# Using Haptics to Convey Cause and Effect Relations in Climate Visualization

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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.

**KEYWORDS:** Data and information visualization, climate simulation, haptic exploration, multi-modal user interfaces

**INDEX TERMS:** H.1.2 [Models and Principles]: User/Machine Systems - Human factors H.5.2 [Information Interfaces and Presentation]: User Interfaces---Haptic I/O; I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism---virtual reality; I.6.3 [Simulation and Modeling]: Applications; I.2.9 [Artificial Intelligence]: Robotics---operator interfaces, commercial robots and applications.

## 1 INTRODUCTION

In this study, we investigate the integration of haptics and information visualization techniques for improving the exploration of complex, multi-dimensional data. Our particular focus is the discovery and learning of cause and effect relationships between patterns in the data. We investigate the interactive exploration of climate data as our application domain.

The data produced by climate simulation programs typically consists of the values of a set of climate variables such as temperature, humidity, wind intensity and direction, precipitation, and cloud water for a set of grid points in the atmosphere. There are some ten such variables of primary interest, and patterns in and relationships among these variables need to be examined in order to understand and reason about climate phenomena. Climate data at different points in time may need to be explored in order to understand differences and their causes. Furthermore, the presentation of climate data must be superimposed with a two- or three-dimensional depiction of the terrain and other geographical data. All of these make the interactive exploration of climate data a challenging problem. The large number of dimensions and constraints particular to this domain make it hard to devise a compelling purely visual representation which allows efficient and natural exploration while displaying overview information intuitively.

In existing systems for visualizing and manipulating earth science data, such as the Grid Analysis and Display System (GrADS) [1] or the tools developed by the National Center for Atmospheric Research [2], topography is typically represented using contours. Pressure is usually represented on maps using contours corresponding to geopotential heights up to 925 mb. The two sets of superimposed contours in these two-dimensional representations make it time consuming to comprehend the topography, pressure and additional climate data which is also visually represented on the same map. Vectoral quantities such as wind velocity are shown with streamlines consisting of vectors with u and v components in two dimensions for different levels over the surface. Wind velocity is shown for a specific pressure level (e.g. 850mb) and is shown either using streamlines or using arrows with size and direction representing the magnitude and direction of the wind. Scalar quantities like temperature, precipitation, rainfall, vegetation cover and humidity are usually represented using different colors. Because of the large number of dimensions present in climate data, purely visual systems are forced to represent data using separate graphs. This makes it harder to see the relationships between different climate variables.

There are also a variety of interactive forecast visualization tools such as IGrADS [3] or the animating forecast visualization tools used by NASA such as CLIMVIS (The Climate Visualization System) [4]**.** On IGrADS, forecast maps allow the display of four parameters, one color filled and three as “contour line” fields. The interface enables forecasters to pick a wide variety of forecast products in line with the needs of the customers. The user can also determine the maximum and minimum for each parameter as well as the interval, contour color and line thickness.

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A method of visualization that uses painted brush strokes of the Impressionist school of painting to represent multidimensional data elements has been also 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 [5]. This system is successful at displaying an intuitive overview of multidimensional data, but is not targeted at exploration, discovery and learning of patterns and cause and effect relationships.

In other domains, studies have shown that multimodality may serve to communicate data better to users by reducing the cognitive load of any one sense. 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 [6]. Jeong et al. have studied the feasibility of adding haptic and auditory displays to traditional visual geographic information systems [7]. Our work is inspired by these studies, but is different in that our goal is to convey cause and effect relationships in a domain with a larger number of related data dimensions than previous studies.

We present CEVIZ (Climate Exploration and VIsualiZation) a system for the presentation and interactive exploration of climate data. CEVIZ is a prototype tool built to demonstrate how visual and haptic representations, and haptic guidance can be used in coordination in order to improve upon purely visual representations. Design choices in CEVIZ were made in order to test the following hypotheses.

I. Haptics can be used to guide exploration along certain paths that correspond to cause-and-effect relationships, and precedence relationships in time, and, in this way, improve the discovery, learning and retention of these relationships
II. Haptic representations of certain kinds of data can reduce visual overload. Furthermore, augmenting visual representations with haptics improves the perception of data dimensions that do not stand out in purely visual representations.
III. Haptics can be used to help guide and/or confine exploration to areas where interesting phenomena occur. This improves the learning and retention of relationships between these phenomena.
IV. Haptics representations provide significant improvement upon purely visual representations in enabling users to notice and remember relationships between different kinds of data variables when they are not paying explicit attention.

In addition to displaying the climate data to the user through visual and haptic channels, our work makes use of a number of information visualization techniques, for instance, the transparent information cube [8]. We discuss these techniques in Section 3 as we present how each climate data dimension is represented visually and/or using haptics. We do not introduce any novel visual representations; instead, we focus on picking a suitable combination of visual and haptic representations that we tried to optimize for the purpose of getting across cause and effect relationships and minimizing perceptual and cognitive overload.

We designed a set of experiments in order to test the hypotheses listed above. In these experiments, subjects were divided into two groups, one group was provided a purely visual system (V) to explore climate data while the other group used the combined visual and haptics system (V+H). The V+H group consistently performed better at tasks. This and other results support our hypotheses.

In Section 2, we provide preliminary information about the study of climate and climate simulation. In Section 3 we present the CEVIZ system, the design considerations and the visual and haptic representations that we used for different climate dimensions. We describe our experiments and results in Section 4 and discuss these results in Section 5.

## 2 PRELIMINARIES

### 2.1 Climate Data, Cause and Effect Relationships

Climate data is provided by simulation programs at points that lie on pressure surfaces in the atmosphere (i.e. a surface that consists of points in the atmosphere having the same air pressure). Conventionally, pressure surfaces at 500mb, 700mb, 850mb and 925mb are used to study climate data. These pressure surfaces may intersect with the terrain.

The output of a climate simulation program is a set of data points at a certain point in time (most often a given day) on a particular pressure surface. Each data point consists of the following dimensions:

- **x and y coordinates (degrees):** the latitude and longitude of the point (shown from now on by (x,y))
- **p-level height (gpm/geopotential meter, the z coordinate, in km):** the height (altitude) of the pressure surface at (x,y)
- **Precipitation (mm):** rain, snow and other forms of water falling at (x,y)
- **Air temperature (K):** measure of the heat content of the air at (x, y, z)
- **Zonal wind (m/s):** The component of the wind velocity at (x, y, z) along the local latitude, i.e., the x component.
- **Meridional wind (m/s):** The component of the wind velocity at (x, y, z) along the local longitude.
- **Specific moisture (kg/kg):** Humidity of the air at (x,y,z)
- **Cloud water (kg/kg):** The total concentration of ice and liquid water particles in a cloud, if one exists, at (x, y, z)
- **Vorticity (K $m^2$ $kg^{-1}$ $s^{-1}$)**: The force defined as the curl of the wind velocity representing the amount of circulation or rotation.

The following is a list of noteworthy interactions and cause and effect relationships among climate data variables and the terrain.

- When wind has enough humidity and enters into a relatively cooler region, clouds form.
- Clouds occur in regions where winds collide with mountains.
- Clouds occur in areas of counterclockwise wind circulation in the northern hemisphere and in areas of clockwise wind circulation in the southern hemisphere.
- For precipitation to occur, humid air must rise (i.e. humidity and vorticity must be high), there must be a significant temperature drop from a higher pressure level (closer to earth surface) to a lower pressure level.

Learning and internalizing these basic climate-related principles becomes important in two settings. First, while climate non-experts are being taught climate phenomena, they need to develop a working knowledge of these principles in order to be able to use them without much cognitive cost while interpreting climate patterns and climate data at different points in time or for different geographical configurations. Second, while climate experts are analyzing and comparing results of climate simulations, it is desirable to convey to them particular occurrences of the above relationships in a way that does not demand too much of their conscious cognitive attention. This allows them to instead focus on what is different about a particular set of climate data. Demonstrating that haptics-augmented visualization techniques facilitate this learning and internalization is the primary contribution of our work.

## 2.2 Climate Simulation

For the experiments we report in this paper, we use climate data provided by the simulation program RegCM3 [9]. RegCM3 makes use of a three-dimensional, sigma-coordinate, primitive equation climate model.

The simulation program RegCM3 takes as input boundary and initial conditions, which are the specific data values in the region of interest corresponding to the day the climate simulation is started. These include the description of the terrain in the form of a height map, i.e. a set of points of the form (x, y, z) where z is the altitude of the terrain (in km) above sea level at coordinate (x, y) and x and y are given as grid points along west-east and north-south directions respectively. The boundary and initial conditions, including the height map and the vegetation cover for the region we want to investigate were provided by the Eurasia Earth Sciences Institute (AYBE) at the Istanbul Technical University. RegCM3 can simulate the evolution of the data variables for various lengths of time.

In order to investigate the effect of certain areas of vegetation or certain terrain features, or in order to evaluate natural changes in climate, climatologists run simulations of the same geographic area with different vegetation or at different points in time, or with particular terrain features modified. The results of such sets of simulations are data files of the same format. In such cases, climatologists are interested in comparing high-level patterns in climate data and finding differences in climate events.

# 3 THE CEVIZ SYSTEM

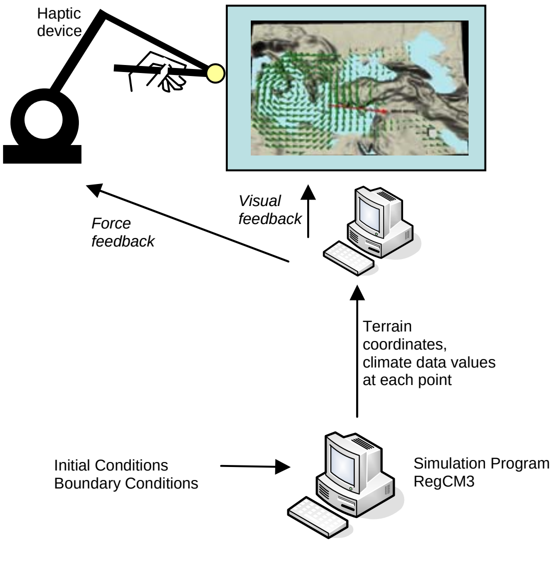

Figure 1. Block diagram of the CEVIZ system.

The CEVIZ system takes as input the climate data files produced by RegCM3, and by using a combination of haptics and information visualization techniques, presents them in an interactive way to the user (Fig.1). Details of how each kind of climate data is presented are provided in Section 3.1. The design choices in the CEVIZ system were arrived at after some experimentation with earlier prototypes. The choice of where and how to use haptics, where to use point rather than overview information, as well as the particulars of how each dimension was represented was made so that a comparison between a purely visual system and a haptics-augmented system would allow us to make conclusions about hypotheses I-IV explained in the Introduction section.

## 3.1 Representation of Climate Data

For each kind of climate data listed below, we explored several visual, haptic and combined representation alternatives. Due to space limitations, in the following we discuss only a few of the alternatives that were considered and discarded.

**Height map:** A three-dimensional mesh representation of topography is formed by connecting the height values for each grid point using the height map provided by AYBE. Height values are mapped to color shades ranging from blue (sea level) to gray. The height map is also rendered by transforming it into a haptic map, which allows the user to feel the topography by touch.

**Pressure Surface:** The p-level height data is used to construct a pressure surface. This surface is not shown visually because it blocks the user's view of the terrain too much. Instead, it is mapped as an invisible haptic surface that the user can feel and move along. Only the parts of the terrain above the pressure surface can be felt by the user.

**Wind:** Wind is represented by conical arrows at grid points (Fig. 2). The apex of the cone points in the direction of the wind, and the radius and height of the cone are proportional to the magnitude of the wind. At the beginning of exploration, none of the wind arrows are displayed. The wind arrows at grid points within a certain distance of the cursor are made visible as the terrain is explored.

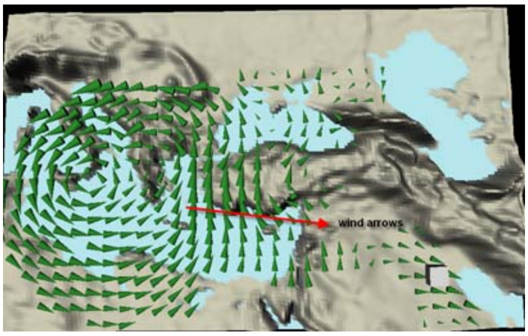

Figure 2. Representation of the winds in the CEVIZ system.

Forces rendered through the haptic device guide the user to follow the path of the winds. This 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 and the meridional winds are mapped as forces in the x and y directions. Forces at points intermediate between grid points are computed by a linear interpolation of the forces at the neighboring four vertices on the grid. We initially experimented with displaying all of the wind data at once statically throughout the entire map and found that, rather than allowing the user to grasp wind overview information rapidly, this representation instead overloads the user and makes it more difficult to retain this information. The user does not absorb the overview at once, instead serially explores the map.

We found that displaying wind information gradually while the cursor is guided by the wind forces gives the impression of traveling with the wind and finding out information about other climate variables simultaneously with wind-guided exploration.

**Cloud water:** Cloud water is represented graphically by white spheres mapped over the pressure surface with radii directly proportional to the cloud water value at that point (Fig. 3). In a quick overview of the terrain, the regions where the spheres are largest and most frequent easily stand out as the regions where there is the largest amount of cloud water. Cloud water is also represented haptically using bump textures mapped onto the pressure surface [10]. The size of the bumps is proportional to their radii.

**Humidity and Temperature: The Information Box.** The cursor in CEVIZ is an information box.

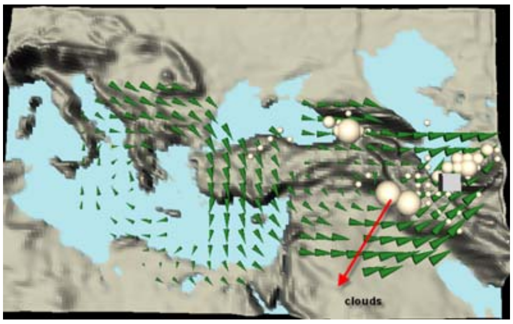

Figure 3. Cloud water represented by the sizes of white spheres.

Humidity (specific moisture) is represented by the size of the information box. There is a linear mapping from the moisture values to the size of the box. Temperature is represented by the color of the information box. Air temperature values are divided into eleven intervals, and each interval is assigned a color (Fig. 4).

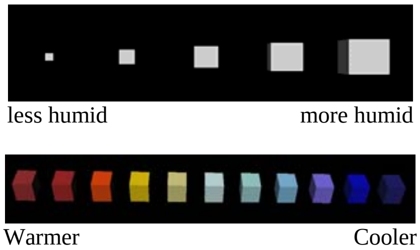

Figure 4. Humidity and temperature are mapped to the size and color of the information box.

The information cube lets the user observe these variables at specific points rather than giving an overview for the whole map. This draws the user's attention to changes in climate data while the cursor's motion is guided by the haptic forces. The user experiences these changes in humidity and temperature that are caused by or happen concurrently with the wind motion. This design choice was made in order to convey cause-and-effect relationships more explicitly.

The information cube has a shadow (Fig. 5) directly beneath it on the terrain which is used to show the exact location of the information box over the x-y plane.

**Figure 5.** The shadow of the information cube shows the location of the cursor on the terrain.

**Rain:** Rain is illustrated by animated 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 (Fig. 6).

**Vorticity and Rain:** Vorticity is a force perpendicular to the plane along which the wind velocity is given. The vorticity makes the wind rise or fall due to the circulation of the air. When there is a counterclockwise circulation in the northern hemisphere or when the wind collides with the mountains air tends to rise. In our system, vorticity is represented by a resistive spring force $F=-k_3*\Delta z$ at each point, the magnitude of the spring constant $k_3$ being inversely proportional to the vorticity force and $\Delta z$ representing the distance the user lifts up from the pressure surface. As a result, it is easier for the user to lift the cursor from a pressure surface in regions where vorticity is high. We chose to render vorticity only in the areas where vorticity and precipitation are high. In these areas, vorticity causes air to rise. These areas were delineated by blue cylinders (Fig. 6).

When the user is outside but close to the boundary of one of the cylinders, haptic forces pull the cursor into the cylinder with a spring force proportional to the distance of the cursor from the cylinder surface. Once inside the cylinder, lateral spring forces help keep the cursor confined within the cylinder. As the user tries to lift up the cursor while inside the cylinder, he/she moves inside a tunnel (a virtual fixture) along a vertical line going up from that point.

When the cursor enters the cylinders, if there is enough humidity, rain starts to fall. The temperature and drop in humidity are represented by the changes in the color and size of the information cube. Since pressure is directly proportional to temperature by the ideal gas law PV=nRT, as the air rises, the pressure drops and causes the temperature to drop as well.

In the cylinders where rain forms, as the user lifts from the surface inside the cylinder he sees rain drops moving as he moves up and down with the information cube. When the user arrives at a pressure surface the rain drops disappear and when he lifts again they reappear. This design choice was made to make more explicit the fact that rain forms when the wind rises.

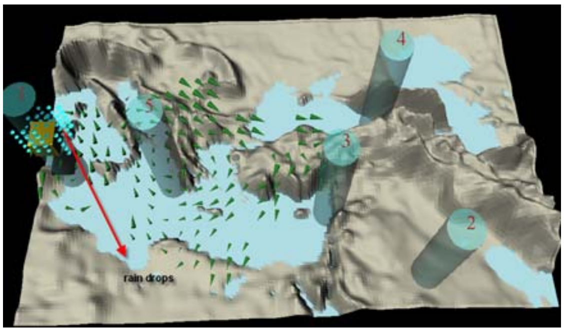

**Figure 6.** The representation of rain cylinders and raindrops.

We experimented with other ways of representing vorticity but found them to be counterintuitive. For instance, we tried rain tunnels which had a force pulling the user up along the axis of the cylinder and moving him to a pressure surface above the current one, at which point the climate data in the newly-reached pressure surface would be displayed. We found that the pull felt very abrupt to users and it was very difficult for them to notice that they had moved up to a pressure surface at a higher altitude. They would be confined to this new pressure surface and haptic forces would work against them if they wanted to repeat the transition from one pressure surface to the other. Users felt this was counterintuitive.

## 4 EXPERIMENTAL EVALUATION AND DISCUSSION

In order to test our hypotheses, we designed five experiments where the user explores the climate system around Turkey for different time periods and attempts to figure out the cause and effect relationships between different geographic and climatic concepts.

We used climate data files produced by RegCM3 for the region surrounding Turkey. Climate data variables were provided on a grid in the (x,y) plane with 24 km in between each grid point. There were 169 grid points along the x direction and 115 grid points along the y direction.

22 human subjects participated to the experiments. Subjects were divided into two groups (11 in each group). As explained in more detail in each experiment below, only visual feedback (V) was provided to the subjects in Group 1 whereas both visual and haptic feedback (V+H) were provided to the subjects in Group 2.

### 4.1 Experiment 1: Wind

**Goal:** The goal of this experiment is to investigate whether haptics helps a user observe and remember wind patterns better.

**Stimuli:** In the visual version (V) of this experiment, as the user explores the surface, he sees the arrows appearing gradually on the screen. The user's goal is to explore the whole surface until all the arrows are visible on the screen (Fig. 7).

In the haptic-enhanced version (V+H), in addition to seeing the wind arrows, the user feels the wind forces in real time through the haptic device. Also, haptic feedback snaps the user onto the pressure surface during the exploration by applying a spring force when the user wants to move away from the pressure surface.

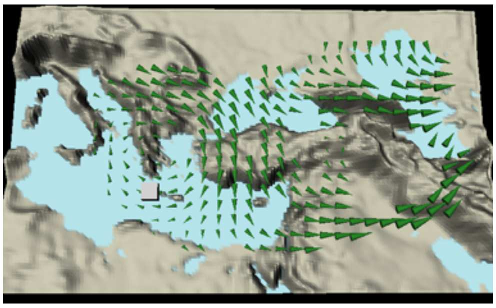

**Figure 7.** The user exploring the wind patterns in experiment 1.

**Procedure:** The users are instructed to explore the whole surface until all the arrows are visible on the screen. At that point, the visual and haptic displays are turned off, and the users are given six different maps representing different wind patterns (see Figure 8 for examples) and asked to choose and rank the three maps that most closely match the one they explored.

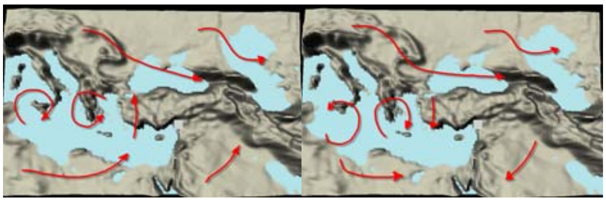

**Figure 8.** Two of the six wind pattern map choices in Experiment 1

**Results:** The columns of the table below titled 1st, 2nd, and 3rd represent the number of subjects in each group who chose the correct answer as their first, second and third choice. The column titled raw score is the number of subjects that chose the right map in any one of their three choices. The penalty-based score is calculated by assigning 3, 2, 1 points to the 1st, 2nd, and 3rd choices.

| | 1st | 2nd | 3rd | Raw Score | Penalty-based Score |
|---|---|---|---|---|---|
| V | 5 | 2 | 0 | 7/11 (64%) | 19/33 (58%) |
| V+H | 7 | 1 | 2 | 10/11 (91%) | 25/33 (76%) |

### 4.2 Experiment 2: Cloud Formation

**Goal:** The statement "When wind has enough humidity and enters a relatively cooler region, clouds form." specifies a cause and effect relationship between climate variables. The goal of this experiment was to test whether the combined haptic and visual approach improves upon a purely visual approach in learning this relationship and later being able to use it to make inferences.

**Stimuli:** In the visual version of this experiment, as the user explores the surface, wind and arrows start appearing. Five locations are marked by numbers on the map (Fig. 9), and the user is asked to choose the regions where clouds are likely to occur. In the haptic version of the experiment, the same visual representations are used for temperature and humidity with the addition of the haptic feedback for representing the winds. The wind forces guide the user to follow the path of the winds and observe the changes in the climate variables along these paths.

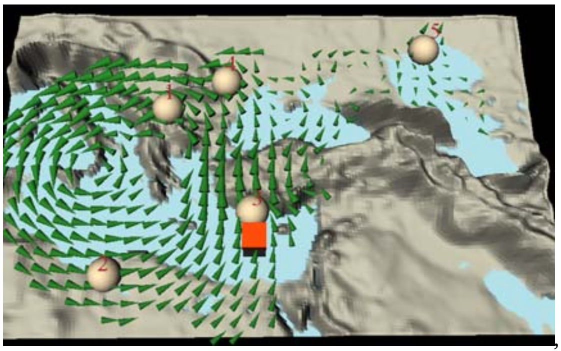

**Figure 9.** Winds and clouds in experiment 2.

**Procedure:** The subject is given a handout explaining that 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 relatively cooler region, clouds form."* The subject is then asked to explore the pressure surface and decide in which of the five regions clouds are likely to form. Subjects are allowed to choose as many regions as they like.

**Results:** The results of this experiment are shown in the table below. The raw scores represent the number of participants that gave 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 wrongly-chosen region.

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

### 4.3 Experiment 3: Locating Clouds

**Goal:** The goal of this experiment is to investigate whether haptic feedback helps the user construct a link between the cloud location, the wind patterns, and the terrain. Differently from experiment 2, no statement is given to the subjects about the relations between climate variables in order to test whether haptics helps users learn without explicitly paying attention.

**Stimuli:** Both versions of this experiment consist of a learning phase followed by a testing phase.

In the learning phase of the visual version of the experiment, the user observes 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 (Fig. 10). In the testing phase, 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. During this second part of the experiment where the user's learning is being tested, as the user explores the surface, only the wind arrows appear on the screen. The user is asked to find the location of the cloud clusters.

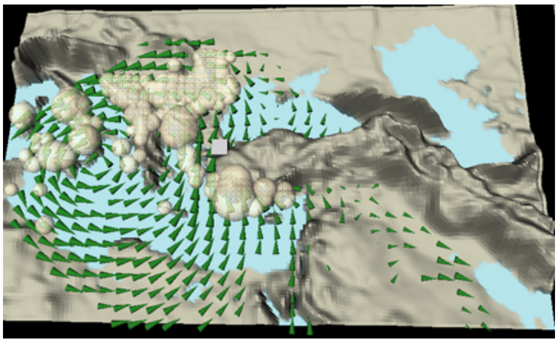

**Figure 10.** Winds and clouds in experiment 3.

In the haptic version, haptic feedback enables the user to feel the winds, the pressure surface, and the terrain. Also, a bump texture is haptically mapped (as explained in Section 3) onto the surface to represent the clouds during the exploration along with the visual sphere representations. The testing phase of the haptic version is the same as that of the visual version.

**Procedure:** Once all the arrows and clouds fully appear on the screen, the training phase of the experiment is over, and haptic and visual displays are turned off. The participant is then asked to pick which of the following statements 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 testing phase of the experiment, the user is given the same system, but this time without the visual and haptic representation of the clouds. The image of a cloud is virtually coupled to the cursor and the user is able to drop this structure at any location on the geographic map. He is given five clouds and is asked to place the clouds at the places where he thinks larger clouds are located.

**Results:** The correct answer for the first part of the experiment was the choices "b" and "e". The distribution of the subjects' responses is given below. 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%) |
| H | 9/11 (82%) | 20/22 (91%) |

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 average of positional errors for cloud location in Experiment 3 was 27.69 ± 1.34 km. for V subjects and 23.10 ± 2.48 km. for V+H subjects.

### 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:** Five cylinders in vertical position are displayed to the user on the screen (Fig. 6, Section 3). If the cursor enters a cylinder the user can investigate whether or not rain forms in the cylinder. The five cylinders are located so that each has different characteristics in terms of humidity, vorticity, wind pattern, and rain formation.

In the haptic version of the experiment, as described in Section 3, when the cursor is close to a cylinder, haptic forces draw the cursor inside the cylinder. While inside the cylinder, as the user moves the cursor up, he feels side forces inhibiting him from going out of the cylinder creating a tunnel effect. In the cylinders where the vorticity is high and the forces allow him to lift, rain starts to fall if the air has enough humidity, i.e., if the information box is large. The user is also 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. In order to create a visual effect that matches the haptic interaction as closely as possible, we adjust the positional displacements of the visual cursor based on the vorticity values inside cylinders. When the vorticity force is weak, the visual cursor does not move up much in response to the movements of the user's hand. If vorticity is low, until a certain cursor displacement threshold is exceeded, the visual cursor does not move at all in response to the movement of the stylus.

**Procedure:** At the end of the exploration, the user is asked to answer the following questions for each cylinder:

**Q 4.4.1:** Why does/doesn't rain occur in Cylinder n?

A. The temperature difference between the pressure surfaces is/isn't significant.
B. The humidity when the cylinder is entered is high/low.
C. The wind inside the cylinder is/is not able to rise

**Q 4.4.2:** Which of the below are true for this region?

a) There is clockwise wind circulation.

b) There is counterclockwise wind circulation.
c) There is no circulation.
d) The wind collides with the terrain.
e) The wind doesn't collide with the terrain.

**Q 4.4.3** The user is asked to fill in the following questionnaire:

- Air can/cannot rise
- There is clockwise/counterclockwise circulation
- Wind collides with terrain/There is no circulation and wind does not collide with the terrain
- There is/is not a significant temperature drop
- Wind has/does not have significant humidity
- When rain occurs, humidity
    a) drops b) rises c) stays the same.

Then, a new case with four different cylinders is displayed. The user is asked to pick 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.

**Q 4.4.4** Cylinder `?`: No/little/a lot of rain will occur.

**Q 4.4.5** Which cylinder shown in the training system is similar to this cylinder? Give two answers you think match best.

**Results:** The percentage of correct answers for each question is given for both categories of subjects below.

| | Q4.4.1 | Q4.4.2 | Q4.4.3 | Q4.4.4 | Q4.4.5 |
|---|---|---|---|---|---|
| V | 46% | 71% | 74% | 36% | 41% |
| V+H | 96% | 85% | 97% | 89% | 77% |

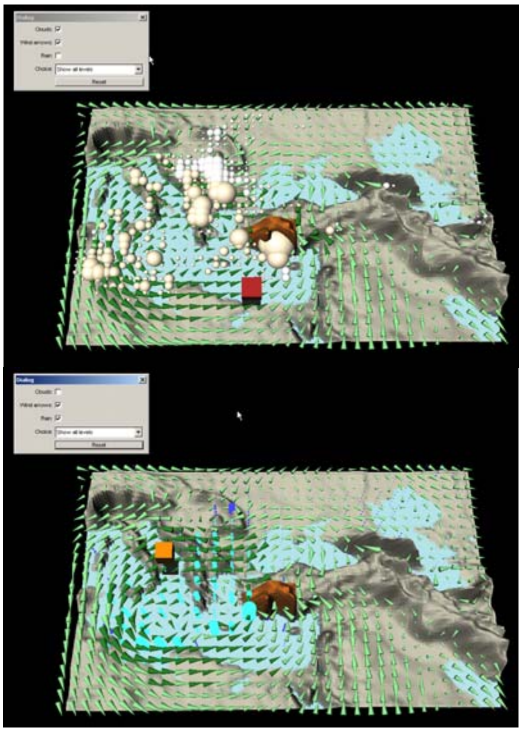

**Figure 11.** Cloud and rain patterns in experiment 5.2

## 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.

**Stimuli:** In experiment 5.1, the mountains in the North East region are removed. In experiment 5.2, the heights of the mountains in the Antalya region (south coast of Turkey on the Mediterranean Sea) are increased.

The information appearing on the first window is data for the unmodified terrain. As the user explores the surface, the representation of the climate data corresponding to the modified terrain replaces the original data in areas within certain proximity of the cursor. The user can reset the map to display the original data at any time. He can also turn on/off the information for cloud, rain and wind. In the haptic version of the experiment, haptic feedback guides the user to explore climate changes along paths of strong winds. As usual, the user is able to feel the terrain surface in addition to the winds.

**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 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:** The percentage of correct answers by V and V+H subjects in experiments 5.1 and 5.2 are shown in the table below.

| | Exp. 5.1 | Exp. 5.2 |
|---|---|---|
| V | 64% | 27% |
| V+H | 100% | 95% |

## 5 DISCUSSION

The results of *Experiment 1* 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 the winds blowing from five different directions. It was observed that the visual explorers reacted completely differently from the haptic explorers when they were given the question after the exploration of winds. Most V subjects indicated that they had not paid any attention to the directions of the winds whereas V+H subjects remembered some of the wind patterns quite well, especially at the locations where they were exposed to a strong force feedback.

We believe that V+H subjects 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 his arm was being circulated in the clockwise direction, whereas it was harder for the visual user to remember which direction the circulation was. Even though the users were not told to pay attention to wind patterns, they built a haptic memory that they were later able to recall.

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. It was observed that V+H subjects were able to identify the locations where the temperature dropped along the path of the wind and where the wind entered into a relatively cooler region allowing the clouds to form. V subjects were able to approach to the same locations from any direction since they were not guided by the wind forces. The results of this experiment indicate that this made it difficult for the V subjects to detect and retain the temperature patterns along the wind paths. This supports our hypothesis that haptic guidance leads users to observe changes in climate variables in a particular sequence that corresponds to the cause and effect relationships and although the same information is there in the purely visual model, the unguided exploration makes it difficult to notice and/or retain these relationships.

The results of *Experiment 3* were consistent with the results of Experiments 1 and 2. It was observed that V+H subjects learned that clouds formed in areas of counterclockwise circulation and where the circulating wind was colliding with the terrain better than V subjects. V+H subjects performed significantly better at the cloud location task. It was observed that V+H subjects paid attention to the texture mapped on the surface at cloud locations, whereas, the V subjects reported making their decisions about the cloud locations based on their geographic knowledge and visual memory. The results confirm that haptics helped the user form a link between cloud formation, wind structure and terrain even though the user was not explicitly told to pay attention to these variables.

In *Experiment 4*, all of the V+H subjects noticed that wind inside some of the rain cylinders was able to rise whereas V subjects reported answering the related question randomly. In the training portion of this experiment, subjects in the V+H group were able to recognize the relation between the wind rise and the resistive force inside the cylinders. We believe V+H subjects performed better at remembering the changes in temperature and humidity inside the cylinders better than V subjects because during exploration, the haptic feedback allowed the user to move in a more controlled way inside the rain tunnels. Results of this experiment show that the haptic users were significantly better in remembering the cause and effect relationships in rain formation even though they were not told to pay attention on it.

The second, “testing” part of the experiment asked the users to consider a new map and to identify in which of the cylinders rain was likely to form by applying what they had learned in the training part. It was observed that the V+H group was significantly more successful in locating the cylinders in which rain formed and matching the new cylinders with the ones in the first part. We believe that this is because the V+H subjects were trained better in the first part. This lends further support to our hypothesis that when certain differences are rendered in haptics, they are detected and remembered better.

In *Experiment 5*, we investigated if haptics improves the understanding and interpretation of 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 V+H subjects performed significantly better. The difference in performance was especially pronounced 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.

The experimental results strongly support hypotheses I-IV in the introduction and indicate that carefully designed haptic guidance and haptic rendering of certain data dimensions can be very instrumental in conveying cause-and-effect relationships in a high-dimensional data space. It could be argued that once these cause-and-effect relationships and their manifestations in a certain map are known, it is possible to find better visual representations for them, such as animating the winds and the clouds. It is noteworthy, however, that our haptics-augmented system allows the user to naturally notice the manifestations of these relationships on a map and internalize them while allowing him to direct the exploration. Our system accomplishes this without needing to pre-process, interpret and detect patterns in the data first.

## 6 CONCLUSION

We designed, built and experimented with a prototype that combines haptics and information visualization in order to improve the discovery, learning, and retention of cause-and-effect relationships in a multidimensional data space. Our experiments confirmed that the inclusion of haptics significantly improves results. Our findings suggest that a similar approach can be applied to other domains for educational purposes as well as data exploration by domain experts.

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