Using Haptics to Convey Cause and Effect Relations in Climate Visualization

by

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This is to certify that I have examined this copy of a master's thesis by

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ABSTRACT

We investigate the potential role of haptics in augmenting the visualization of climate data. In existing approaches to climate visualization, different dimensions of climate data such as temperature, humidity, wind, precipitation, and cloud water are typically represented using different visual markers and dimensions such as color, size, intensity, and orientation. Since the number of dimensions in climate data is large and climate data needs to be represented in connection with the topography, purely visual representations typically overwhelm users. Rather than overloading the visual channel, we investigate an alternative approach in which some of the climate information is displayed through the haptic channel in order to alleviate the perceptual and cognitive load of the user. In this approach, haptic feedback is further used to provide guidance while exploring climate data in order to enable natural and intuitive learning of cause and effect relationships between climate variables. As the user explores the climate data interactively under the guidance of wind forces displayed by a haptic device, we believe that she/he can understand better the occurrence of events such as cloud and rain formation and the effect of climate variables on these events. We designed a set of experiments to demonstrate the effectiveness of this multimodal approach. Our experiments with 22 human subjects show that haptic feedback significantly improves the understanding of climate data and the cause and effect relations between climate variables as well as the interpretation of the variations in climate due to changes in terrain.

ÖZET

Bu araştırmadaki amacımız, bilgisayar ortamında iklim verilerini incelerken görme duyumuzun yanı sıra dokunma duyumuzu da kullanmanın algılamamızı nasıl etkileyeceğinin incelenmesidir. Günümüzde kullanılan iklim görselleştirme yaklaşımlarında ısı, nem, rüzgar, bulut suyu ve yağmur gibi veriler renk, boyut, yoğunluk, ve yönlendirme gibi görsel işaretler ve şekiller kullanılarak temsil edilmektedir. İklim veri boyutlarının çok geniş kapsamlı oluşu ve bu verilerin topografya bilgileri ile de bağlantılı olarak görüntülemeyi gerektirmesi kullanıcının bu verileri sadece görsel yollarla algılamasını zorlaştırmaktadır. Biz kullanıcının algılama ve kavrama yükünü biraz olsun hafifletebilmek amacıyla, kişinin dokunma duyusunu devreye sokarak, alternative bir yaklaşımla, bazı iklim verilerine farklı bir anlam kazandırmaya çalışmaktayız. Bu yaklaşımda, dokunma duyusunun geri-beslemeli bir robot kolu aracılığıyla kullanıcıya aktarılması, iklim verileri arasındaki sebep-sonuç ilişkisinin daha iyi anlaşılmasını sağlamaktadır. İnanıyoruz ki, kullanıcı rüzgar gücünün elini yönlendirmesiyle, bulutların veya yağmurun oluşumunu çok daha iyi algılayacak, iklim değişimlerinin bu olaylar üzerindeki etkisini daha iyi kavrayacaktır. Bu çok yönlü yaklaşımın, iklim görselleştirmesinde daha iyi sonuçlar vereceğini ispat etmek için bir dizi deney tasarladık. 22 insan deneği ile yaptığımız çalışmalar sonucunda, dokunma duyusu ile zenginleştirilmiş görsel verilerin daha iyi algılandığını ve iklim verileri arasındaki sebep-sonuç ilişkisisinin daha iyi anlaşıldığını gözlemledik.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1

INTRODUCTION

As information gets complicated it becomes very difficult to transform the data into a visual form enabling the viewer to observe, understand and make sense of it. The task is even more challenging if the information will be used in an educational setting targeting an audience who does not have expertise in interpreting the given data. In our attempt to make real climate data available to be explored by non-expert users, we merge interactive information visualization techniques with haptics to augment vision, to enhance the digestion of data and help the user build memory in a more retainable way.

We present a system where we use haptics for guidance in exploring climate data in a constructive setting. In doing so, we use the idea that people learn through experimentation and exploration. Climatic events are simulated more naturally by the help of haptic feedback, letting the user touch information, feel the winds, interact with clouds and go through tunnels where rain is formed. We hypothesize that investigation of data in a multi-sensory environment including vision and touch helps the users relate to what they discover and understand the cause and effect relationships among different variables. Since information is retrieved by two channels, the haptic and visual channels, we believe that it gets more endurable in memory. Also, we present a setting where the users are able to make experiments with real data, changing the topography and observing the changes in the climate data accordingly. We test the conjecture that by exploring the climate data in an interactive manner and observing the climate consequences of changes in topography, users will learn the cause-effect relationships among climate variables and retain this information better. These ideas will be demonstrated by the results of the relevant experiments conducted to test our hypotheses.

1.1 Organization of the dissertation

The dissertation begins with the introductory chapter that briefly describes the problem and the solution we present to tackle the problem.

Chapter 2 provides the necessary background and literature review of the current information visualization and geographic visualization systems in order to justify the need to integrate haptics into information visualization to enhance the digestion of data. The challenges and problems facing the current visualization systems are set out. The solutions that have been suggested to overcome these challenges are put forward and how these solutions can further be improved is discussed. The importance of self-exploration and learning through case studies are emphasized.

Chapter 3 describes the system we have designed: CE-Viz (Climate Exploration and Visualization). The working principles of the system are laid out. A flow chart is drawn explaining the data flow in our system: how data is retrieved from the geographic simulation program RegCM3, how the output of the simulation software is used as the input to our software and how the output of our system is designed. Visual and haptic representations and interaction and navigation in the system will be described, giving details about what other representations have been considered and why these representations have been decided to fit best.

The fourth chapter explicates the experiments done, to figure out how the presented system improves the understanding, learning and interpretation of the user. Each of the five experiments will be explained separately spelling out the design, stimuli, goal, procedure and results of each individually.

Finally, Chapter 5 consists of discussion and conclusions. Here, a summary of the presented system is given based on the concrete results of the experiments, emphasizing the fact that in our system haptic augments vision and improves the perception and cognitive abilities of the individual, facilitating him to remember and learn the given information better.

Chapter 2

LITERATURE REVIEW

This chapter aims to introduce the different visualization systems, providing an in-depth understanding of the advantages as well as the shortcomings of the current visualization systems to the reader. Taking information visualization into closer account, the lack of multidimensionality and multimodality will be discussed. Moreover, due to the unavailability of educational systems allowing non-technical users to assess the effects of geographical structures on climatic outcomes in real conditions, the advantages of using a virtual multimodal virtual environment to augment vision and enhance perception and cognition in a geographic learning system will be examined.

2.1 Definition and Subcategories of Visualization

Visualization acts as a bridge between the human mind and the computer. It involves transforming data, information and knowledge into a visual form taking advantage of people's natural strengths in visual pattern recognition. Effective visual interfaces enable us to observe, manipulate, search, navigate, explore, discover, understand and interact with large volumes of data. Research in visualization has first become essential with the scientific community's efforts to cope with the huge volumes of scientific data generated by massive supercomputer simulations. [5].

An emerging subcategory of visualization, *information visualization,* combines aspects of scientific visualization, human-computer interfaces, data mining, imaging and graphics. In contrast to most scientific visualizations, which focus on concrete data, information visualization focuses on information which is often abstract and does not have a real visual representation. The aim of information visualization is to enable users to reach and interpret the information they need and make sense of it in a short amount of time. While scientific visualization generally serves highly trained scientists, information visualization appeals to a more diverse and non-technical community, with different levels of education, backgrounds, capabilities and needs [5].

A recently emerging subfield of visualization, *geographic visualization* (GVis) is a branch of scientific visualization and focuses on spatial data which can be applied to problem-solving in geographical analysis, development of initial hypotheses, knowledge discovery and evaluation. While information visualization is developing in different areas, the contribution of geographers has accelerated GVis research. The advancement of geographic visualization in the past decade has placed geographers in a unique position not only in the research of GVis but also information visualization. Visualization appeals to the cognitive system of the geographer, presenting data in new ways, offering different perspectives to stimulate the exploration of new hypotheses [2]. The greatest contribution of visualization to scientific thinking is that it sets free the brain from the activity of information retrieval and manipulation required to produce an image. Thus, it allows the brain to give its time and energy to higher levels of analysis [12].

Climate visualization is a kind of geographic visualization where atmospheric data such as humidity, precipitation, temperature, cloud water and wind velocity is represented in different ways to facilitate the research of climate scientists investigating different climate models.

2.2 Overview of Visualization Systems

From a historical perspective, the literature of information visualization has started with 1D and 2D representations of information. Information involving relationships have been visualized using a graph with nodes representing the entities and link representing the relationships between them. Although graphs were effective in representing relationships in small information sets, as the sets got larger it was overwhelming and visually confusing to use graphs [5]. As the 1D and 2D representations became insufficient to describe complex data sets, 3D InfoVis techniques and metaphors started to emerge to visualize information in an efficient way. *Fish-eye views* have been suggested presenting information in the narrow, tunnel-visioned approach that a fish might see in. *Landscapes* were used presenting information in real and imagined landscapes in a 3D environment. *Networks* were employed to display information using networks in a 3D environment. *Perspective* *walls* emerged as a technique for focusing on a particular area of linearly structured information while still maintaining some degree of location [13]. The transparent *Information Cube* has been proposed to visualize hierarchical information in a structured way [14]. Interactive 3D graphics and animations have replaced the more primitive visualization techniques. Virtual environment (VE) technologies have extended the power of information visualization methods and have brought a new point of view to scientific as well as geographic visualization [1].

As the information visualization techniques became more case-specific and able to describe complex natural events of real life matters, they also begun to be used overwhelmingly in the field of geography. In this vein, climate visualization systems such as The Grid Analysis and Display System (GrADS) used for easy access, manipulation and visualization of earth science data [15] or the tools developed by NCAR (National Center for Atmospheric Research) [16] have emerged. These tools have different representations for topography, precipitation, pressure, rainfall, vegetation cover, water vapor, wind velocity, temperature and humidity. In these systems, topography is typically represented using contours; wind velocity is classically shown with streamlines consisting of vectors with u and v components in two dimensions for different levels over the surface. Pressure is usually represented with graphs showing the surface pressure and geopotential heights up to 850 mb. Quantities like temperature, precipitation, rainfall, vegetation cover and humidity are usually represented using different colors in different contexts. Different data is usually represented using separate graphs, which makes it harder to see the relationships among them. Besides the static maps, there are also a variety of interactive forecast visualization tools such as IGrADS designed for the US Armed forces or the animating forecast visualization tools used by NASA [17]. On IGrADS, forecast maps allow the display of four parameters, one color filled and three as "contour line" fields. The user can determine the maximum and minimum for each parameter as well as the interval, contour color and line thickness [7].

2.3. Major Challenges Faced by the Existing Visualization Systems

As the information gets complicated it gets increasingly more challenging to display all of the data simultaneously in a way that the user can understand, interpret and digest the information. While it is challenging even for the experts to interpret the data in these complicated models, it is ever more difficult for the system to appeal to a wider range of users. Despite the fact that there are many visualization models satisfying the needs of climate scientists, few attempts have been made to design a system to enable non-experts to understand and investigate natural climatic events and explore the cause and effect relationships among different climate data. Also, the effect of haptic feedback in enhancing the perception, cognition and digestion of data in complex information spaces by non-expert users has not been investigated sufficiently.

2.3.1 Multidimensionality in Information Visualization

Although making the visualization systems three dimensional provides a new dimension to the information space helping the problem of displaying complex data, by itself it is not enough to solve the problem. The problem gets even more complicated when the data is multidimensional. The visualization of multiple overlapping data fields together in the same display is much more difficult than representing a single data field in isolation. Designing techniques to represent multidimensional datasets in an effective way is an open area of research in visualization [4]. There are different approaches trying to represent multidimensional data. A method of visualization that uses painted brush strokes of the Impressionist school of painting to represent multidimensional data elements has been proposed. In this method, the attributes of different data elements like precipitation, temperature, wind speed, pressure in climate visualization are used to vary the visual appearance of the brushstroke, being mapped to its color, size, orientation or texture [4]. Also, interactive forecast tools have been proposed, such as IGrADS, allowing four parameters to be displayed on the same map [7].

2.3.2 Lack of Multimodality

Another challenge faced by information visualization systems is the lack of multimodality. Humans interact with information using multiple senses in their everyday lives. The eyes pick up shape information from the object's outline while the hands supply tactile and haptic shape information. Various sensory modes are used to acquire the optimal amount of information from the environment using our vision, audition, smell, taste, skin, vestibular and kinesthetic senses [9]. Yet, computer-based information systems are dominantly visual which makes these systems limiting. Attempts have been made to come up with multimodal geographic information systems supporting haptic and auditory displays. Harding has proposed combining 3D Graphics, Sonification and Haptics into multisensory systems in order to manipulate geoscientific data interactively, which he suggested would facilitate many complicated tasks that geoscientist in academia and industry (especially oil and gas industry) face [9]. Also, studies have been made to discover the feasibility of adding haptic and auditory displays to traditional visual geographic information systems [3]. In these studies single information like the number of male nurses per capita for each state was displayed on a 2-D map. The goal of these experiments was to understand if the users preferred when the information was displayed with changing vibrations or volumes when the mouse came over each state. Although these studies provide a basis for multimodal information systems, insignificant research has been made to investigate the use of haptics to represent information in different areas like climate visualization and in representing more complicated and multilayered information systems.

One of the challenges of representing multilayered information systems is that representing the information through one channel only becomes overwhelming when several layers of information are displayed simultaneously. Rather than overloading the visual channel, we suggest that some of the information can be displayed through the haptic channel in order to alleviate the perceptual and cognitive load of the user. For example, the haptic texturing idea proposed by Basdogan et al. can be used to add a new dimension to the layers of information. Basdogan, Ho and Srinavasan have developed efficient methods for displaying surface properties of objects such as texture and friction through a haptic device [8]. They have suggested different methods like using fractals or Fourier series to create haptic textures over the surface. While using the Fourier Series approach to haptic texturing they have observed that different textures can be generated by modifying the variables of the bumps like height, wavelength and stiffness. They have also implemented the noise textures by dividing the space that surrounds the 3D object into a lattice of cubical cells and assigning a unit pseudo-random vector to each corner of the cell [8]. Using these texturing methods, information can be represented in different ways, opening up the visual channel by representing some of the information through the haptic channel.

2.3.3 Perception and cognition in complex information systems

Another challenge in human-centered visualization is investigating visualization systems based on human capabilities of perception and information processing. In order to improve perception and cognition in complex information systems, first it should be well understood how humans interact with information, how we perceive information visually and non-visually, how the mind works while searching for known and unknown information and how the mind solves problems [5]. While good human-computer interaction is a must, it needs to be better scrutinized what we know about how humans understand and interact with information and the perceptual system. The user interfaces should be flexible, the navigation tools and search methods should be appropriate for each of the existing types of users, applications and tasks [5].

Research studies focusing on the user's cognition using different information channels in GIS have found that the user's satisfaction improves with multimodal environments including haptic and auditory display. Since we, human beings use multiple senses when interacting with the environment, it is reasonable to use multiple senses along with vision in information systems, augmenting the existing visualization of scientific data [3].

Shadmer and Brashers-Krug have examined motor learning and haptic memory building. They have conducted experiments measuring how long the memory built though motor training retained. They stated that motor practice results in memories that have at least two functional components: one part lasts soon after completion of practice while some other motor skills last at least 5 months after training [6]. Other experiments have been conducted, investigating the use of different senses to receive information in the computer models. It has been reported that the nervous system loses single-cue information when cues from within the same sensory modality are combined, but does not lose information when cues from different modalities (vision and haptics) are combined [18]. Thus, it is reasonable to design models which give information through different channels, so that the user retrieves and digests the information better. In the field of psychophysics Bara, Gentaz, Cole and Sprenger-Charolles have examined the effect of using a visuo-haptic and haptic exploration of letters in a training designed to develop phonemic awareness, knowledge of letters and letter/sound correspondences on 5-year-old children. They observed that the haptic training after the visual training improved the decoding skills of the young children. Thus, it appears that using multiple senses has a positive effect on the perception and cognition of the users.

2.3.4 Usability by a large group of people

While cognition is a challenge for current visualization systems, another important setback is the accessibility to a wide group of diverse users [10]. A growing number of applications are being developed for the general public. To address the problem of universal usability, designers need to consider larger and more diverse groups of users. Technological advances are necessary not only to deal with user diversity but also with the variety of technology used and any specific gaps in a user's knowledge. Information Visualization has been shown to be a powerful visual thinking or decision tool for some average users receiving a minimum of training. It is becoming important for services to reach every citizen regardless of their background [10].

The scientific visualization systems are usually designed only for a very limited population, only for the use of experts of the field. People who want to explore and learn about scientific concepts using real information cannot understand these complicated systems. The same problem exists for climate visualization, too. Although climate scientists or field experts can understand and interpret the data (generated by the complicated climate models) in the complicated climate models using the mental map they have about the mutual relationship between topography, wind, temperature, humidity and rainfall, it is very hard for a person, not involved in climate research to understand the driving forces behind natural phenomena by looking at the complex diagrams and maps. Climate scientists can tell that the wind coming from a certain area has caused the rainfall and temperature change in a different location by investigating the visual representation and combining it with the knowledge they have accumulated over the years about the effect of wind on different geographic features. However it is very difficult for a non-expert person, who is eager to learn climatic concepts, to understand the data and tell the story behind the classical visual map. As a result of private communication with Dr. Omer Sen, professor of climate sciences at Istanbul Technical University, we learned that he has a hard time explaining his students the climate events with the current tools. He has stated that it is very difficult for a non-expert to interpret the complicated maps offered by traditional climate visualization systems.

2.3.5 Inefficiency of comparing data and interpreting case studies

A known technique which improves learning is case-based learning. The use of case studies is a great pedagogical technique for teaching. Cases usually require people to analyze data in order to reach a conclusion, think in a more creative way and interrogate but not memorize the given facts. Even highly trained scientists use cases to understand better how different variables in their fields of research behave in different conditions. The climate scientists usually try to understand why certain natural events happen by altering the current geographic conditions, like topography or vegetation cover, and see how it affects the other variables. For example, a group of climate scientists have investigated the reason for the floods around the Antalya Region located in the Southern Turkey [11]. Using a high-resolution regional climate model in their study, they investigated the relationship between the topography of Antalya region and severe precipitation events that take place in this region by changing the topography in that region and exploring the effects[11].

Although this technique of doing experiments with real data is very efficient for exploration and learning, it cannot be used outside of the scientific community since the visualization tools cannot be used efficiently by non-experts. The existing climate visualization tools give a variety of graphs and diagrams for different geographic quantities. Comparing a variety of graphs and diagrams and understanding the reasons behind the changes is highly challenging for a non-technical user.

2.4. Information visualization systems in an educational setting

For decades science education has emphasized learning by discovering, in which children are given experimental materials such as springs and pulleys, marbles and ramps and are expected to discover the scientific principles on their own. This approach is based on the teachings of two intellectuals: developmental psychologist Jean Piaget and educational philosopher John Dewey. While Piaget believed that children would learn better when they learned on their own Dewey has tried to motivate students with real-world problems. However, some experiments cannot be done in the real world – like altering the topography and seeing the effects on the climate. For this purpose, scientists use complicated computer models where they explore about different relationships in data.

Using the data generated by these computer models, our system lets a non-expert user experiment and explore about different relationships in climate data with an intuitive and easy-to-understand way and user interface, taking advantage of the user's ability to perceive and learn information better using multiple senses.

Chapter 3

CE-Viz (Climate Exploration and Visualization)

This chapter presents an overview of our system (CE-Viz), giving a deep understanding of how it displays geographic data in an intuitive way and how information is processed using real data generated by the simulation program RegCM3. In *Section 3.1,* visual and haptic metaphors used to represent data are elucidated, while *Section 3.2* gives a deeper insight into the exploration and navigation tools used in the system. Lastly, *Section 3.3* explicates a technique used to display the changes when topography is manipulated.

CE-Viz provides an educational setting where real climate and geographic data is displayed in a multimodal virtual environment, jointly utilizing visual and haptic feedback. In our attempt to assist non-technical users in learning climatic concepts, we also carry on the objective of facilitating the understanding of cause and effect relations of geographic data in an intuitive way. Our system provides a real setting where the user can investigate issues like the formation of rain, the pre-requisites for the appearance of clouds, the consequences of different wind structures and the driving forces behind various climatic events in greater detail. Moreover, it allows the user to conduct experiments in a virtual environment that cannot be carried out in real life circumstances. Since it allows the users to manipulate the topography and explore the resulting changes in other geographic data, it also encourages the user to think creatively.

Our system uses accurate scientific data provided by the simulation program RegCM3, which is a 3-dimensional, sigma-coordinate, primitive equation climate model [19] to provide realistic conditions for exploration. This software generates geographic as well as climatic data for regions around the world in general, and in our case, for Turkey and its adjacent countries in specific. The data retrieved from RegCM3 is then transformed into visual and haptic metaphors by our system to present an easy-to-use, intuitive graphical user interface. As a result, the user is able to explore the wind structure, cloud and rain formation, temperature and humidity for various time periods around Turkey and scrutinize the cause and effect relationships among climate variables.

The process that our system goes through is described in *Figure 3.1*. The simulation program RegCM3 takes in boundary and initial conditions, which are the specific data values in the region of interest corresponding to the day we initialize the simulation, as the input. The boundary conditions for the region we want to investigate are provided by Eurasia Institute of Earth Sciences (EIES) at Istanbul Technical University. The geographic data in the form of a height map and the vegetation cover are also supplied by EIES.

The height map is a set of points in the form of coordinates (x, y, z) where z is the altitude of the terrain (in km) above sea level at grid coordinate (x, y). The grid points are along west-east and north-south directions, with 24 km between each. There are 169 grid points along the x direction and 115 grid points along the y direction in our maps. Thus, our height map covers an area of (24*169) by (24*115) km along the x-y plane. This height map provided by EIES is used by our program to construct a 3D mesh of the topography (Step 1 in *Figure 3.1*). When the climate data is mapped on the original terrain, we keep the height map as is. On the other hand, when the variations in climate data for the changes in terrain are investigated, we change the z-coordinate in related regions and as a result a new height map is formed (Step 2 in *Figure 3.1*).

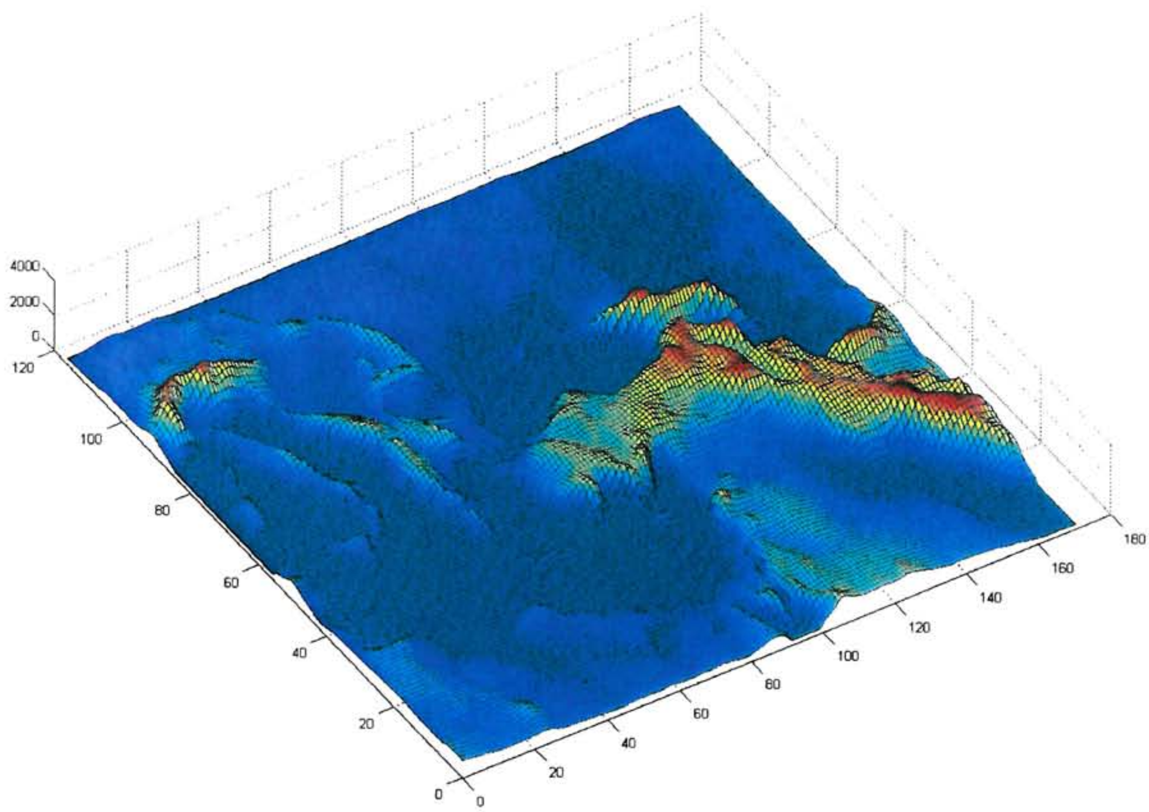


Figure 3.1. The height map received from AYBE to show the topography.

The height map is then given as an input to the simulation program RegCM3. The simulation program takes in the boundary and initial conditions for the day the simulation is performed (Step 3 in *Figure 3.1*). It generates output containing the sea level pressure, precipitation, p-level height, air temperature, zonal wind, meridional wind, specific moisture, cloud water and vorticity for the first ten days after the day simulation starts (Step 4 in *Figure 3.1*). All of this data is generated for different pressure surfaces, corresponding to the pressure levels for 500mb, 700mb, 850mb, and 925mb, for each day. Our program utilizes the output of RegCM3 for a specific day and pressure surface. Each data file used for visualization in our system consists of 169*115 rows and 10 columns. The rows represent the different grid points whereas the columns represent climate information for each data point. The climate variables included in the data file are the following:

x direction (west-east): the x-coordinate of the data point.

y direction (north-south): the y-coordinate of the data point.

Precipitation (mm): rain, snow and other forms of water falling from the sky.

p-level height (gpm/geopotential meter): the height at which the pressure is equal to 850mb.

Air temperature (K): measure of the heat content of the air.

Zonal wind (m/s): The wind component along the local latitude.

Meridional wind (m/s): The wind component along the local longitude.

Specific moisture (kg/kg): humidity of the air.

Cloud water (kg/kg): The total concentration of ice and liquid water particles in a cloud.

Vorticity ($K\ m^2\ kg^{-1}\ s^{-1}$): force defined as the curl of the wind velocity representing the amount of circulation or rotation.

The results of the simulation program are then received by our system: CE-Viz. Given the climate and geographic data, our system renders the climate data superimposed on the geographic data (Step 5 in *Figure 3.1*). The geographic data is represented as a 3D polygonal model which is also rendered using haptic feedback. CE-Viz uses ***the p-level height (gpm)*** information for 850mb to create a 3D mesh for the pressure surface. The *pressure surface* consists of points with x and y coordinates on the grid and the z coordinate standing for the p-level height for each x and y coordinate along the longitude and latitude. The pressure surface is not shown visually because if it shown visually over the topography, the sight of topography is blocked. Therefore, it is mapped as an invisible surface that the user cannot see but can feel by the help of haptic feedback while moving over it. The other information coming from the simulation program like the ***precipitation***, ***air temperature***, ***zonal wind***, ***meridional wind***, ***cloud water*** and ***vorticity*** are also given corresponding to the 850mb surface level. Hence, our system maps them over the invisible haptic pressure surface using different paradigms both visually and haptically. These paradigms will be explained further in ***Section 3.1: Visual and Haptic Representations*** of the chapter. Also, the changes in climate data as a result of topography manipulations are displayed by a dynamic information visualization technique that we have implemented to show the cause and affect relationships behind the changes in a time sequence. Haptic feedback is used to give the user guidance in exploring the changes that have occurred as a result of the topographic changes. This technique will be explained in further detail in **Section 3.3**: **Terrain Manipulation**.

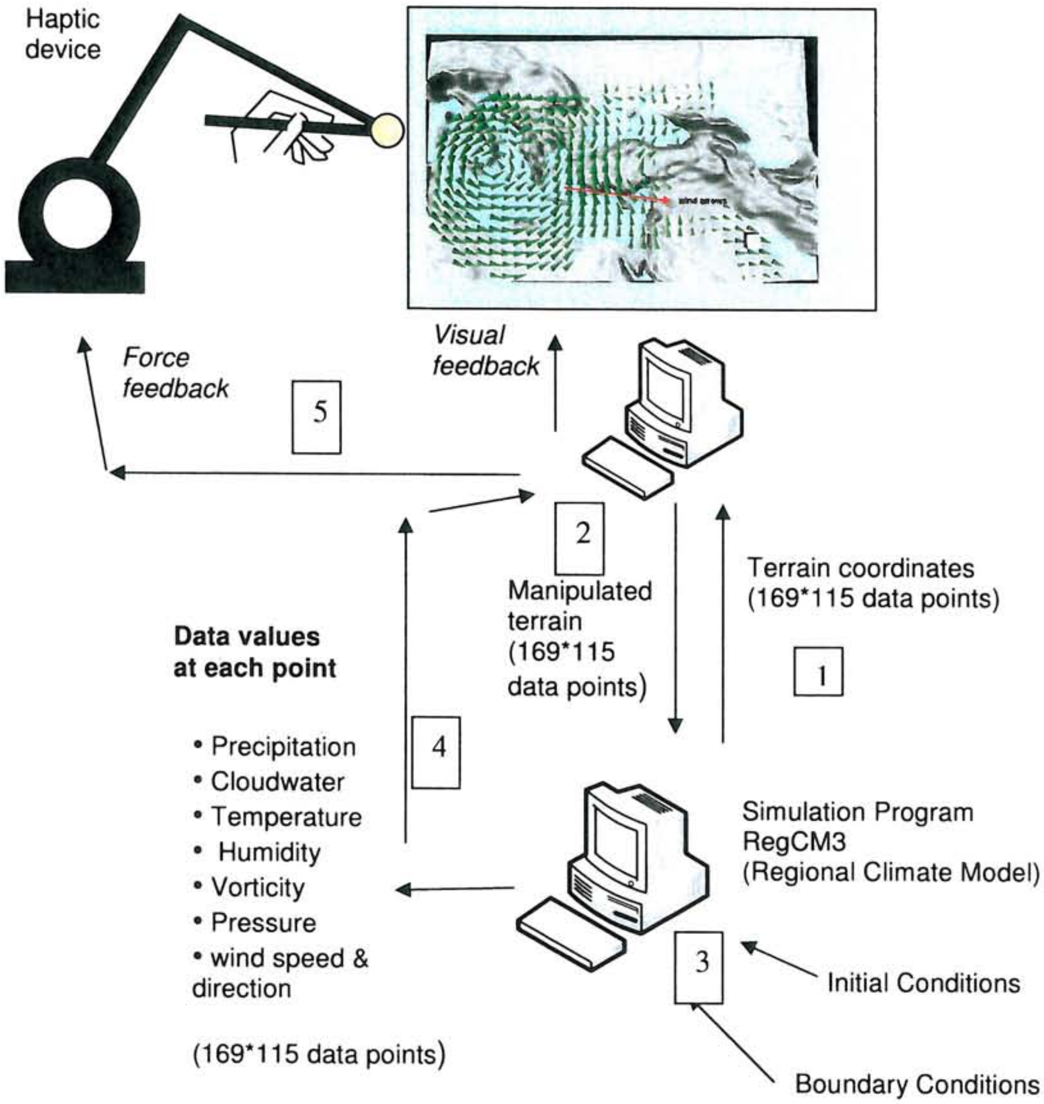


Figure 3.2. The process CE-Viz goes through to display the climate data

3.1 Visual and Haptic Representations:

This section explains the different paradigms and metaphors used to represent climate data using visual and haptic feedback.

Height map: A 3D mesh representation of topography is formed by connecting the height values for each grid point using the height map provided by EIES. The mesh is colored to make it more realistic, the height values of zero corresponding to the sea level being colored blue, and the height values above zero being colored gray (different shades of gray are provided by Open Inventor). It is also transferred into a haptic map allowing the user to feel the topography by touch.

For each data point on the 3D mesh:

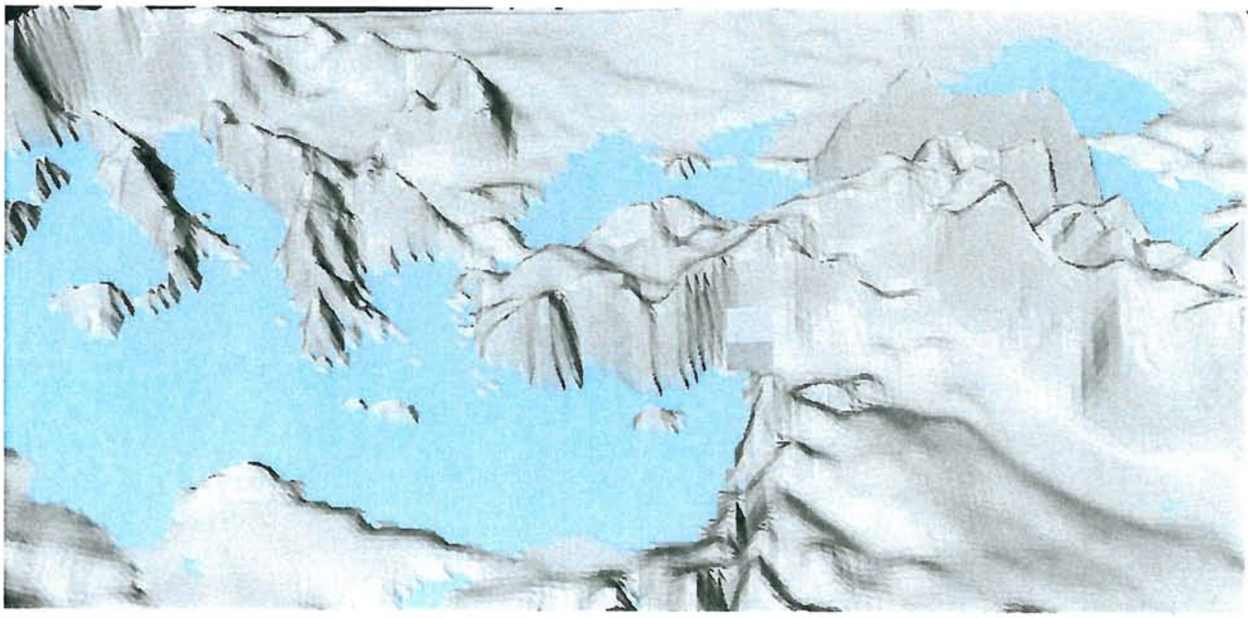


Figure 3.3. The 3-D mesh of the topography formed by CE-Viz.

Pressure Surface:

The data column related to the **p-level height (gpm/geopotential meter)** is used to construct a pressure surface. The surface consists of all points at which the pressure is 850mb. This surface is not shown visually because if the mesh is shown visually by a color mapped onto the surface, it covers the terrain, blocking the user's view of the topography structure. Instead, it is mapped as an invisible haptic surface that the user cannot see but feel and navigate on it. All other climate variables like wind, cloud water, precipitation given for this pressure surface are mapped onto the surface in a way that they will not block the topography. Below is a picture of the pressure surface shown visually with temperature mapped as a color over it blocking the topography.

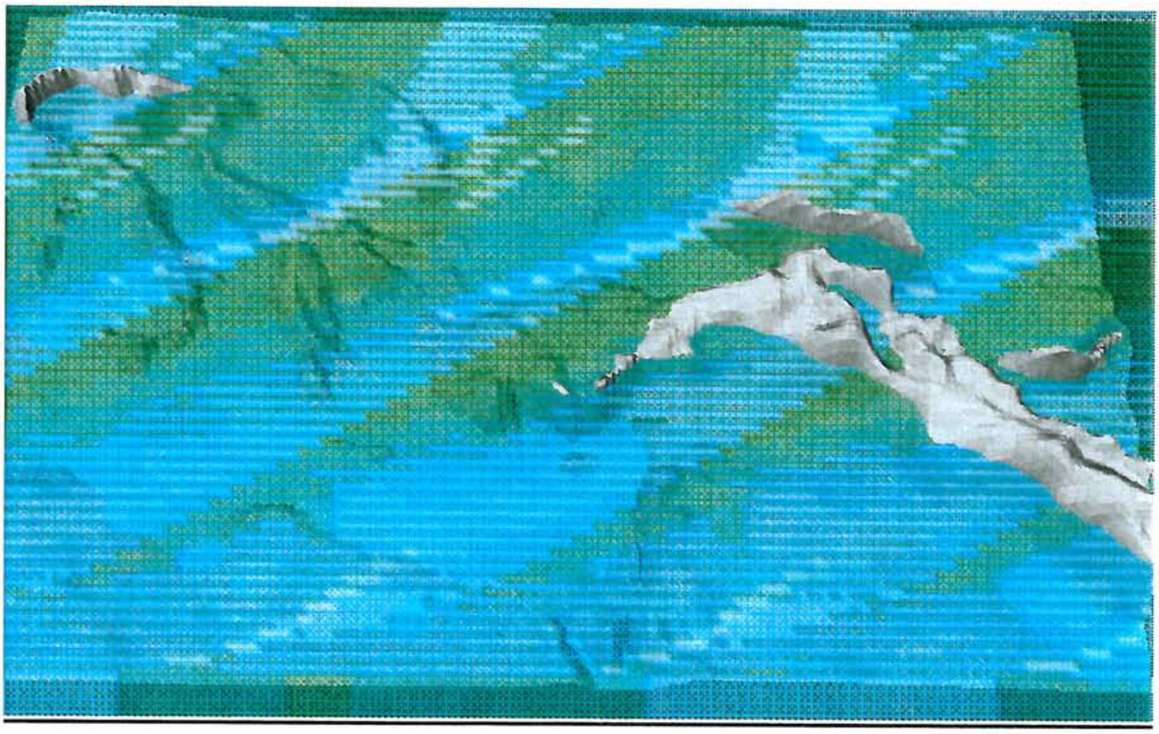


Figure 3.4. The pressure surface mapped as a visual layer blocking the terrain.

Wind: Wind speed and wind direction at each point are mapped as an arrow over the pressure surface, the size of the arrow being proportional to the magnitude of wind and the course of the arrow showing the direction of wind. The arrows are represented by cones, the radius and height of the cone being proportional with the wind magnitude. The cones are all invisible at the beginning of exploration; they start to appear as the user explores the surface. Rather than giving a static map where all the information is displayed together, this constructive structure allows the data to be displayed gradually so that the user can explore information in an interactive manner.

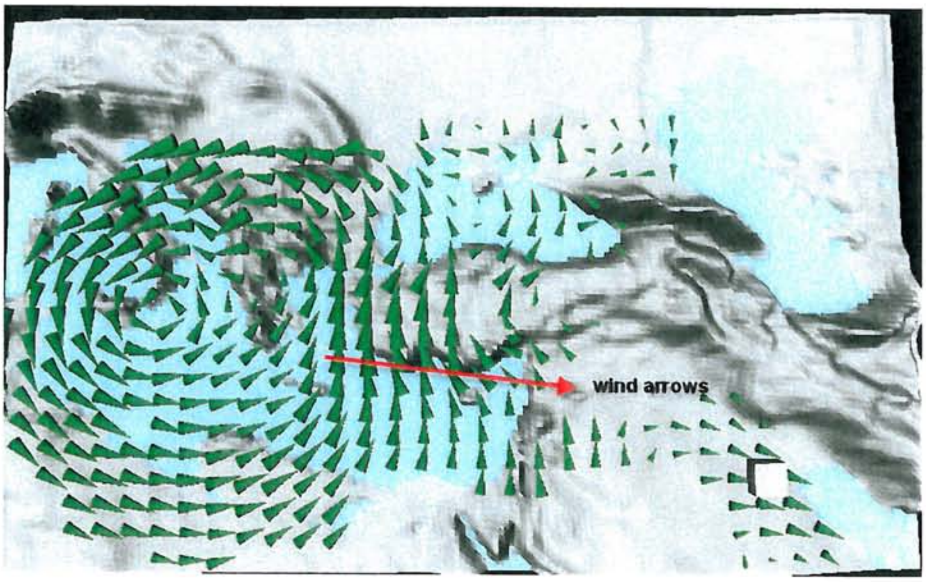
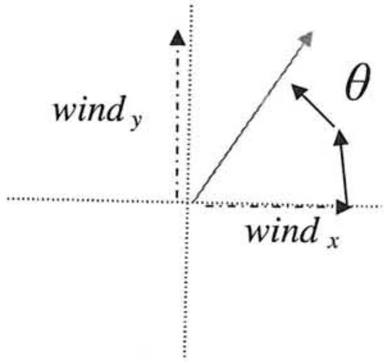


Figure 3.5. Wind arrows superimposed over terrain.

$$wind_x = zonalwind(m/s)$$
$$wind_y = meridionalwind(m/s)$$
$$wind_{magnitude} = \sqrt{zonalwind(m/s)^2 + meridionalwind(m/s)^2}$$

$$\theta = \begin{cases} \arctan(\frac{wind_x}{wind_y}) & if \quad wind_x > 0 \quad \& \quad wind_Y > 0 \\ \arctan(\frac{wind_x}{wind_y}) & if \quad wind_x > 0 \quad \& \quad wind_Y < 0 \\ \Pi - \arctan(\frac{wind_x}{wind_y}) & if \quad wind_x < 0 \quad \& \quad wind_Y > 0 \\ \Pi + \arctan(\frac{wind_x}{wind_y}) & if \quad wind_x < 0 \quad \& \quad wind_Y < 0 \end{cases}$$



$wind_x$=x component of the wind
$wind_y$=y component of the wind
$wind_{magnitude}$=magnitude of the wind

Haptic Representation of the Wind:

As the user travels over the pressure surface, the wind arrows are displayed at the places the user passes over and the haptic guidance helps the user to follow the path of the winds. This structure is implemented by dividing the map into gridlines on the x-y plane and assigning a force vector to each point in the grid. The zonal wind and the meridional wind are mapped as forces in the x and y directions consequently. If the user is at a point not exactly on the gridlines but in between them, then the force feedback at that point is calculated by interpolating the forces at the neighboring vertices on the grids.

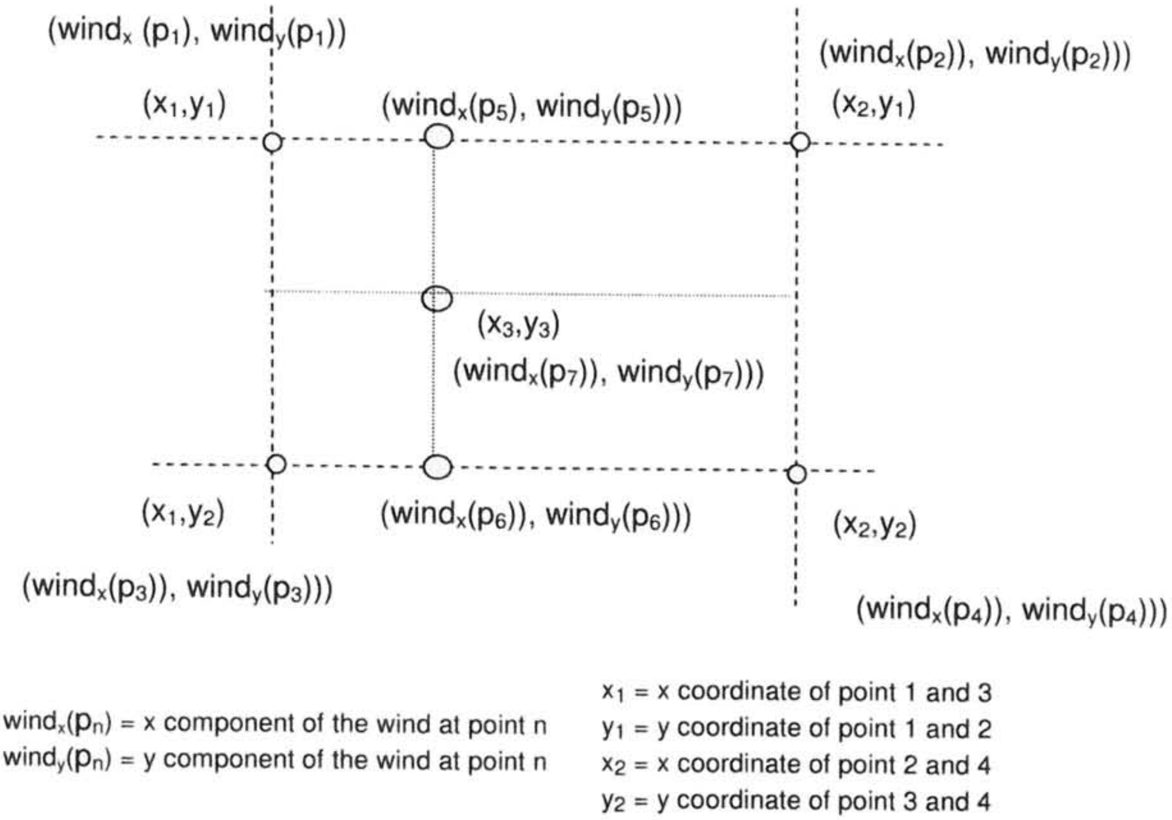


Figure 3.6. Interpolation technique used to display the haptic representation of the wind.

$$wind_x(p_5) = wind_x(p_1) + (wind_x(p_2) - wind_x(p_1))\frac{x_3 - x_1}{x_2 - x_1}$$

$$wind_x(p_6) = wind_x(p_3) + (wind_x(p_4) - wind_x(p_3))\frac{x_3 - x_1}{x_2 - x_1}$$

$$wind_x(p_7) = wind_x(p_5) + (wind_x(p_6) - wind_x(p_5))\frac{y_3 - y_1}{y_2 - y_1}$$

$$wind_y(p_5) = wind_y(p_1) + (wind_y(p_2) - wind_y(p_1))\frac{x_3 - x_1}{x_2 - x_1}$$

$$wind_y(p_6) = wind_y(p_3) + (wind_y(p_4) - wind_y(p_3))\frac{x_3 - x_1}{x_2 - x_1}$$

$$wind_y(p_7) = wind_y(p_5) + (wind_y(p_6) - wind_y(p_5))\frac{x_3 - x_1}{x_2 - x_1}$$

Cloud water: Cloud water is represented by white spheres mapped over the pressure surface. The radius of each sphere is proportional to the cloud water value at that grid point. Thus the regions where the spheres are largest and dense stand out as the regions where cloud water is most remarkable.

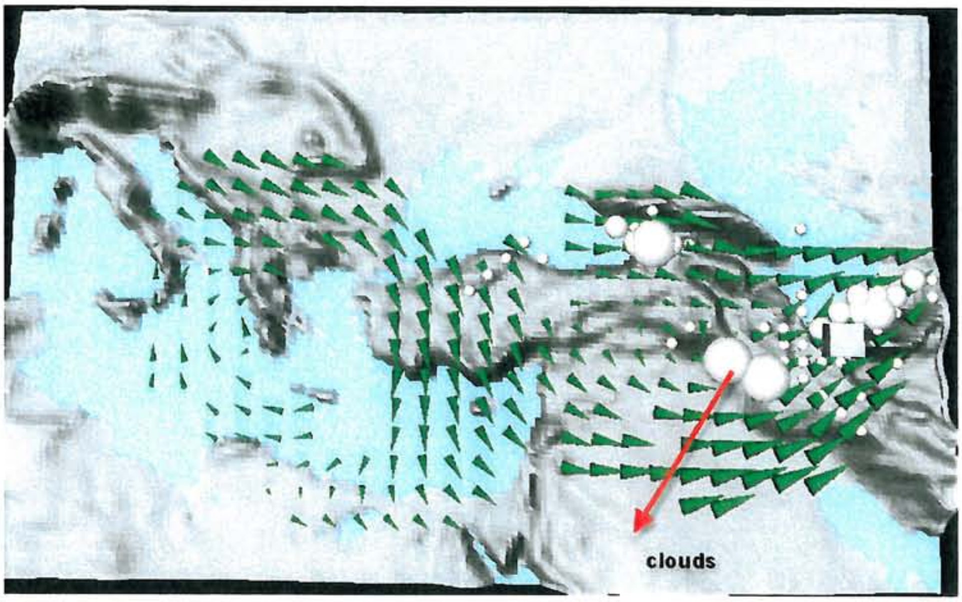


Figure 3.7. The cloud water values mapped as white spheres of different radii over the terrain.

Haptic Representation of the cloud water:

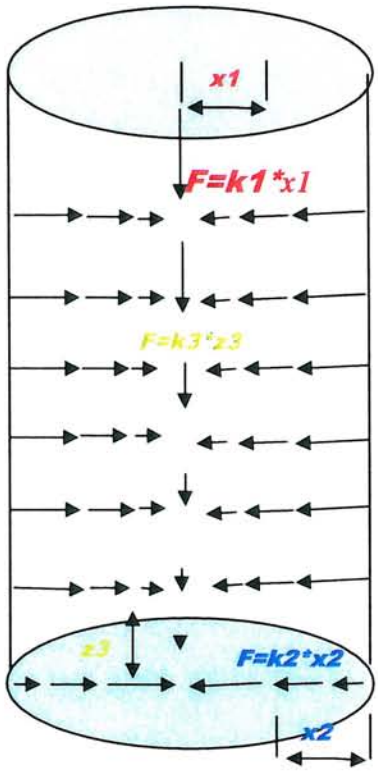
Bump textures are mapped onto the pressure surface using "Fourier" series [8]. The size and frequency of bumps are directly proportional to the value of the cloud water at the grid points. The user feels the bumps as she/he passes over the clouded areas, drawing his attention to the clouded regions.

Vorticity and Rain: The data coming from the simulation program includes the *vorticity* at each point. Vorticity is a mathematical concept used in fluid dynamics related to the amount of circulation or rotation in a fluid, as explained before. It is defined as the curl of the velocity, thus it is a force perpendicular to the plane including the velocity.

$$\vec{\omega} = \vec{\nabla} \times \vec{v}.$$

In our case, vorticity is the force which makes the wind rise or fall due to the circulation of the air. When there is a counterclockwise circulation or when the wind collides with the mountains air tends to rise. In our system, the vorticity is represented by a resistive spring force $F=-k3*z3$ at each point, the spring constant k3 being inversely proportional with the vorticity force and x3 representing the distance the user lifts up from the pressure surface. (Figure 3.3) If the vorticity force is weak, k is large, thus the user is not be able to lift from the pressure surface. If the vorticity force is strong on the other hand, k is small, thus there will be a smaller resistive force as the user wants to lift from the surface. In this way, the user is able to relate when she/he is able to lift from the surface that wind is able to rise at that point.

Other ways to represent vorticity have also been considered but were found out to be counter-intuitive. We have tried rain tunnels which had a force pulling the user up in the center and moving her/him to a higher pressure level where new information in that layer would be displayed. However, we realized that the pull was very abrupt for the users and it was very difficult for them to realize that they had moved up to a higher level in which they were stuck and couldn't go back and try again. Thus, we decided to keep our model simpler by having one pressure surface and letting the user explore how much they could lift by going back and forth at each point.



Rain tunnel

x1=distance from the center
x2= distance from the boundary of the cylinder
x3= how much the user has lifted from the base of the cylinder (the pressure surface)

Figure 3.8. The forces displayed inside the rain tunnel.

On the pressure surface, there are long cylinders in places where the vorticity is high. As she/he moves around the cylinder she/he is pulled into the cylinder (F=k2*x2), and once she/he enters the cylinders she/he will be able to see that she/he can lift from the surface very easily while in other places where the vorticity is low the user cannot lift easily and is stuck onto the surface. If she/he enters the cylinders, and tries to lift up, she/he moves up inside a tunnel keeping her/him on the track (virtual fixture). When she/he enters the cylinders, if there is enough humidity in the information box, rain starts to fall. Also, she/he experiences the temperature and humidity drop by observing the color and the size of the information cube changing as she/he lifts up. Since pressure is directly proportional with temperature in the Ideal Gas Law PV=nRT, as the air rises, the pressure drops thus causing the temperature to drop. Also, when the user is on the pressure surface, she/he is able to feel the wind forces, giving her/him an idea about the wind structure at that point. So the user is able to understand the relationship between wind structure, humidity, rising force and rain.

In the cylinders where rain forms, rain is illustrated by animating small blue cones with radii directly proportional with the precipitation value (mm) at that point. At each point, five cones of the same size are placed with the highest one being placed over the pressure surface and the others being placed below it consequently. As the user navigates over the pressure surface, the rain drops do not appear. When she/he enters the cylinder and moves up, they start to appear, explicating the relation that rain forms when the wind rises.

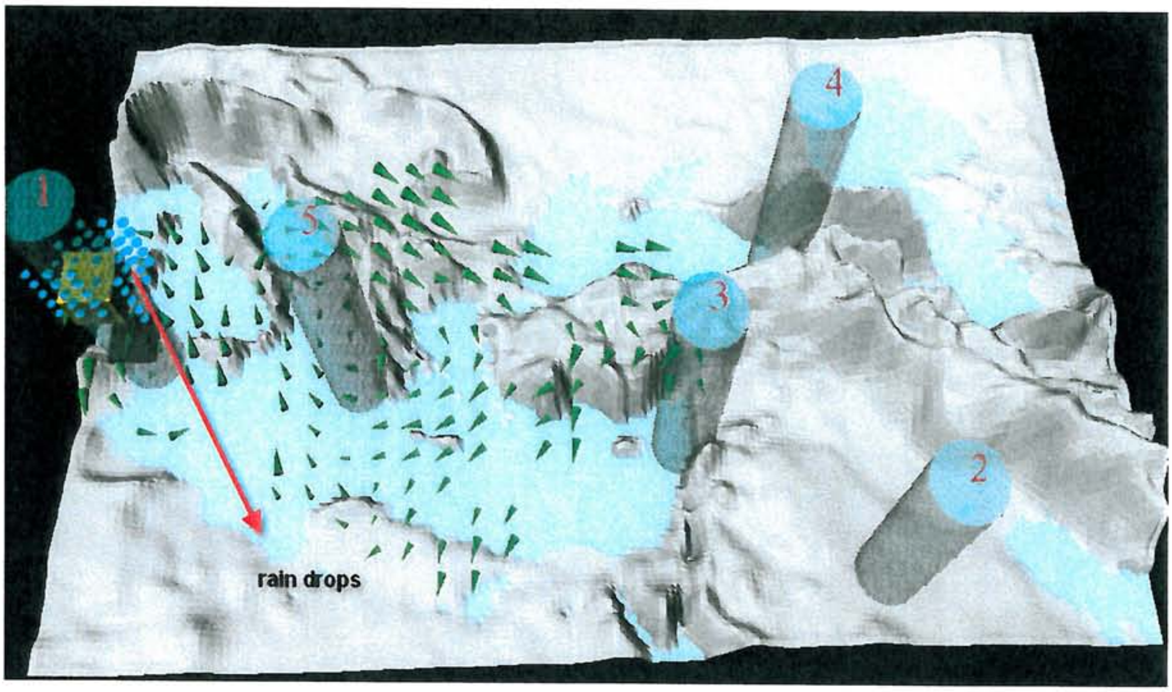
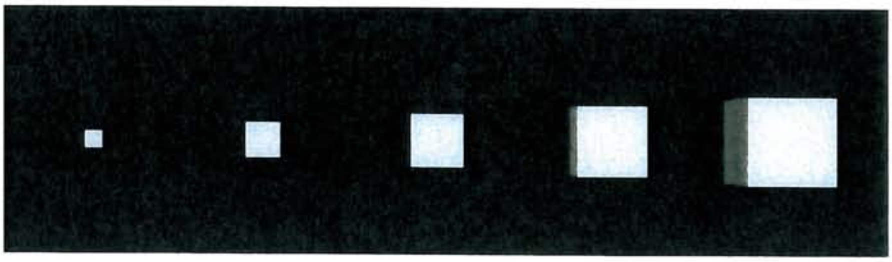


Figure 3.9. The representation of rain cylinders and raindrops.

Humidity: An information box carrying information about different geographic quantities at the point of location is connected to the cursor moving together with the user. The information cube lets the user observe the climate values at specific points rather than giving an overview over the whole map. It helps the user help the changes in climate data while moving over the surface. Humidity (specific moisture) is represented by the size of the information box. There is a linear mapping from the specific moisture values received from the data file to the size of the box.

Size scala:



less humid → → → → → → → → → → → → → → → → → → → more humid

Figure 3.10. The size scala mapped to the specific humidity.

Temperature: Temperature is represented by the color of the information box (warm to cool: red, orange, yellow, white and blue). The range of temperature in the data file is divided into eleven intervals, where each interval is assigned by a color ranging from red to blue.

Color scala:

warmer → cooler

Figure 3.11. The color scala mapped to the air temperature.

***Shadows*:** The information cube has a shadow on the topography which is used to emphasize the location of the cursor on the x-y plane (grid plane).

Figure 3.12. The shadow of the information cube showing the exact location over the topography.

3.2 Exploration and Navigation:

As the user travels over the pressure surface mapped as a haptic mesh, the wind arrows are displayed over the surface and the haptic guidance helps the user to follow the path of the wind. The wind forces mapped onto the pressure surface guides the user to move along the path of the wind letting her/him explore information in a time sequence.

As the user travels over the surface, clouds represented by white spheres start appearing. As she/he moves on the surface guided by the wind she/he also feels the topography in places where the topography is higher than the pressure surface. This feature of the system allows the user to feel and memorize the places where the wind collides with the mountains, helping her/him establish a correlation between the cloud structure, wind structure and terrain. We have experimentally tested our hypothesis that haptic feedback helps the user make this correlation better and our results will be revealed in the Experiments chapter. Also, there is a texture mapped onto the pressure surface with bumps of size and frequency directly proportional to the radii of the clouds. Thus, the user feels bumps as she/he passes over clouded areas, drawing his attention to the clouded regions.

As the user moves along the surface, she/he is snapped into long cylinders, which are placed in regions where the vorticity is higher than a threshold, in which she/he can move up and down. If the user enters the cylinders, she/he realizes that she/he can lift from the surface very easily while in other places where the vorticity is low she/he cannot lift easily and is stuck onto the surface. If she/he moves up in the cylinder, she/he lifts inside a tunnel keeping her/him on the track going up from that point. In the cylinder she/he observes that as she/he moves up, the temperature drops (displayed by the color of the cube), and the size of the box gets smaller illuminating the fact that humidity drops as well. The user observes that if there is enough humidity, rain starts to fall. Also, when the user is on the pressure surface, she/he will be able to feel the wind forces, letting him understand the wind structure at that point. So the user will be able to understand the relationship between wind structure, humidity, rising force and rain. We believe that haptic feedback and controlled guidance helps the user realize the cause and effect relations between these quantities better. The experiments testing our hypothesis will be discussed in the Experiments chapter.

Other ways to represent and explore the data have also been considered but after preliminary experiments, the above paradigms have been chosen to be the most user-friendly, intuitive and comfortable ones to use.

3.3 Terrain Manipulation:

We believe that people learn best by working on case studies and exploring the what-if scenarios. In our system, we allow the user to manipulate the terrain and see how the geographic data displayed changes accordingly.

Different topographic manipulations have been considered: removing the mountains in the northern part of Turkey, making the mountains in the northern part of Turkey higher, removing the mountains in the Antalya region (southern Turkey), making the mountains in the Antalya region higher, making the Alp Mountains higher, removing the Kafkas mountains, connecting the Kafkas mountains with the mountains in the northern part of Turkey, lowering all of the mountains in Turkey and exaggerating the height of mountains in the Girit Island on the mediterranean sea.

The climate simulation program RegCM3 takes few hours to run each case given above, which restricts us from doing our calculations on the fly. The user cannot manipulate the topography and observe changes in climate in real-time. Therefore we have to work with pre-calculated data. After communication with Dr. Omer Sen, professor of Climate Sciences at Istanbul Technical University, we have selected the case studies which we believed would cause major differences in climate and help the users learn and understand the concepts and cause and effect relations better. The procedure of preparing the data was as follows: We have changed the z coordinate of the grid points where the terrain is manipulated. The manipulated mesh is then inputed to the climate simulation program. The simulation program generates a new output file which contains precipitation, humidity, cloud water, temperature, vorticity and wind velocity values corresponding to the days in the previously simulated data for the original terrain structure. The output file has been processed by our system. The manipulated data for all of these case studies have been processed by the simulation program. As we examined the results of our program, we have realized that the most striking results came out to be for the cases: lowering the North Eastern Mountains in Turkey and making the mountains in the Antalya region higher.

Lowering the Northern Mountains in Turkey:

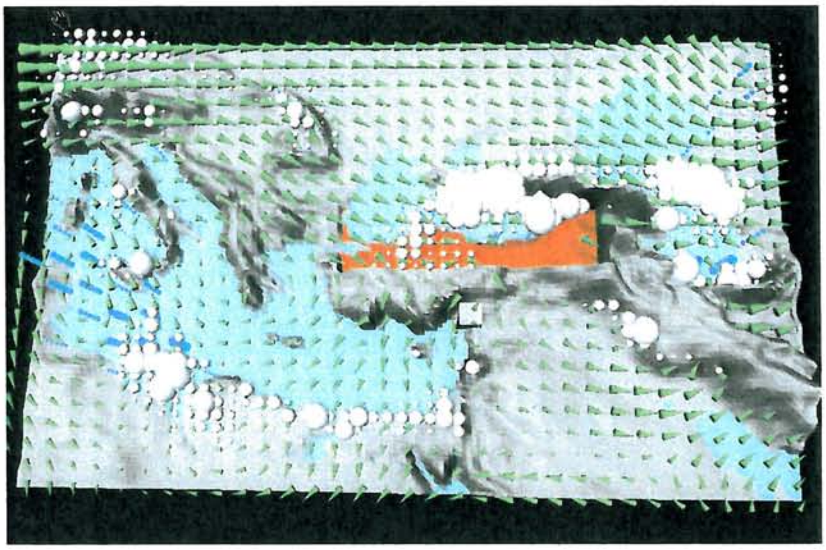


Figure 3.13. *Before* picture showing the climate data before the mountains in the north of Turkey were removed.

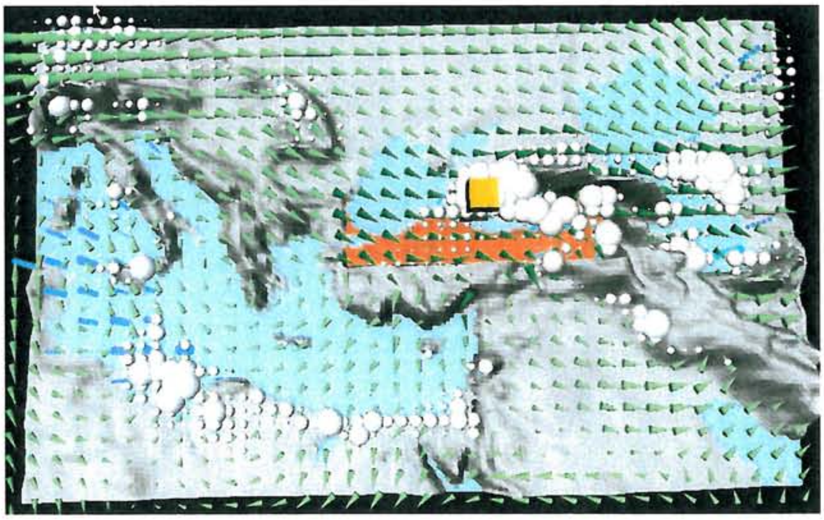


Figure 3.14. *After* picture showing the climate data after the mountains in the north of Turkey were removed

When the mountains in the north of Turkey were removed, the clouds and rain moved south, revealing the fact that clouds and rain in that region are formed by the winds coming from the north colliding with the mountains. Since the mountains are moved south, the rain and clouds also move south. This fact is shown in an interactive way with our proposed system. First the *before* picture appears on the screen with the old information appearing on the map (Figure 3.13). The terrain has been manipulated and the changed part has been colored orange to make it clear. As the user travels over the surface with the guidance of the haptic feedback, the visual and haptic depiction of old data is gradually replaced with that of the new data. As the new data appears, the user can make interpretations about the cause and effect relations between climate variables and better understand the variations in climate due to changes in terrain.

Making the mountains in the Antalya region higher

We increased the height of the mountains in the Antalya region and observed the changes.

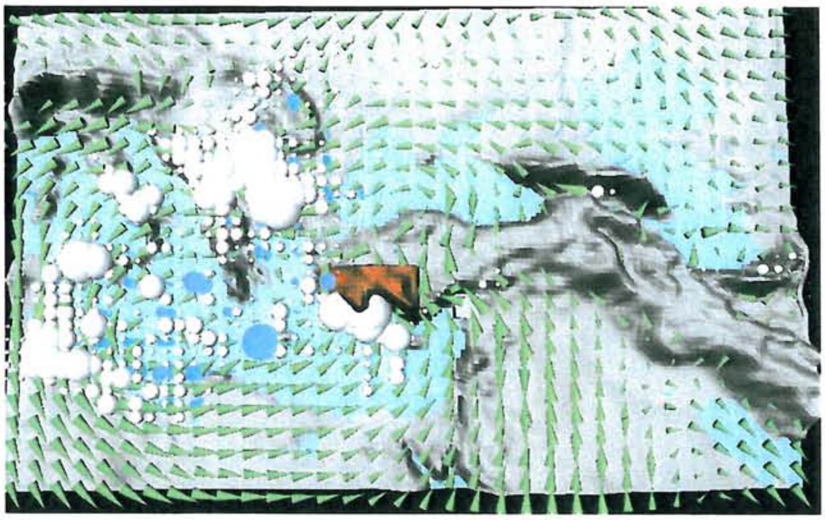


Figure 3.15. *Before* picture showing the climate data before the mountains in the Antalya region were made higher.

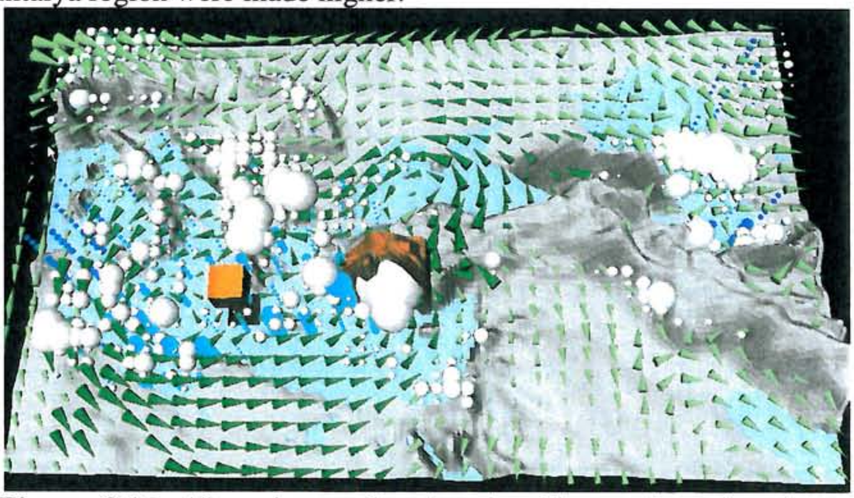


Figure 3.16. *After* picture showing the climate data after the mountains in the Antalya Region were made higher.

In this case, the modification caused the circulation in the west part of Turkey to get slightly larger in radius and result in more rain and clouds as the circulating wind hit the higher mountains.

In both cases, haptics lets the user explore the information in a more controlled and conscious way giving her/him guidance to investigate the relationships among different climate variables as well as the effect of terrain on the climate. It helps the user observe information in a time sequence rather than being exposed to all at the same time. It also divides the information into two channels: visual and haptic facilitating the digestion of the data more easily. The validity of these statements was tested via human experiments which will be discussed in Chapter 4.

Chapter 4

EXPERIMENTS

In order to investigate the role of haptics in the user's perception and learning, we have designed five experiments where the user explores the climate system around Turkey for different time periods and tries to figure out the cause and effect relationships between different geographic and climatic variables.

Design: Twenty-two human subjects participated to the experiments. Subjects were divided into two groups (eleven in each group): Group 1 and Group 2. Only visual feedback (V) was displayed to the subjects in Group 1 whereas visual and haptic feedback (V+H) was displayed together to the subjects in Group 2.

4.1 Experiment I: *Wind*

Goal: The goal of this experiment is to investigate whether haptics helps the user perceive and remember the directions of the wind mapped on a geographic data better.

Stimuli: In the visual version of this experiment, as the user explores the surface, she/he sees arrows appearing gradually on the screen corresponding to winds at a certain pressure level. The size and the direction of the arrows show the magnitude and the direction of the wind force respectively. The goal of the user is to explore the whole surface until all the arrows are visible on the screen.

In the haptic version of the same experiment, in addition to seeing the wind arrows, the user feels the magnitude and direction of the wind forces in real time through the haptic device. The mapping of the winds to force was explained in Section 3.1. Also, haptic feedback snaps the user onto the pressure surface during the exploration by applying a spring force when the user wants to rise in the z direction.

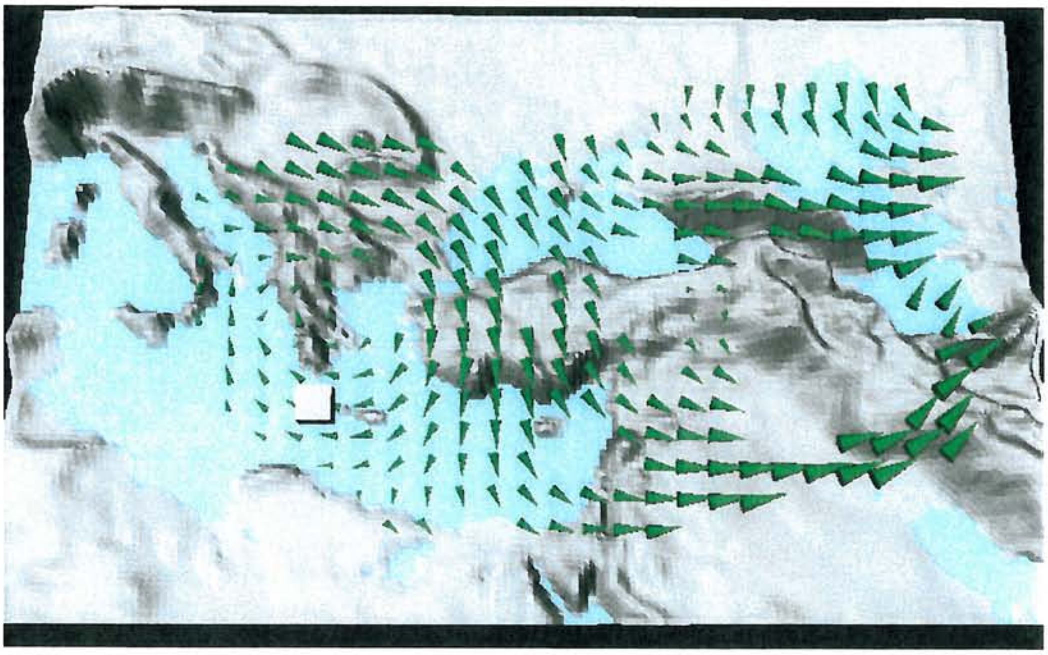


Figure 4.1 User exploring the surface in Experiment 1.

Procedure: Before starting the experiment, the user is given a handout explaining the procedure. The users are instructed to explore the whole surface until all the arrows are visible on the screen. After all the arrows are visible, the visual and haptic displays are turned off, and the users are given six different wind maps (see Figure 4.1) and asked to match the map they just explored to one of the six maps by ranking their three best choices.

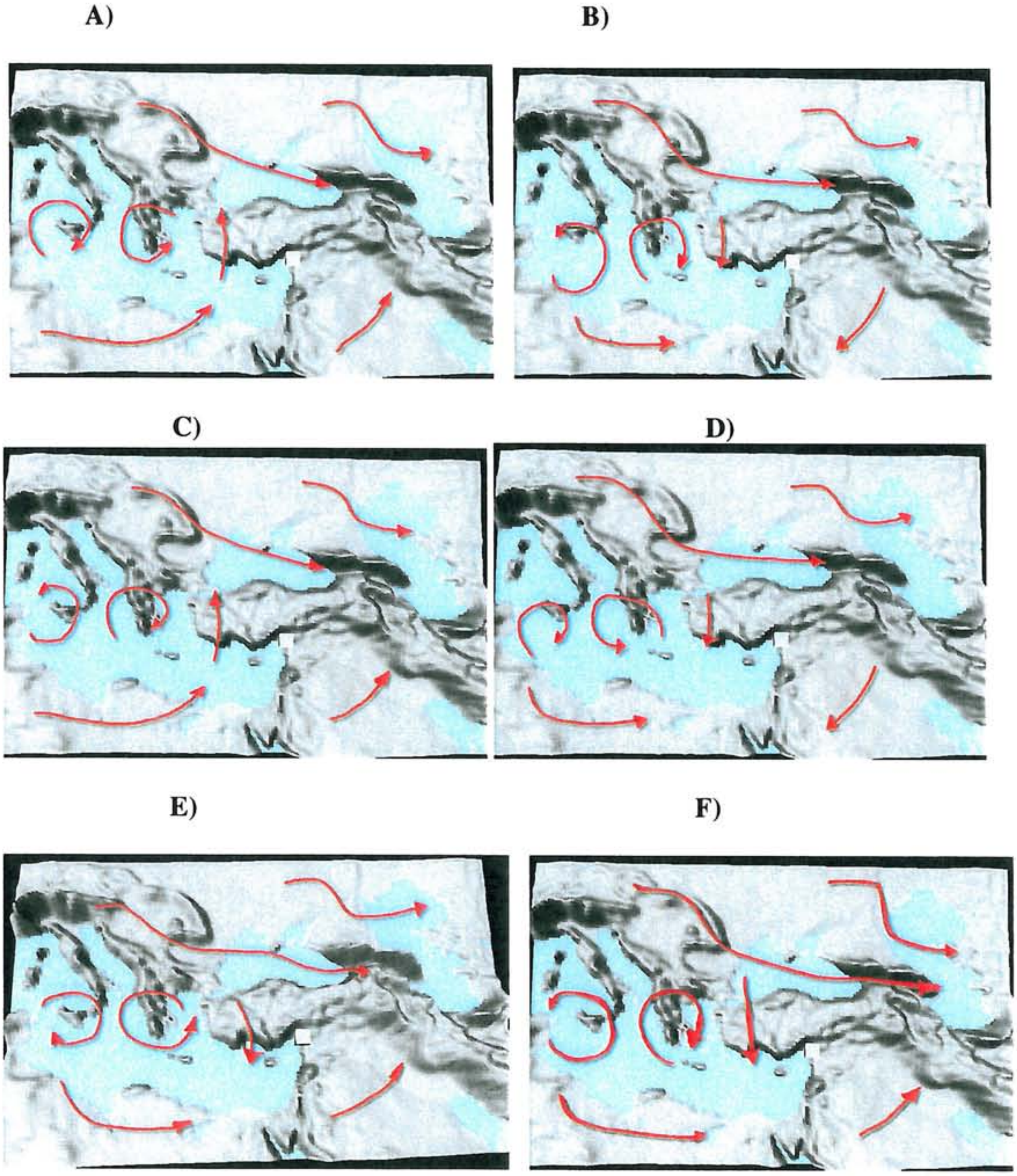


Figure 4.2. The maps displayed to the user after the exploration of winds in Experiment

Results:

Table 4.1. The results of the Experiment 1. The second column of the table, 1st choice, represents the number of subjects in each group who chose the correct answer "F" as their first choice. The third column of the table, 2nd choice, represents the number of subjects in each group who chose the correct answer "F" as their second choice. The fourth column of the table, 3rd choice, represents the number of subjects in each group who chose the correct answer "F" as their third choice. Raw score is calculated by adding up the number of users who chose "F" in any of their choices in each group. Penalty based score is calculated by assigning "+3" to the first choice, "+2" to the second choice and "+3" to the third choice.

	1st choice	2nd choice	3rd choice	Raw score	Penalty based score
V	5	2	0	7/11	19/33
V+H	7	1	2	10/11	24/33

4.2 Experiment 2: *Cloud Formation*

Goal: The goal of this experiment is to investigate whether the guidance of the haptic helps the user find the locations of the clouds by interpreting a statement given about the cause and effect relation between humidity, wind, temperature and formation of clouds.

Stimuli: In this experiment, humidity was represented by the size of the information box coupled to the cursor while the temperature was represented by the color of the box. (Warm to cool: red, orange, yellow, white and blue) Also, as the user explores the surface wind arrows start appearing on the screen like in the previous experiment. On the screen, the user observes five different locations each assigned a number and the user is asked to choose the regions where she/he thinks clouds are likely to occur, in the light of the information given in the handout.

In the haptic version of the experiment, the same mappings are used for temperature and humidity with the addition of the haptic feedback for feeling the winds. The guidance of the winds forces the user to follow the path of the winds and interpret the given information better to determine in which of the regions clouds are likely to occur.

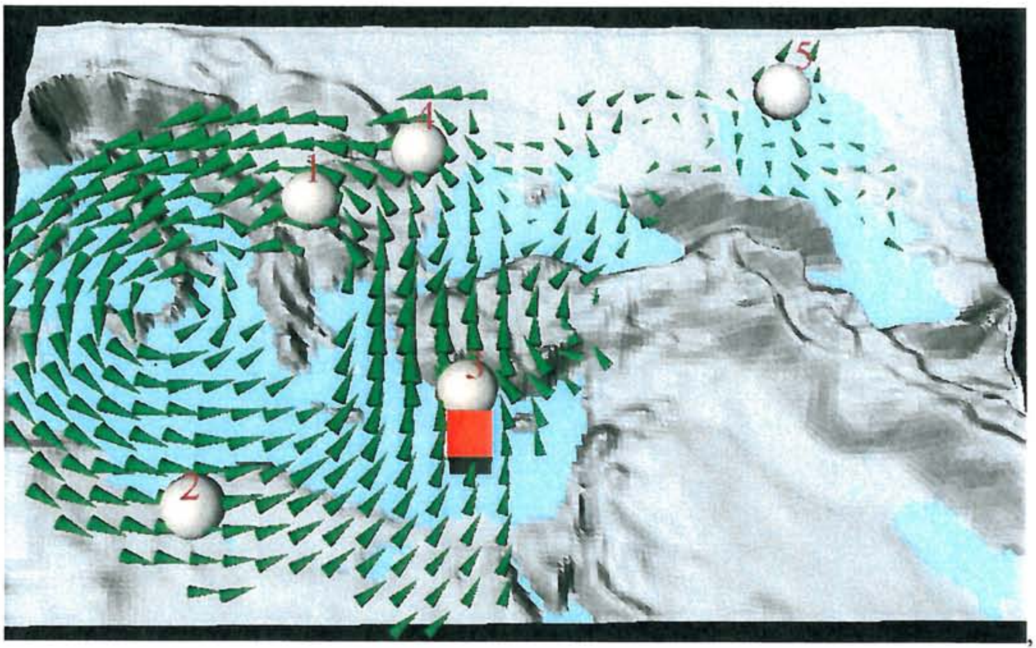


Figure 4.3. User trying to decide in which of the cloud figures clouds are likely to form in Experiment 2.

<u>Procedure</u>: Before the experiment, the subject is given a handout explaining that she/he will investigate the cause and effect relationships between humidity, wind, temperature and formation of clouds in the experiment. He is given the statement *"Wind carries humidity. If* *the wind has enough humidity and enters into a* <u>*relatively*</u> *cooler region, clouds form."* After reading this statement, the subject is asked to explore the wind surface and decide which of the five regions clouds are likely to form. Subjects are allowed to choose as many regions as they like.

<u>Results</u>: The correct answer was the regions 1, 3 and 4. The distribution of the subjects' responses is given below:

Visual:
Two subjects: 1-3-4
Two subjects: 1-2-4
Two subjects: 1-2-3-4
Three subjects: 1-4
One subject: 1-2-4-5
One subject: 4

Haptic:
Nine subjects: 1-3-4
One subject: 1-2-4
One subject: 1-4

Table 4.2. The percentage of the correct responses in Experiment 2. The raw scores represent the perfect answer (1-3-4) while the penalty based scores are calculated by assigning "+1" to each region chosen correctly and "-1" to each wrong region.

	Raw Score	Penalty based score
V	2/11 (18%)	21/33 (64%)
V+H	9/11 (82%)	30/33 (%91)

4.3 Experiment 3: *Cloud Location*

<u>Goal</u>: The goal of this experiment is to investigate whether haptic feedback helps the user construct a link between the cloud location, the wind structure and terrain. Differently from

Experiment 2, no statement is given to the subjects about the relations between climate variables.

Stimuli: In the visual version of the experiment, the user sees clouds appearing on the surface together with the wind arrows. First, the user explores the whole surface until all the arrows and clouds are visible on the screen and then the user is given the same system, but this time without the clouds appearing on the surface and is asked to guess the location of three cloud clusters in five trials. As the user explores the surface, only the wind arrows appear on the screen.

In the haptic version of the same experiment, the user is able to feel the winds and the terrain on the surface. Also, "Fourier Series" texture is haptically mapped onto the surface to represent the clouds during the exploration along with the visual sphere representations. The wavelength and height of the texture is directly proportional to the cloud water values at the grid points. Thus, as the user explores the surface she/he will feel bumps where significant amount of cloud water exists. The user will feel smaller bumps for smaller cloud water values and larger bumps in regions where the cloud water value is high. After the exploration is completed, (the second part of the experiment) the same system is given where the user feels the wind forces and terrain structure while exploring but does not visualize the clouds and feel the texture (the information related to clouds is hidden like in the visual case). Again, the user is asked to find the location of the cloud clusters.

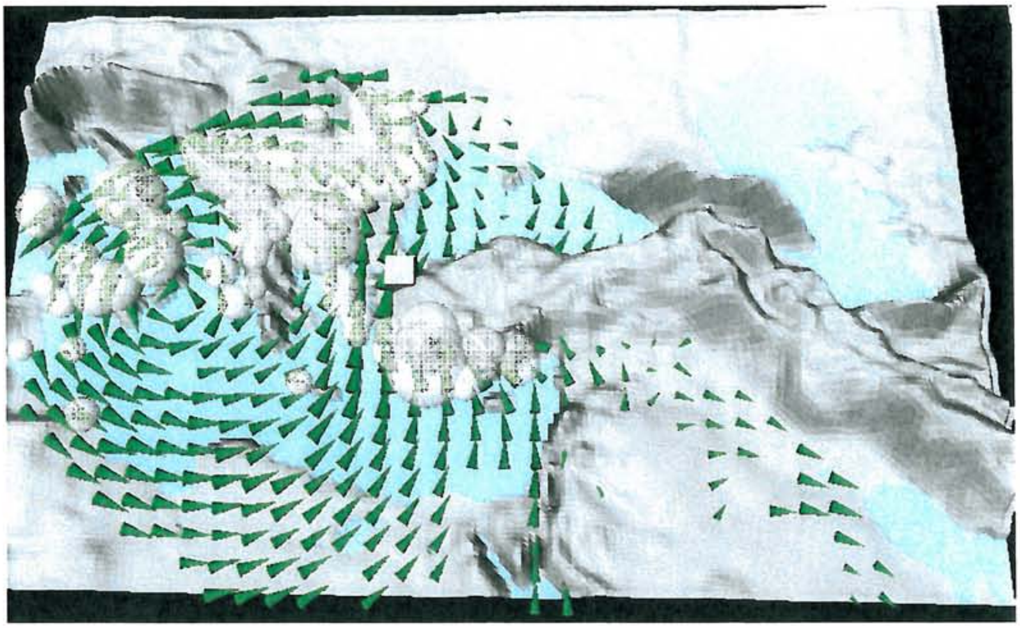


Figure 4.4 Clouds and wind arrows forming as the user explores the surface in Experiment 3.

Procedure: Before the experiment, the subject is given a handout explaining the procedure. Once all the arrows and clouds fully appear on the screen the haptic and visual displays are turned off and she/he is asked to answer the following question:

Which of the statements below is true?

a) Clouds occur in regions of clockwise circulation
b) Clouds occur in regions of counterclockwise circulation
c) Clouds don't occur in regions of circulation
d) Clouds occur both in regions of clockwise and counterclockwise circulation
e) Clouds occur in regions where the wind collides with the mountains.

In the second part of the experiment, the user is given the same system, but this time without the visual and haptic representation of the clouds. A cloud structure is virtually coupled to the cursor and the user is able to drop this structure at any location on the geographic map by pressing the 'S' button. She/he is given five clouds and is asked to place the clouds at the places where he thinks the major clouds are located.

Results: The correct answer for the first part of the experiment was the choices B and E (refer to the question above). The distribution of the subjects' responses is given below:

Visual:

A: 1 subject
B: 3 subjects
C: 3 subjects
D: 3 subjects
E: 1 subject

Haptic:

A:
B: 2 subjects
C:
D:
E:
B-E: 9 subjects

Table 4.3. The results for Experiment 3 (Part 1). The penalty based score was calculated by assigning "+1" to each correct answer (i.e. to each "B" or "E" chosen by the user) and "-1" is assigned to each wrong answer (i.e. to each "A","C" or "D" chosen by the user).

	Raw Score	Penalty based score
V	0/11 (0%)	-3/22 (-14%)
V+H	9/11 (82%)	20/22 (91%)

Table 4.4. The results for Experiment 3 (Part 2). The results in each column, TrialX, represent the average of positional error made by the subjects in locating the cloud cluster (with the variation across the subjects). To calculate the positional error for each trial, we have calculated the center of mass of each cloud cluster, we have calculated the distance from the trial cloud to each of the three center of masses and we have chosen the smallest of these three distances. The last column shows the variation across the trials.

	Trial1	Trial2	Trial3	Trial4	Trial5	mean
V	20.34±12.91	24.42±10.68	25.19±11.83	20.47±12.62	25.08±10.42	23.10±2.48
V+H	25.76±18.72	29.12±4.63	28.57±9.34	26.98±14.56	28.01±11.78	27.69±1.34

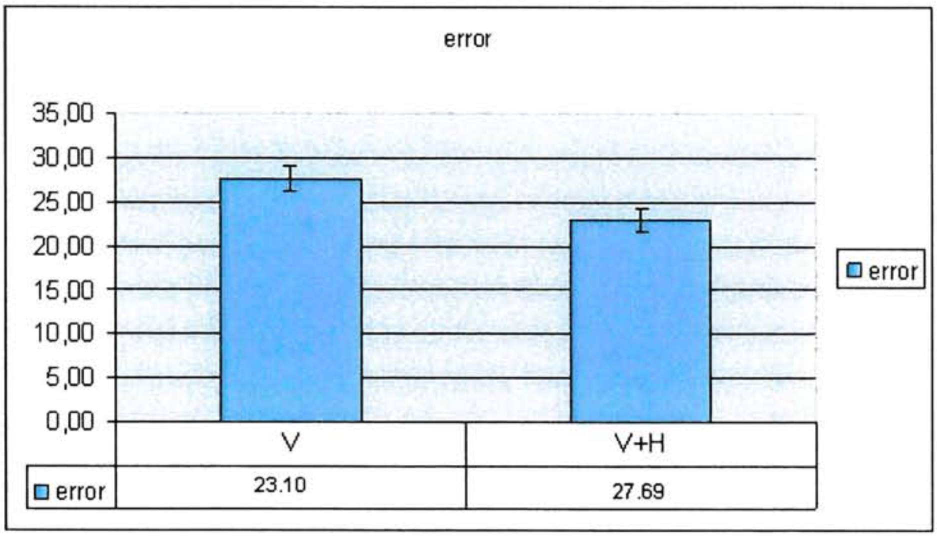


Figure 4.5 The average of positional errors for cloud location in Experiment 3 (Part 2). To calculate the error made by each subject in locating the clouds, clouds are clustered first and then the center of mass of each cluster is identified. The error is defined as the distance from the point marked by the user to the center of mass of the nearest cloud cluster. The addition of haptic feedback improved the response significantly ($p<0.01$).

4.4 Experiment 4: *Rain*

Goal: The aim of this experiment is to investigate whether haptic feedback helps the user realize that the air must rise (vorticity being positive and high) in order for rain to occur and observe the changes in other climate variables, like temperature and humidity, during the rain formation.

Stimuli: In this experiment the user investigates the formation of rain. Five cylinders in vertical position are displayed to the user on the screen. If she/he enters each of them she/he is able to investigate whether or not rain forms in there. The five cylinders are located in such a way that each of them has different characteristics in terms of humidity, vorticity, wind structure and rain formation.

In the haptic version of the experiment, there is a resistive spring force $F=-k*\Delta z$ at each point inside the cylinder. The spring constant k is inversely proportional with the vorticity force (the force lifting the air upward). If the vorticity force is weak in the cylinder, k is large, thus the user is not able to lift from the pressure surface. If the vorticity force is strong on the other hand, k is small, thus there is a smaller resistive force as the user lifts from the surface. Moreover, if he enters the cylinders and moves up, he feels side forces inhibiting from going out of the cylinder creating a tunnel effect. In the cylinders where he can lift, rain starts to fall if the air has enough humidity (if the information box is large). Also, the user is able to feel the circulating wind forces around the cylinder.

The visual version of the experiment is similar, except that the user is not able to feel any forces including the ones in the cylinders. However, to create the experimental conditions matching the haptic case, the positional displacements of the visual cursor have been adjusted based on the vorticity values inside cylinders. (e.g when the vorticity force is weak, the visual cursor does not move up much. In fact, even if the haptic cursor moves up the visual cursor does not move at all if a certain threshold is exceeded).

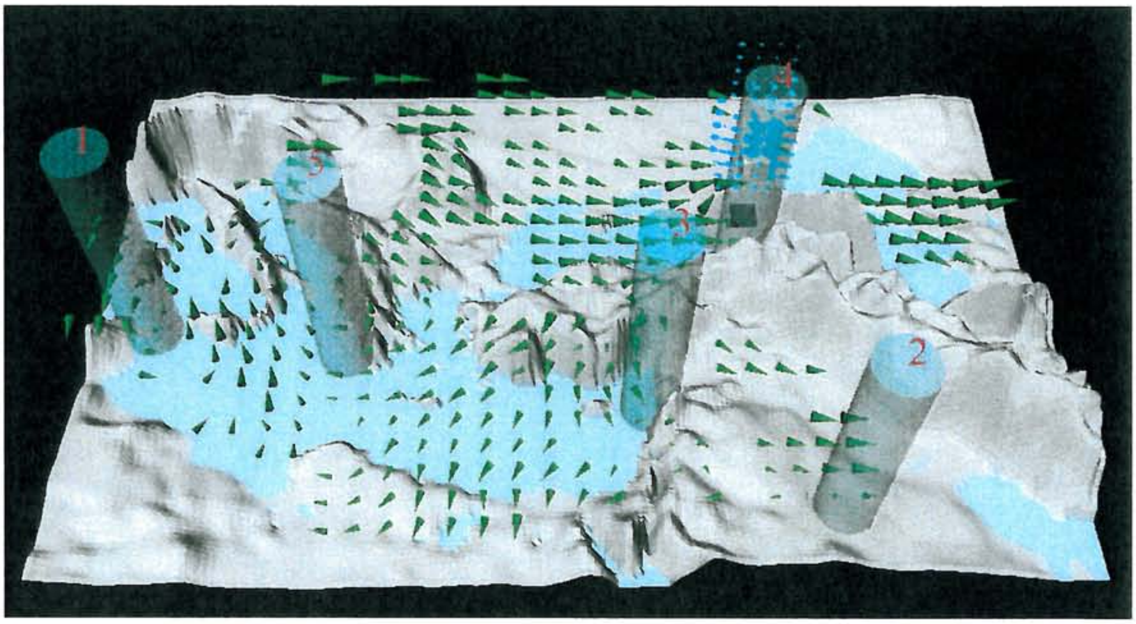


Figure 4.6 Rain forming as the user enters the cylinders in Experiment 4.

<u>Procedure</u>:

At the end of the exploration, the user is asked to answer the following questions for each cylinder: (The answers are marked with bold)

Cylinder 1. Why does rain occur?

Reasons:

1) temperature change: INSIGNIFICANT **SIGNIFICANT**

2) humidity when cylinder is entered: INSIGNIFICANT **SIGNIFICANT**

3) wind inside cylinder is able to rise : **YES** NO

Which of the below are true for this region?

a) clockwise circulation
b) **counterclockwise circulation**
c) no circulation
d) wind collides with terrain
e) wind doesn't collide with terrain

Cylinder 2. Why doesn't rain fall?

Reasons:

1) temperature change: **INSIGNIFICANT** SIGNIFICANT

2) humidity when cylinder is entered: INSIGNIFICANT **SIGNIFICANT**

3) wind inside cylinder is able to rise : YES **NO**

Which of the below are true for this region?

a) clockwise circulation
b) counterclockwise circulation
c) no circulation
d) wind collides with terrain
e) wind doesn't collide with terrain

Cylinder 3. Why is there little rain?

Reasons:

1) temperature change: INSIGNIFICANT **SIGNIFICANT**

2) humidity when cylinder is entered: **INSIGNIFICANT** SIGNIFICANT

3) wind inside cylinder is able to rise : **YES** NO

Which of the below are true for this region?

a) clockwise circulation
b) counterclockwise circulation
c) no circulation
d) wind collides with terrain
e) wind doesn't collide with terrain

Cylinder 4. Why does rain occur?

Reasons:

1) temperature change: INSIGNIFICANT **SIGNIFICANT**

2) humidity when cylinder is entered: INSIGNIFICANT **SIGNIFICANT**

3) wind inside cylinder is able to rise : **YES** NO

Which of the below are true for this region?

a) clockwise circulation
b) counterclockwise circulation
c) no circulation
d) wind collides with terrain
e) wind doesn't collide with terrain

Cylinder 5. Why doesn't rain occur?

Reasons:

1) temperature change inside cylinder: **INSIGNIFICANT** SIGNIFICANT

2) humidity when cylinder is entered: **INSIGNIFICANT** SIGNIFICANT

3) wind inside cylinder is able to rise : YES **NO**

Which of the below are true for this region?

a) clockwise circulation
b) counterclockwise circulation
c) no circulation
d) wind collides with terrain
e) wind doesn't collide with terrain

Then the user is asked to fill in the following table to explore the relationship between terrain, temperature, humidity, rising force and rain by putting checkmarks.

Rain occurs when:

Air can rise	Air cannot rise
There is clockwise circulation	There is counterclockwise circulation
Wind collides with terrain	There is no circulation and wind doesn't collide with terrain
There is no significant temperature drop	There is a significant temperature drop
Wind has insignificant humidity	Wind has significant humidity

When rain occurs:

Humidity drops	Humidity rises	Humidity stays the same

After filling out this questionnaire, a new case with four different cylinders is displayed. The user is then asked to predict in which of the cylinders rain is likely to form. The user is also given the picture of the previously explored system (i.e. the training system) and is asked to respond to the following question for each cylinder in the new system.

Cylinder `?`

a) no rain will occur
b) little rain will occur
c) a lot of rain will occur

Which cylinder shown in the training system is similar to this cylinder? Give two answers you think will match best.

Best match: 1 --- 2 --- 3 --- 4 --- 5
Second match: 1 --- 2 --- 3 --- 4 --- 5

Results:

Table 4.5. The distribution of the results of the visual only (V) experiment for the training system in Experiment 4 (Part 1). Correct answers are shown with bold.

		Cylinder 1	Cylinder 2	Cylinder 3	Cylinder 4	Cylinder 5
Temperature change	Insignificant	0	**8**	6	7	**8**
	Significant	**11**	3	**5**	**4**	3
humidity	Insignificant	3	7	**8**	8	**7**
	Significant	**8**	**4**	3	**3**	4
Wind can rise	yes	**8**	3	**4**	**8**	7
	no	3	**8**	8	3	**4**
question	A	0	1	1	0	**11**
	B	**10**	1	1	0	0
	C	0	**7**	**7**	10	0
	D	1	1	2	**4**	0
	E	0	1	1	0	1

Table 4.6. The distribution of the results of the visual and haptic feedback together (V+H) experiment for the training system in Experiment 4 (Part 1). Correct answers are shown with bold.

		Cylinder 1	Cylinder 2	Cylinder 3	Cylinder 4	Cylinder 5
Temperature change	Insignificant	0	**10**	0	0	**10**
	Significant	**11**	1	**11**	**11**	1
humidity	Insignificant	0	0	**11**	1	**7**
	Significant	**11**	**11**	0	**10**	4
Wind can rise	yes	**11**	0	**11**	**11**	0
	no	0	**11**	0	0	**11**
question	A	0	0	0	1	**11**
	B	**10**	1	2	0	0
	C	0	**10**	**7**	4	0
	D	1	0	4	**9**	2
	E	1	2	1	0	0

Table 4.7. The summary of the results for the question related to the temperature change (training system) in Experiment 4 (Part 1).

	Temperature change inside cylinder				
	Cylinder 1	Cylinder 2	Cylinder 3	Cylinder 4	Cylinder 5
V	11/11 (100%)	8/11 (73%)	5/11 (45%)	4/11 (36%)	8/11 (73%)
V+H	11/11 (100%)	10/11 (91%)	11/11 (100%)	11/11 (100%)	10/11 (91%)

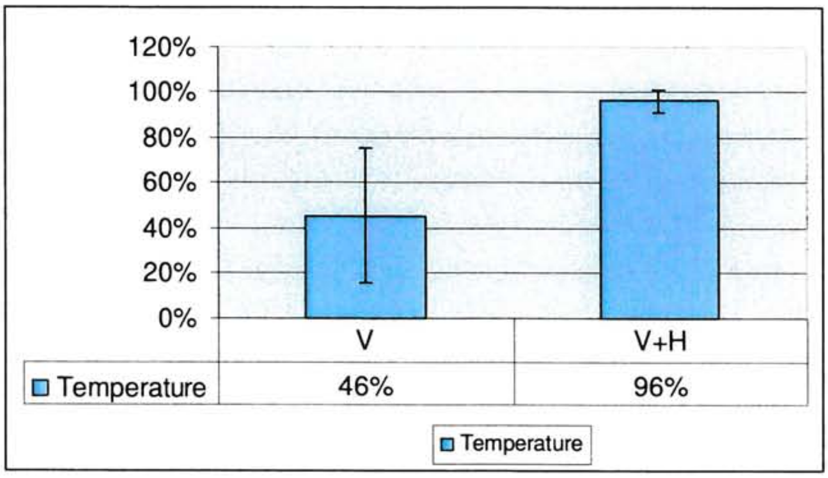


Figure 4.7 The average of percent correct responses for the question related to temperature change in Experiment 4 (Part 1). The addition of haptic feedback improved the response significantly ($p<0.05$).

Table 4.8. The summary of the results for the question related to the humidity (training system) in Experiment 4 (Part 1).

Humidity when cylinder is entered

	Cylinder 1	Cylinder 2	Cylinder 3	Cylinder 4	Cylinder 5
V	8/11 (73%)	4/11 (36%)	8/11 (73%)	3/11 (27%)	8/11 (73%)
V+H	11/11 (100%)	11/11 (100%)	11/11 (100%)	10/11 (91%)	7/11 (64%)

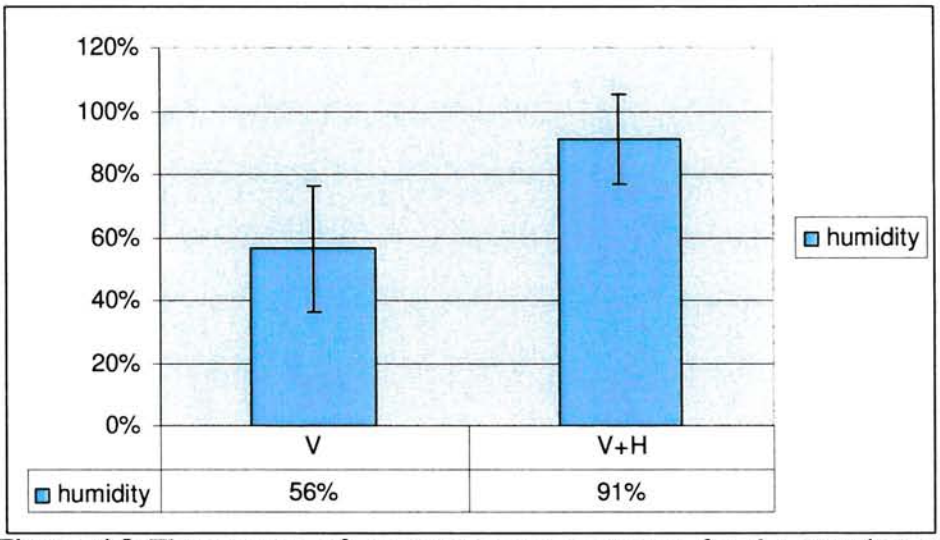


Figure 4.8 The average of percent correct responses for the question related to humidity in Experiment 4 (Part 1). The addition of haptic feedback improved the response significantly ($p<0.05$).

Table 4.9. The summary of the results for the question related to the wind inside the cylinders (training system) in Experiment 4 (Part 1).

	Wind inside cylinder is able to rise				
	Cylinder 1	Cylinder 2	Cylinder 3	Cylinder 4	Cylinder 5
V	8/11 (73%)	8/11 (73%)	4/11 (36%)	8/11 (73%)	4/11 (36%)
V+H	11/11 (100%)	11/11 (100%)	11/11 (100%)	11/11 (100%)	11/11 (100%)

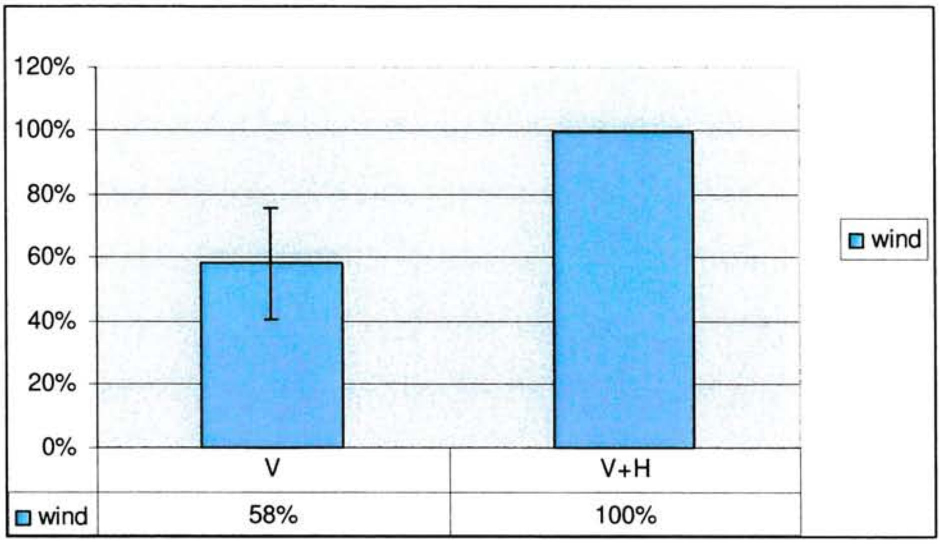


Figure 4.9. The average of percent correct responses for the question related to the wind inside the cylinders Experiment 4 (Part 1). The addition of haptic feedback improved the response significantly ($p<0.01$).

Table 4.10. The summary of the results for the question related to the reason why rain forms inside the cylinders (training system) in Experiment 4 (Part 1).

	Question				
	Cylinder 1	Cylinder 2	Cylinder 3	Cylinder 4	Cylinder 5
V	10/11 (91%)	7/11 (64%)	7/11 (64%)	4/11 (36%)	11/11 (100%)
V+H	10/11 (91%)	10/11 (91%)	7/11 (64%)	9/11 (82%)	11/11 (100%)

Figure 4.10. The average of percent correct responses for the question related to the reason why rain forms inside the cylinders in Experiment 4 (Part 1). The addition of haptic feedback did not improve the response significantly.

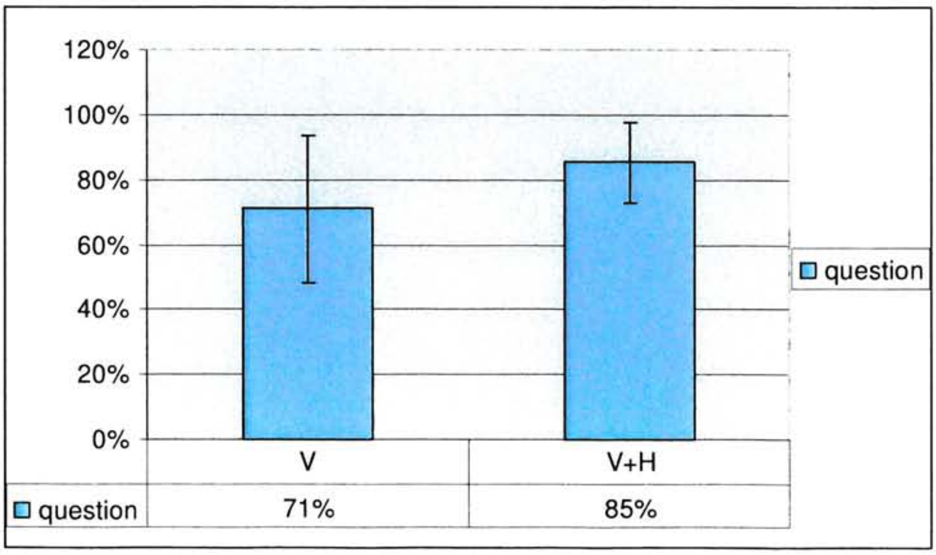


Table 4.11. The results for the questionnaire filled by the subjects in the visual (V) group in Experiment 4.

Air can rise:6 subjects	Air cannot rise:1 subject
There is clockwise circulation: 4 subjects	There is counterclockwise circulation: 8 subjects
wind collides with terrain : 9 subjects	there is no circulation and wind doesn't collide with terrain : 2 subjects
There is no significant temperature drop : 1 subjects	There is a significant temperature drop: 9 subjects
Wind has insignificant humidity: 2 subjects	Wind has significant humidity: 9 subjects

When rain occurs:

Humidity drops 8 subjects	Humidity raises 3 subjects	Humidity stays the same

Table 4.12. The results of the questionnaire filled by the subjects in visual and haptic (V+H) group in Experiment 4.

Air can rise: 11 subjects	Air cannot rise
There is clockwise circulation	There is counterclockwise circulation: 10 subjects
wind collides with terrain: 10 subjects	there is no circulation and wind doesn't collide with terrain
There is no significant temperature drop	There is a significant temperature drop: 11 subjects
Wind has insignificant humidity	Wind has significant humidity:11 subjects

When rain occurs:

Humidity drops:11 subjects	Humidity raises	Humidity stays the same

Table 4.13. The summary of the results of the questionnaire in Experiment 4.

	Air can rise	Ccw rotation	Wind collides with terrain	Significant temperature drop	Significant humidity	Humidity drops
V	6/11 (55%)	8/11 (73%)	9/11(82%)	9/11(82%)	9/11(82%)	8/11(73%)
V+H	11/11(100%)	10/11(91%)	10/11 (91%)	11/11(100%)	11/11(100%)	11/11(100%)

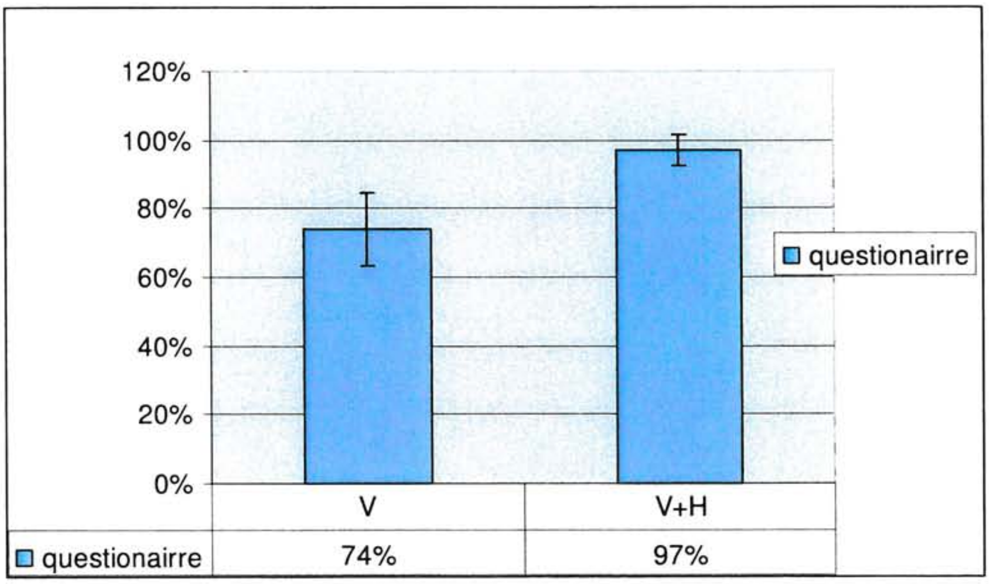


Figure 4.11. The percent correct response of the subjects filling the questionnaire in Experiment 4. The addition of haptic feedback improved the response significantly ($p<0.01$).

Table 4.14. The correct answers for the Experiment 4 (Part 2).

	Cylinder 1	Cylinder 2	Cylinder 3	Cylinder 4
Rain?	c	b	a	c
Best match	1	3	2-5	4

Table 4.15. The results of the group (V) in Experiment 4 (Part2).

	Cylinder 1	Cylinder 2	Cylinder 3	Cylinder 4
Rain?				
A	1	6	**6**	4
B	4		2	3
C	**6**	5	3	**4**
Best match				
1	**5**	2		
2		3	5	5
3	1	**2**	4	3
4	2	1		**3**
5	2	2	**3**	
2nd match				
1		1		1
2	1	1		
3	1			
4	1		1	
5			2	

Table 4.16. The results of the group (V+H) in Experiment 4 (Part 2).

	Cylinder 1	Cylinder 2	Cylinder 3	Cylinder 4
Rain?				
A		5	**11**	
B		**6**		
C	**11**			**11**
Best match				
1	**9**		1	
2		4	2	
3		**7**	2	1
4				**10**
5	2		**6**	
2nd match				
1	2			
2			2	
3		1		1
4		1	1	
5	1	1	1	1

Table 4.17. The summary of the results for the question on rain forming in Experiment 4 (Part 2).

	Rain forming			
	Cylinder 1	Cylinder 2	Cylinder 3	Cylinder 4
V	6/11(55%)	0/11(0%)	6/11(55%)	4/11(36%)
V+H	11/11(100%)	6/11(55%)	11/11(100%)	11/11(100%)

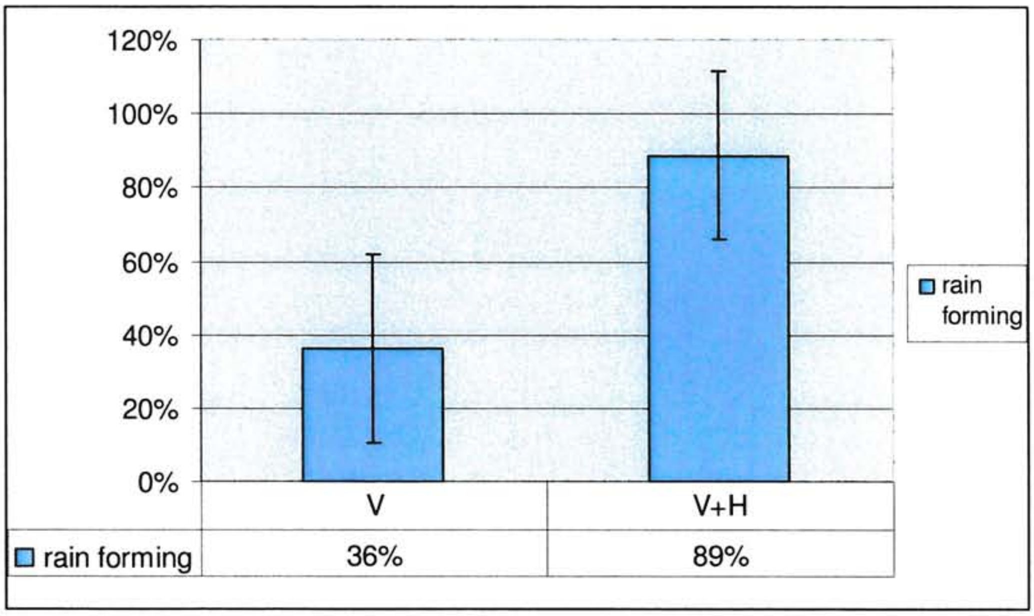


Figure 4.12. The percent correct response on rain forming for Experiment 4. The addition of haptic improved the response significantly ($p<0.05$).

Table 4.18. The summary of the results for the matching part of the Experiment 4(Part 2). The penalty based score is calculated by assigning "+2" to each correct answer chosen as the best match and "+1" to each correct answer chosen as the second match.

	Matching							
	Raw Score				Penalty Based Score			
	Cylinder1	Cylinder2	Cylinder3	Cylinder4	Cylinder1	Cylinder2	Cylinder3	Cylinder4
V	5/11(45%)	2/11(18%)	8/11(73%)	3/11(27%)	10/22(45%)	4/22(18%)	18/22(82%)	6/22(27%)
V+H	9/11(82%)	7/11(64%)	8/11(73%)	10/11(91%)	20/22(91%)	15/22(68%)	19/22(86%)	20/22(91%

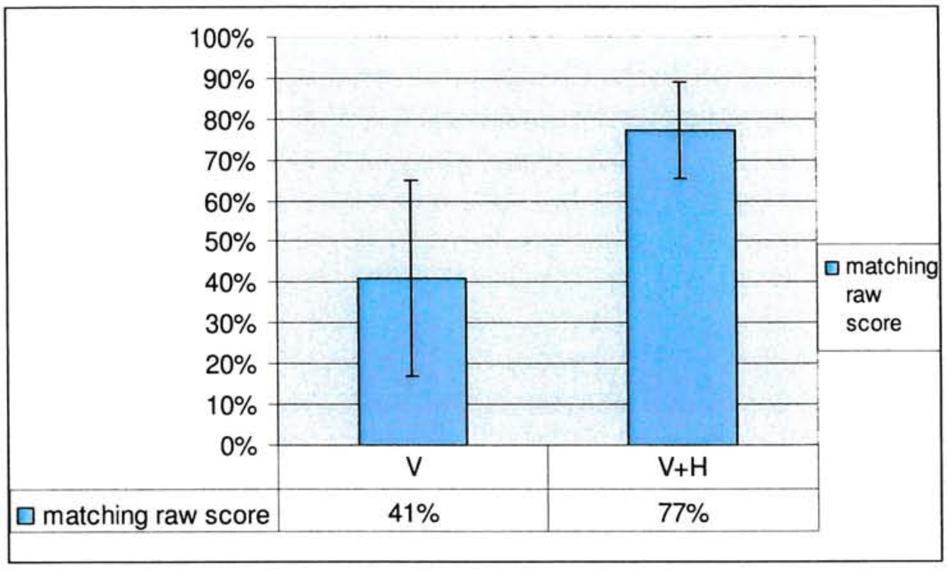


Figure 4.13. The raw scores of the matching part in Experiment 4 (Part 2). The addition of haptic feedback improved the results significantly ($p<0.05$).

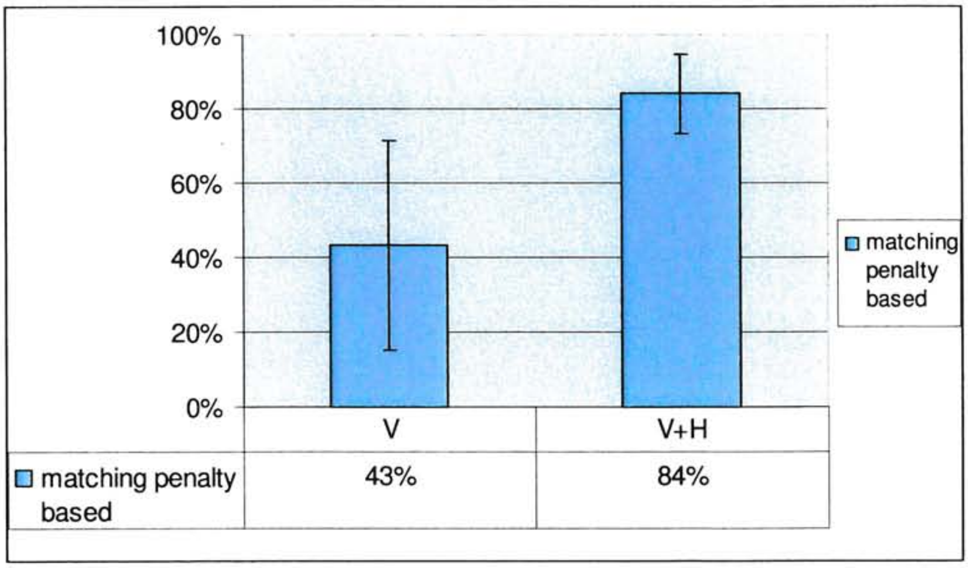


Figure 4.14. The penalty based scores of the matching part in Experiment 4 (Part 2). The addition of haptic feedback improved the results significantly ($p<0.05$).

4.5 Experiment 5: *Terrain Manipulations*

Goal: The visual representations of climate data "before" and "after" terrain manipulation shown on the same map overwhelm the user. This experiment investigates if haptic feedback helps the user understand and interpret the differences between two maps with overloaded information.

Case Study 1: Mountains in the NorthEast region are removed

Stimuli: In the first case study, the mountains in the North East region are removed. The information appearing on the first window is data for the original terrain structure. As the user explores the surface, new information is updated showing the data after the mountains have been removed. The user can go back to the original data at any time instance by pressing on the reset button. She/he can also turn on/off the information for cloud, rain and wind using the check buttons.

For the haptic version, haptic feedback guides the user for exploration. The user is able to feel the winds and the terrain surface while exploring the surface, thus having a better idea about what caused the rain fall or cloud formation.

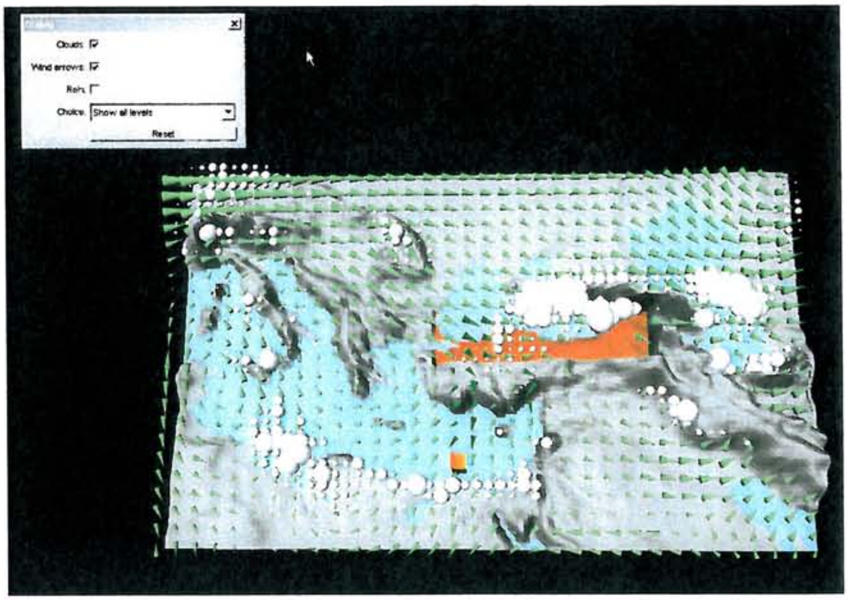


Figure 4.15 The layout of the clouds before the user starts exploring for Experiment 5 (Case Study 1)

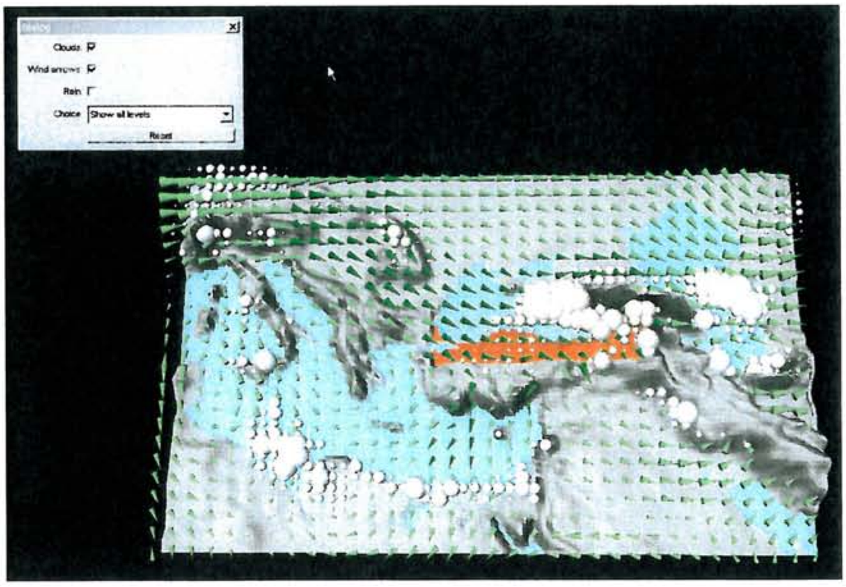


Figure 4.16 The layout of the clouds as the user explores the surface for Experiment 5 (Case Study 1)

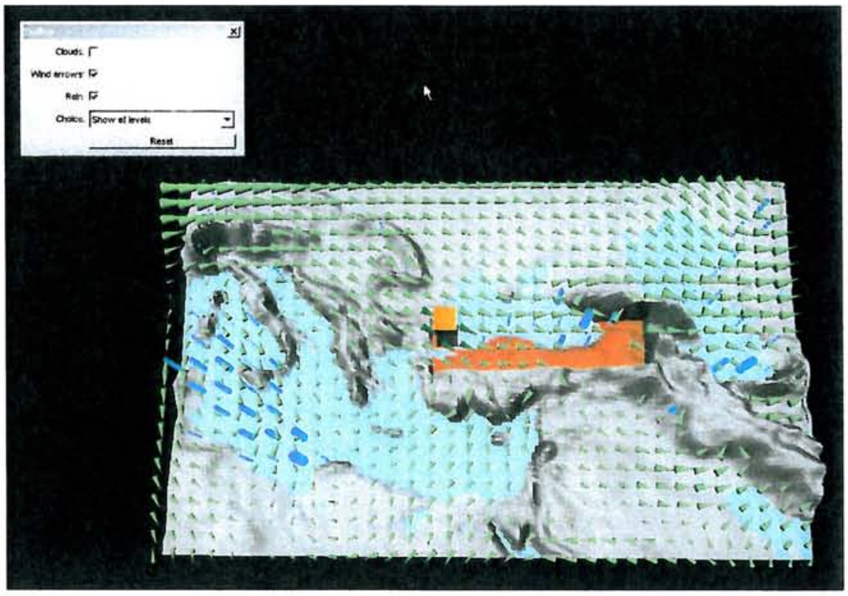


Figure 4.17 The layout of rain before the user starts exploring for Experiment 5 (Case Study 1)

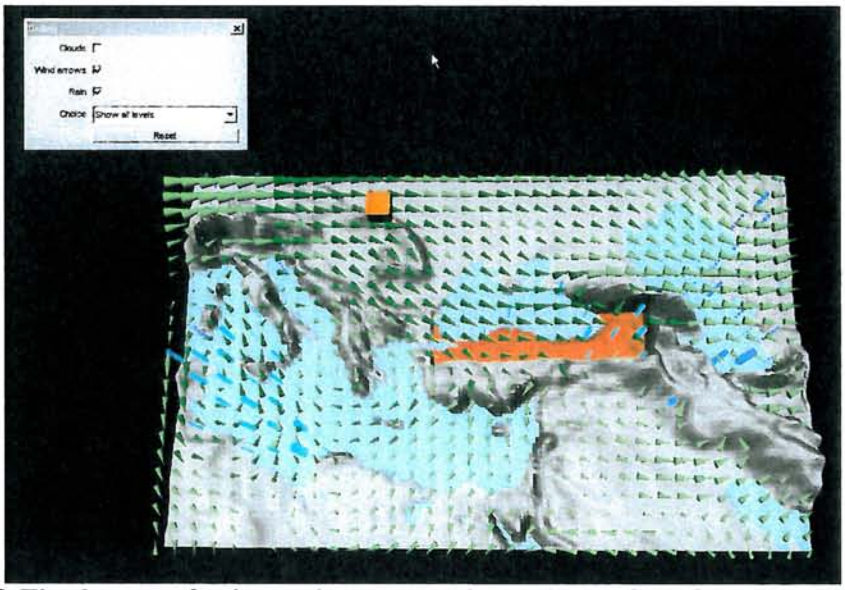


Figure 4.18 The layout of rain as the user explores the surface for Experiment 5 (Case Study 1)

Procedure:

The user is initially given the original system and asked to explore the surface to observe the changes. After the user is finished exploring, she/he is asked to explain the changes by answering the following question, based on the knowledge she/he has gathered from the earlier experiments.

What do you think played a role in the changes that occurred? (You can choose more than one answer)

a) clockwise circulation of the wind
b) counterclockwise circulation of the wind
c) no circulation of the wind
d) wind collides with terrain

Results:

Table 4.19. The results of group (V) for Case Study 1 in Experiment 5.

Why?	a	
Correct answer: d	b	
	c	2
	d	11

Table 4.20. The results of group (V+H) for Case Study 1 in Experiment 5

Why?	a	2
Correct answer: d	b	
	c	1
	d	7

Table 4.21. The summary of the results for Case Study 1 in Experiment 5.

	Why?
V	11/11(100%)
V+H	7/11(64%)

Case Study 2 – Increasing the height of the mountains in the Antalya Region
In this case study the height of the mountains in the Antalya region are increased.

<u>Stimuli:</u> same as Case Study 1

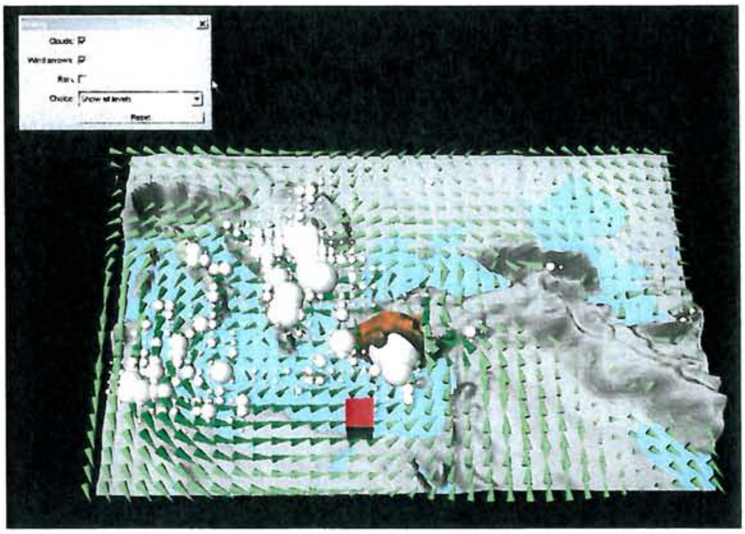


Figure 4.19 The layout of the clouds before the user starts exploring for Experiment 5 (Case Study 2)

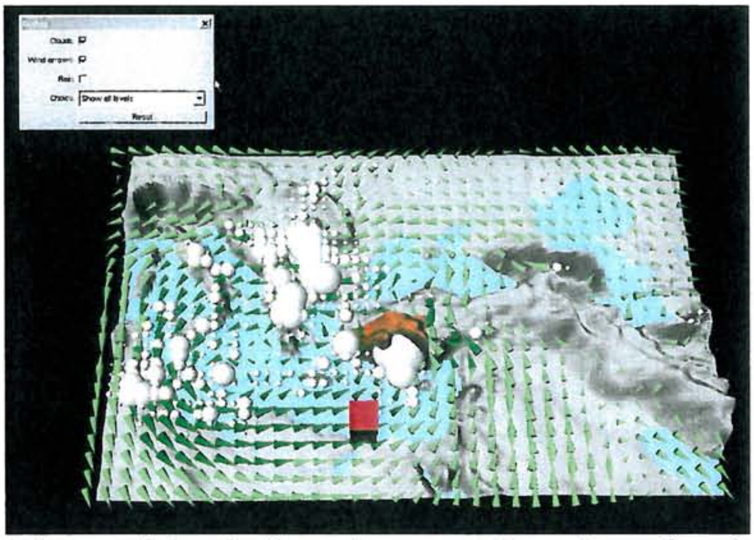


Figure 4.20 The layout of the clouds as the user explores the surface for Experiment 5 (Case Study 2)

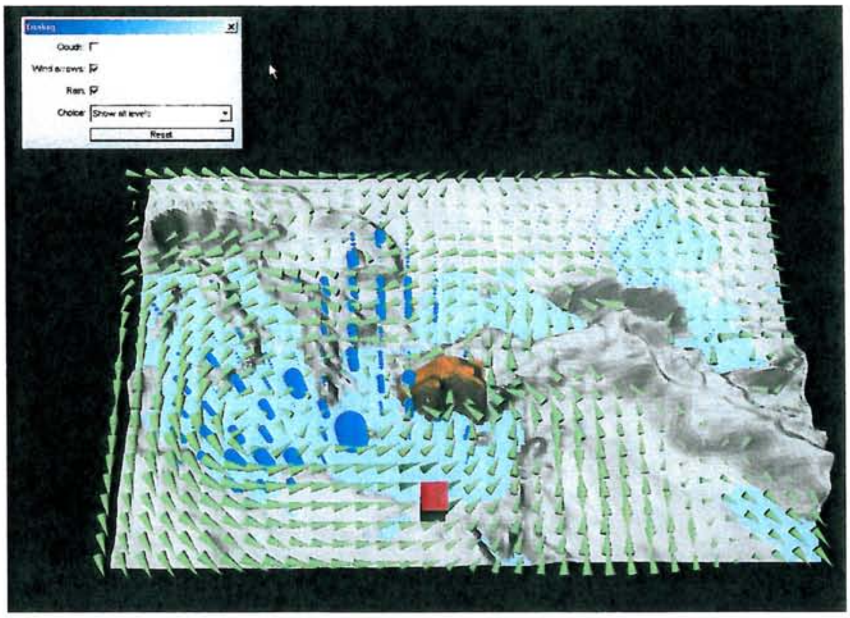


Figure 4.21 The layout of rain before the user starts exploring for Experiment 5 (Case Study 2)

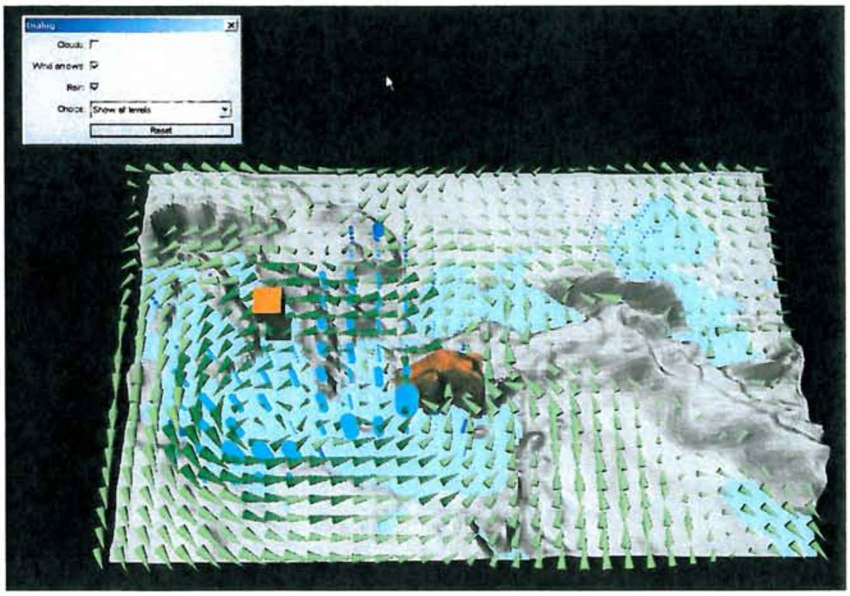


Figure 4.22 The layout of rain as the user explores the surface for Experiment 5 (Case Study 2)

Procedure: same as Case Study 1

Results:

Table 4.22. The results of group (V) for Case Study 2 in Experiment 5.

Why?	a	1
Correct answer: b-d	b	1
	c	4
	d	5

Table 4.23. The results of group (V+H) for Case Study 2 in Experiment 5.

Why?	a	
Correct answer: b-d	b	11
	c	
	d	10

Table 4.24. The summary of the results for Case Study 2 in Experiment 5.

	Why?
V	6/22(27%)
V+H	21/22(95%)

In this chapter we have presented the experiments, including the goal, design, stimuli, procedure and results of each experiment. The raw results were given without explaining how the results are relevant with our hypotheses. These results will be interpreted and discussed in the next chapter.

Chapter 5

DISCUSSION AND CONCLUSION

In our attempt to make real climate data superimposed on a geographic map available to be explored by non-expert users for educational purposes, we have developed a visualization system called CE-Viz (Climate Exploration and Visualization) to merge interactive information visualization techniques with haptics to augment vision, enhance the digestion of data and help the user build memory in a more retainable way.

The developed system significantly improves the user's understanding of cause and effect relations between different climate variables: terrain, wind, humidity, temperature, cloud formation and rain. Since the information is retrieved through different sensory channels in our daily life, it is not unexpected that the developed multimodal system improves the user perception and understanding of the climate data. Rather than overloading the visual channel only, shifting some part of the perceptual and cognitive load to the haptic channel enables the user to digest more information. The results of the human experiments conducted using this system reveal that haptic feedback augments vision in climate visualization while enhancing the learning and digestion of information.

In ***Experiment 1***, we investigated whether haptics helps the user perceive and remember the wind structure mapped on a geographic data better. The results show that haptic feedback helps the user remember the direction of the winds better. The task was highly challenging since the user had to remember the direction of two wind circulations and five different winds. It was observed that the visual explorers reacted completely differently than the haptic explorers when they were given the question after the exploration of winds. The first reaction of most of the subjects who had explored the map visually was "There is no way that I can remember the direction of the winds. I didn't pay any attention". For this reason, some of them made random guesses. On the other hand, the haptic explorers remembered some of the wind structures perfectly especially at the locations where they were exposed to a strong force feedback. We observed that the haptic explorers tried to remember how their hand was guided by the wind forces during the exploration. As a result, they eliminated some of the wrong answers right away.

The users who had the haptic experience remembered the map better because their motor senses were stimulated and they committed to memory the direction and the magnitude of the forces better. For example, it was observed that the haptic user remembered that her/his arm was being circulated in the clockwise direction under the guidance of strong forces, whereas it was harder for the visual user to remember which direction the circulation was. Thus, we can see that even if the user was not told to pay attention on the wind structure, she/he built a haptic memory which helped her/him perceive and remember the wind structure mapped onto the geographic data better.

In ***Experiment 2***, we investigated whether haptic feedback helps the user understand the cause and effect relations between humidity, wind, temperature and formation of clouds. A statement about the relationship between climate variables was given to the subjects and they were asked to find the places where clouds are likely to occur by interpreting the given information. It was observed that when the user was guided by the haptic feedback forcing him to follow the path of the wind, he was able to identify the locations where the temperature dropped along the path of the wind, where the wind entered into a relatively cooler region allowing the clouds to form. On the contrary, in the visual case, the user was able to approach to the same locations from any direction since she/he was not guided by the wind forces. Therefore she/he could not observe the temperature along the path of the blowing winds, since there was a temperature drop along one approaching direction while temperature increased along another direction.

In ***Experiment 3***, it was observed that the haptic explorers learned that clouds formed in areas of counterclockwise circulation and where the circulating wind was colliding with the terrain better than the visual explorers. Also, in the second part of the experiment, when they were asked to locate the cloud clusters, the haptic group performed better. They remembered that the clouds mainly formed inside the circulation and in places where the circulating wind collided with the mountains, whereas the visual users could not remember vividly the wind circulation or the terrain inside the circulation. Furthermore, the texture mapped on the surface at cloud locations captured the attention of the haptic explorer and augmented their perception. On the other hand, it was observed that the visual group made their decisions about the cloud locations based on their geographic knowledge and visual memory. Thus, haptics helped the user form a link between cloud formation, wind structure and terrain even though the user was not told to pay attention on these quantities. Furthermore, the results of this experiment support the results of Experiments 1 and 2.

In ***Experiment 4***, we investigated whether haptic feedback helps the user perceive that the air must rise in order for rain to occur and observe the other climate changes, such as temperature and humidity, during the rain formation. All of the haptic explorers realized that wind inside some of the rain cylinders was able to rise whereas the visual explorers had no clue about the rising force of the rain and answered the related question randomly. The subjects in the haptic group were able to recognize the relation between the wind rise and the resistive force inside the cylinders. Moreover, since the haptic feedback allowed the user to move in a more controlled way inside the rain tunnels, the haptic explorers were able to note the changes in temperature and humidity inside the cylinders better than the visual explorers. After the exploration part of the experiment, the questionnaire filled by the subjects showed that the haptic users were significantly better in remembering the cause and effect relationships in rain formation, although they were not told to pay attention on it.

In the second part of the experiment, the users were given a new case and asked to identify in which of the new cylinders rain was likely to form by applying the knowledge they had learned in the first part (training part). It was observed that the (V+H) group was significantly more successful in locating the cylinders in which rain formed since they could form a mapping in their minds between the rising force provided by the haptic interface and rain formation. Also, this group's results were significantly better in matching the new cylinders with the ones in the first part. Since the haptic users were trained better in the first part, they were more successful in matching the cylinders in the second part. Thus, we can see speculate that when certain differences are rendered in haptics, they stand out better and are remembered better.

In ***Experiment 5***, we have investigated if haptic feedback helps the user understand and interpret the differences between two maps with overloaded information. Given the task of interpreting the changes in climate data when topography was manipulated, we observed that the users who had the haptic training were able to apply their knowledge and make interpretations about why the changes occurred better than the ones who were trained by visual feedback only. The results were especially very significant in the Antalya case

(Section 4.5), where rain increases when the mountains are made higher as a result of counterclockwise circulating wind colliding with the manipulated terrain. Almost all of the haptic users were able to identify the causes of the change due to counterclockwise circulation and wind colliding with terrain. On the other hand, only half of the visual users presumed that the wind colliding with terrain had an impact on the climate causing a change and only one subject was able to realize that counterclockwise circulation played a role in the change. Thus, it can be concluded that haptic feedback helped the users digest information and use the accumulated knowledge to make interpretations.

In conclusion, we can see that haptics can be used as a device to guide exploration which lets the user confine (not completely, but suggestively enough) exploration to a region in which interesting things are happening. Exploring in this confined region focuses attention and improves learning. Also, haptics lets the user guide exploration along certain trajectories which also correspond to cause-effect relationships and one thing happening after another in time. It is possible to approximate these features visually to some extent, but not in a natural way that still allows interactive exploration.

As future work, the terrain can be manipulated using haptic feedback and the effects of this manipulation on the climate can be shown in real time. For this purpose, the climate model must be running in real time which is computationally challenging. Moreover, real time manipulation of the terrain using haptic feedback is not trivial. Another improvement could be the development of multi-resolution models to investigate the climate changes more locally. We believe that the findings we put forward in this thesis can be applied to other domains for educational purposes. Since haptic feedback acts as a tool guiding the user to explore in a controlled way, the method we have suggested tying education, lots of data needing to be represented, haptics and infoviz can also be used in other fields.

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VITA

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