right in the graphics window.

In the data window, your position is at the center of the gray arrowhead (marked with a colored dot depicting the value of the weather parameter where you are), and you are looking in the direction toward which the point is aimed. There is a sliding vertical scale on the right of the data window. When you collect weather data at any point, you also have collected it at all points above and below it (notice how the colors change at that dot when you slide up or down). You can go back to the exact spot (location and elevation) where you collected a specific weather parameter by clicking on that entry in the data table.

For today, we will use the structure below to investigate the storm. Please answer the questions below by spending time navigating all around the storm. In addition, keep in mind your own questions that you raised above. In some of the questions below, you will need to take temperature and wind measurements.

1. Explore the storm and sketch what you think the cloud area and precipitation area would look like if viewed from directly above, as though a weather satellite were seeing it.

2. Find the tornado in the storm, and note its location on your sketch on the previous page.

3. Describe the general wind pattern outside of the storm (what directions are the winds blowing, and how do these change as you go up in the atmosphere)?

4. Describe how the patterns of cloud and precipitation relate to the location of the tornado, and give possible reasons for any symmetry or asymmetry you see (in other words, is the tornado right in the middle, toward the side, etc., and why do you think it is where it is).

5. Determine where the coldest temperature perturbation exists near the ground, and discuss what you see going on there.

6. Explain why the temperatures may have become so cool there.

7. Explore the area within 1-2 miles of the tornado near the ground and describe what the temperature field looks like (what are the temperature perturbations and how do they vary)?

8. Explain what you think is happening to produce the temperature perturbations you see near the tornado (if it is cold, why is it cold; if it is warm, why is it warm).

9. REFLECTION: How have your ideas about severe thunderstorms changed, if at all?

10. Try to answer your own questions that you wrote down earlier. If you need to, explore the storm and collect additional data you think you might need to answer your questions. What do you think the data are showing with respect to your questions?

11. Finally, write an explanation of tornadic storms that you would use if you had to teach 10th grade students at a local high school about the storms.

Appendix B. Quiz

EVALUATION OF SEVERE STORM UNDERSTANDING
MTEOR 206 -- SPRING 2004 – Quiz # 11

Please enter your ISU # and answer the following questions using the bubble sheet. Since this quiz is longer and more difficult than the quizzes we normally have in class, each question is worth 0.5 points.

1) What is the key ingredient that can turn an ordinary thunderstorm into a severe thunderstorm capable of producing a tornado?
- a) unstable atmosphere
- b) strong wind shear
- c) clash of cold and warm air
- d) heavy rainfall

2) The tornado in a storm is usually found where within the storm?
- a) the middle
- b) the north end
- c) the south end

3) You are on the east side (front side) of the storm and need to drive to the west side (back side) of the storm. What is the safest route to take?
- a) drive north a few miles and then head west
- b) drive straight west from your position
- c) drive south one mile and then head west
- d) drive south a few miles and then head west

4) You are in a position where you can't see more than a few feet in any direction and it is very dark and cold compared to what it was like an hour before the storm hit. Where are you?
- a) inside of the tornado
- b) under the storm's main updraft
- c) in the precipitation area closest to the main updraft (1 mile northeast of the tornado)
- d) in the rain core 5 miles northeast of the tornado
- e) under the anvil cloud 20 miles northeast of the tornado
- f) in front of the storm, 5 miles east of the tornado

5) You are now in a position where the sky is medium gray, and only light rain is falling. However, giant hailstones are also falling, and the air feels cool. Where are you?
- a) inside of the tornado
- b) under the storm's main updraft
- c) in the precipitation area closest to the main updraft (1 mile northeast of the tornado)
- d) in the rain core 5 miles northeast of the tornado
- e) under the anvil cloud 20 miles northeast of the tornado
- f) in front of the storm, 5 miles east of the tornado

6) You are in a position where nothing is falling from the sky, but overhead you can see a very flat, well-defined dark cloud base, and it seems to hang lower from the sky than the clouds farther away from you. To your north and west everything disappears into fuzzy darkness. To your east and south you can see blue sky closer to the horizon. Are you in danger here?
- a) No, the storm has moved past my location
- b) Yes, large hailstones are likely in my location
- c) No, I am in the part of the storm that just gets lots of rain
- d) Yes, I am in the part of the storm where a tornado is most likely.

7) What does the blast of cold air that hits just before the storm's rain arrives mean?
- a) A cold front has just moved through
- b) The darkness of the storm has cooled the air
- c) Evaporation of some rain has cooled the air

8) How big is a typical severe thunderstorm cloud?
- a) about 2 miles by 2 miles across
- b) about 10 miles by 10 miles across
- c) about 10 miles wide and 50 miles long
- d) about 100 miles wide and 200 miles long

9) How much of a severe thunderstorm's area is occupied by a tornado?
- a) about half
- b) about 10%
- c) about 1%
- d) much less than 1%

10) Why is the tornado not located in the middle of the thunderstorm?
- a) wind shear in the atmosphere acts to blow the tornado to the edge
- b) the middle is where the rain is, which creates a downdraft, preventing a tornado
- c) the edge is where the cold front collides with the warm front, creating a tornado

11) Why do forecasters look for a hook shape in the rain area to find a likely location for a tornado?
- a) the hook shape shows where the cold and warm air clash
- b) the hook shape shows where the tornado is throwing debris
- c) the hook shape shows that part of the storm is rotating
- d) the hook shape shows where air is rising the fastest

Appendix C. In-depth Look at 2004 Results

In the year 2004 a total of 24 students volunteered. By coincidence, there were an equal number of female and male subjects. The students were given the option to work alone or in pairs. Eight students worked alone and 16 students worked in pairs. Of the students working alone, seven were male and one was female. Of the eight pairs, four were a pair of females, one was a pair of males, and three were mixed gender.

Along with the information already presented in Chapter 5, data for individual questions was also analyzed. A per question comparison was made between the Virtual Storm quiz results and the Non-Volunteer lecture quiz results. For five of the eleven questions, there was no statistically significant difference in performance when comparing the Volunteer's Virtual Storm Quiz to that of the Non-volunteer's Lecture Quiz. This suggests that the Virtual Storm and the lecture were equally effective in conveying information for about half the questions.

Furthermore, it was found that on two of the eleven questions the highest average score occurred on the Virtual Storm Quiz. Neither of the differences was statistically significant, although the average from the Virtual Storm quiz was 13% above the Lecture Quiz average. Even more interesting is that when comparing the Volunteer's Virtual Storm Quiz results to the Volunteer's Lecture Quiz results, the volunteers actually did worse on these questions the second time they took the quiz. This phenomenon deservers further study. Two factors that may have contributed to this drop in performance are (i) the amount of time between the use of the Virtual Storm and the second quiz, and (ii) that students may have been confused by the material they heard in lecture and could not connect it with their experience in the virtual storm. It is possible that the lecture on severe weather may have contributed to the drop. It would be interesting to research what aspects of the lecture, if any, led to the possible confusion.