GEMS202 - 0102

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DIVA - Data Imaging and Visualization Analysis
Literature Review

We pledge that we have not given or received any unauthorized assistance on this assignment.

Introduction

Over the last few decades, satellites have collected vast quantities of climate and weather data, providing a better picture of Earth's global and regional climates. Interest in understanding Earth's climate has risen in light of human-fueled climate change, which poses an existential threat to the human population. But climate data suffer from what researchers refer to as an "analytical bottleneck", because the data are collected at a far greater rate than they can be understood, obsoleting current data visualization and analysis techniques (Dasgupta et al., 2016). The two current major methods of data visualization are two-dimensional maps and three-dimensional globes. Although these provide some insight into the values and trends of spatial variables, they are not typically interactive, do not display only a few variables, and do not display the effects that different variables would have on each other or on their geographic surroundings. These barriers prevent climate data from being understood by both technical and non-technical audiences, and present room for improvement.

One possible means of improvement to address these shortcomings is to integrate existing methods of data visualization with virtual reality technology, such as Oculus Rift. Current literature reports that virtual reality has many recreational, engineering, and medical uses. Just as it can be used to provide a more interactive experience in these cases, it could also provide users with a more interactive and relatable way to visualize climate data.

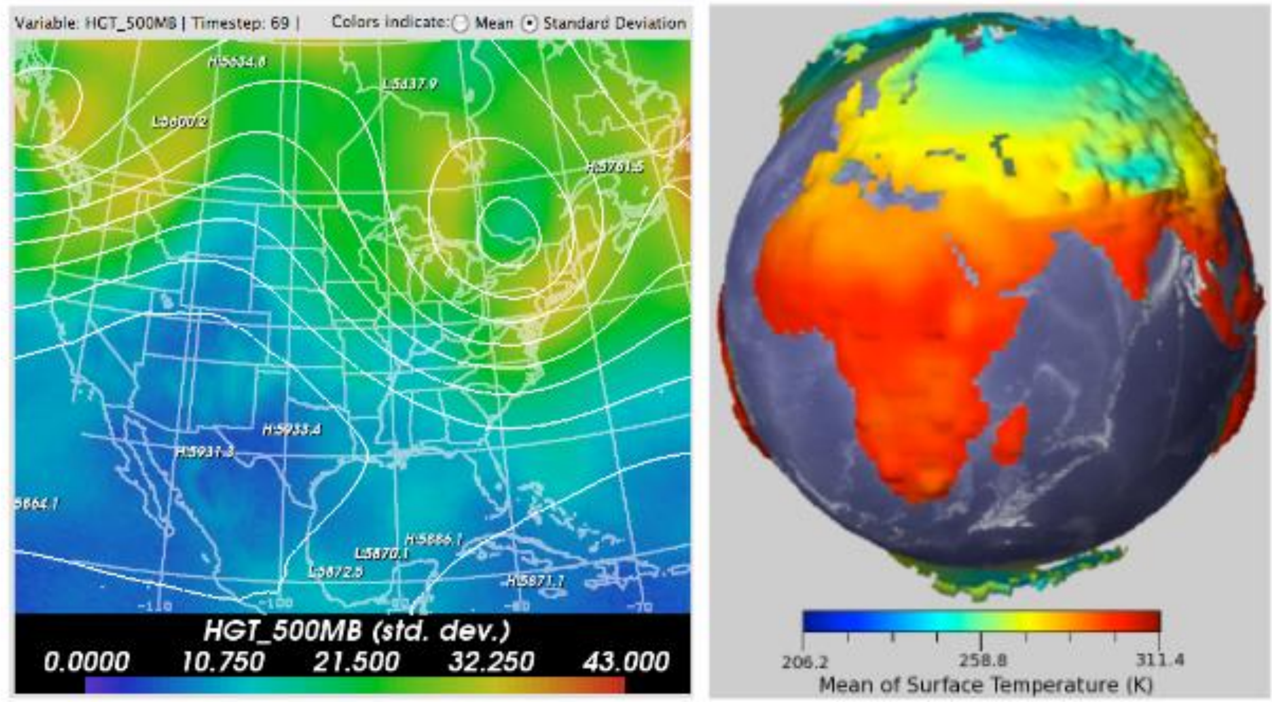
Section 1 - Current Climate Data Visualization Methods

Current methods of visualizing large sets of climate data can be divided into two broad categories: two-dimensional maps, which utilize colors or glyphs to display climate data across a wide area, and three-dimensional globes, which visualize moving weather patterns across interactive globes using programs such as Google Maps and World Wind. Both approaches have their strengths and weaknesses. For instance, two-dimensional maps require minimal processing power, but can only display a limited number of parameters. Conversely, real-time three-dimensional globes require very powerful processors, but can display vectors, volume rendering, and other useful attributes of the data. However, neither method has been tested to conclude how effectively it can convey climate information to technical and non-technical audiences.

Section 1.1 - Two-dimensional Maps

Two-dimensional maps, such as colored maps or glyph-maps, use colors and symbols, respectively, to demonstrate variation in one or more variables over a large geographic area. Numerous methods and apps have been developed to illustrate data this way.

The earliest two-dimensional climate maps use colors, typically varying from red to blue to indicate high to low levels of a parameter. One such map, developed by researchers from the University of Oregon, displays the mean of a parameter through color on a graph, and allows the user to display the standard deviation of the parameter as contour lines or a height field line (Fig. 1) (Potter et al., 2009).



(a) (b)

Fig. 1: *These maps, developed by researchers from the University of Oregon, allow users to display means by color and standard deviations by either contour lines (a) or height fields (b) (Potter et al., 2009).*

However, this approach displays a single variable at a time, so users can gather a limited amount of information from the maps. Other maps have been developed that can display multiple variables through a two-color gradient. For instance, researchers from the Institute for Atmospheric and Climate Science in Switzerland developed one such bivariate color map to display temperature and relative humidity (Fig. 2) (Teuling et al., 2011).

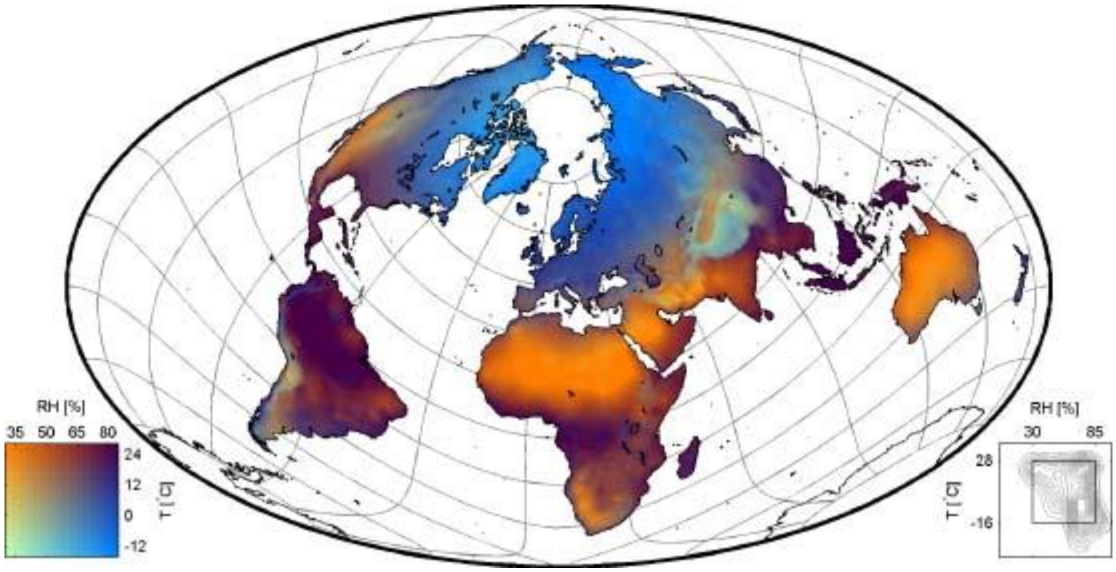
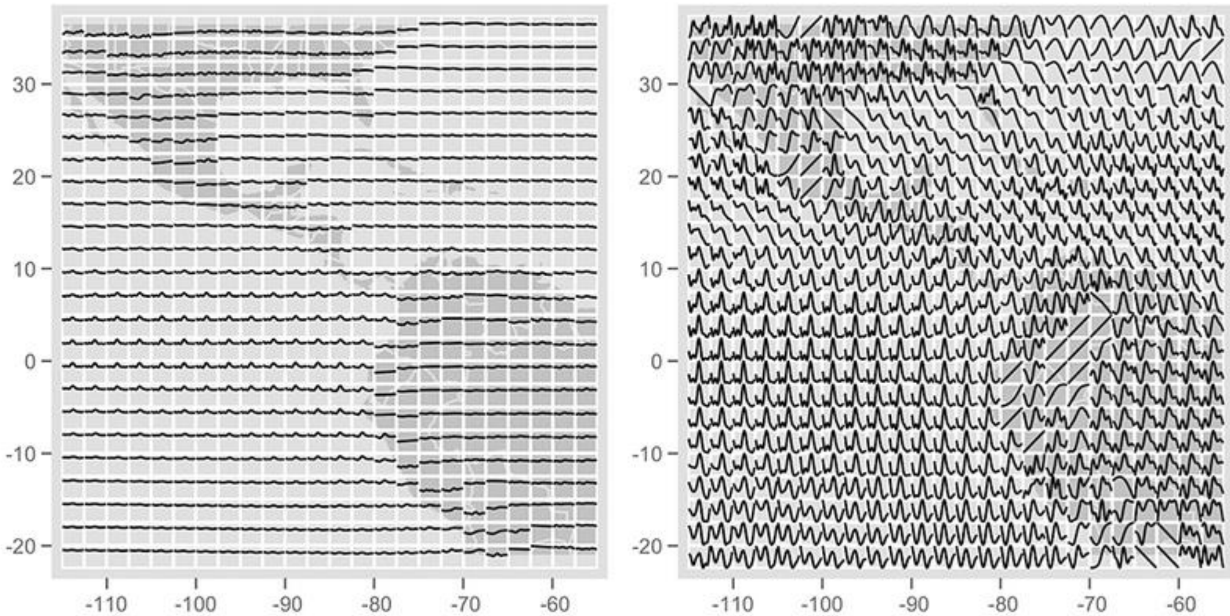


Fig. 2: *Researchers from the Institute for Atmospheric and Climate Science in Switzerland developed this bivariate map, which indicates temperature and relative humidity by mixing colors to varying degrees. The results are intuitive: the Sahara is clearly a desert, the Arctic clearly cold, tropical regions all clearly distinguishable, etc. (Teuling et al., 2011)*

Currently, no existing two-dimensional map in the literature can handle more than two parameters. Furthermore, only a few two-dimensional maps can demonstrate changes in a parameter over time.

One approach to displaying changes in parameters over time is the glyph-map. This type of map was developed by researchers at Rice University to display changes in a single variable over space and time by placing tiny graphs all across a world map, with each graph using the same scale (Fig. 3) (Wickham et al., 2012).

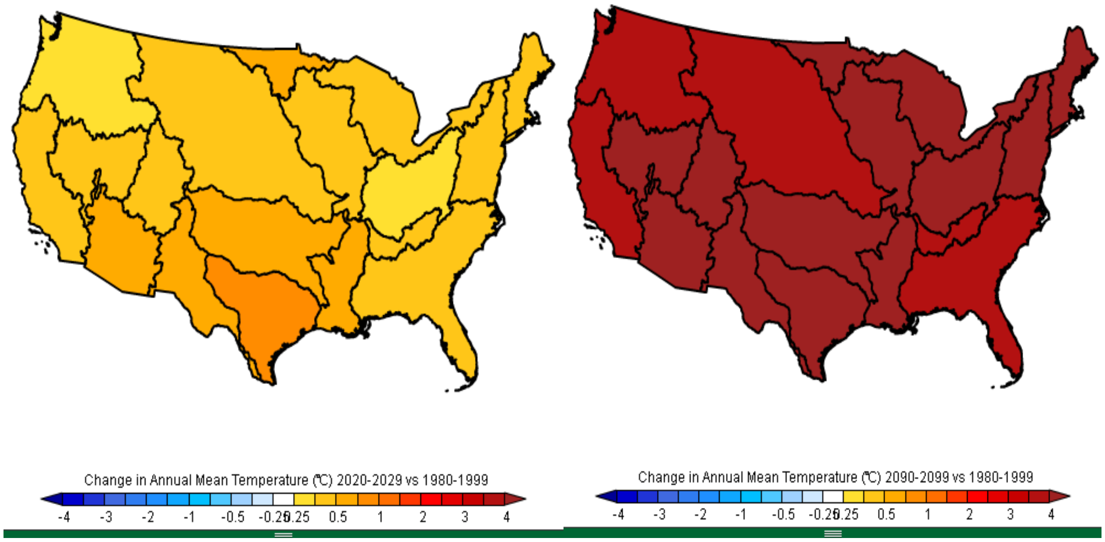


(a) (b)

Fig. 3: *Two glyph-maps representing the same set of temperature data for one year. Graph (a) utilizes a global temperature scale, while graph (b) utilizes a local temperature scale.*

While glyph-maps allow users to view changes in a parameter over time and help highlight aberrations in the data, they may be slightly unintuitive for some meteorologists, technical experts from another field, and the majority of the public.

Alternative 2-D map applications that account for time are the Global and Regional Climate Science Viewers, which were developed by researchers from the U.S. Geographic Survey and the Lawrence Livermore National Laboratory in 2012. They allow users to view predicted changes in parameters such as temperature, soil moisture, and precipitation, with reds indicating significant increases and blues indicating significant decreases (Alder et al., 2013).



(a) (b)

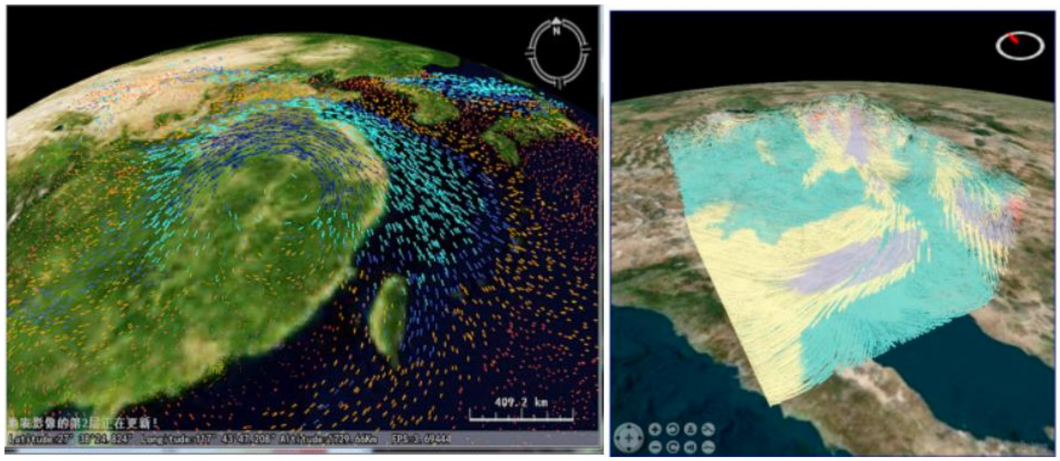
Fig. 4: *The Regional Climate Science Viewer visualizes predicted temperature changes over two time spans: (a) A comparison between the 2040s (predicted) and 1980s. (b) A comparison between the 2090s (predicted) and the 1980s (Alder et al., 2013).*

Both the global and regional tools allow users to compare predicted changes to expected changes over one or more decades. For instance, users can compare the predicted temperature increase from 1980 to 2040 to the expected increase from 1980 to 2090 (Fig. 4). The Regional Viewer also allows users to view predicted changes for specific regions in the U.S. down to the county level. However, while the Climate Science Viewers do convey changes in severity and values of parameters over time, the physical or environmental effects that such changes might have are not apparent from these and other univariate methods of climate data visualization.

All 2-D data visualization maps discussed have strengths and weaknesses. It is valuable for users to see the changes in the data over time, as with the two Climate Science Viewers, but it may be difficult for users to grasp climate patterns when only one parameter is displayed. Conversely, bivariate color graphs are useful for users to see aridity, relative humidity, and temperature, but make it difficult to grasp the changes when no time context is given. Since there are limitations on what static maps can display, none of these maps was used to visualize intricate multivariate phenomena. Moreover, these maps were never tested for effectiveness or reviewed by human factors to determine which characteristics would be most useful to researchers or the public. Without such reviews, objectively quantifying the usefulness of these maps is difficult.

Section 1.2 - Three-Dimensional Globes

As the computational capabilities of machines have increased, it has become possible to project models and large sets of climate data using online simulations and virtual globes, such as Google Earth and NASA’s open-source World Wind API (Liu, Gong, & Yu 2015). These interfaces support vectors to show the paths of particles, and volume rendering to add textures and colors to various sections of 3-space. Furthermore, these vectors and figures change in real time, allowing users to observe the fluctuations of climate phenomena. Researchers from the Chinese Academy of Sciences utilized these features to model the behavior of a cyclone (Fig. 5) (Liu, Gong, & Yu 2015). Their findings suggest that World Wind may be helpful for conceptualizing data sets. For instance, the researchers used vector simulation to determine the wind speeds and directions in general areas that would be affected by a storm (Liu, Gong, & Yu 2015). Similar applications have been developed by other researchers to visualize wind currents and dust storms in real-time (Fig. 5) (Zhang et al., 2015).



(a) (b)

Fig. 5: *(a) Vector simulation of a cyclone in World Wind (Liu, Gong, & Yu 2015).*

(b) Wind currents simulated in World Wind using volume rendering (Zhang et al., 2015).

These three-dimensional APIs can also be used to render data not related to wind patterns or vectors. For instance, Zhenhong Du and his colleagues at Zhejiang University developed an API to display CO2 fluxes over the oceans (Fig. 6) (Du et al., 2015). Flux levels ranged from were displayed using colors, ranging from blue (downward flux), to red (upward flux), with elevation indicating the carbon content of a region of the ocean.

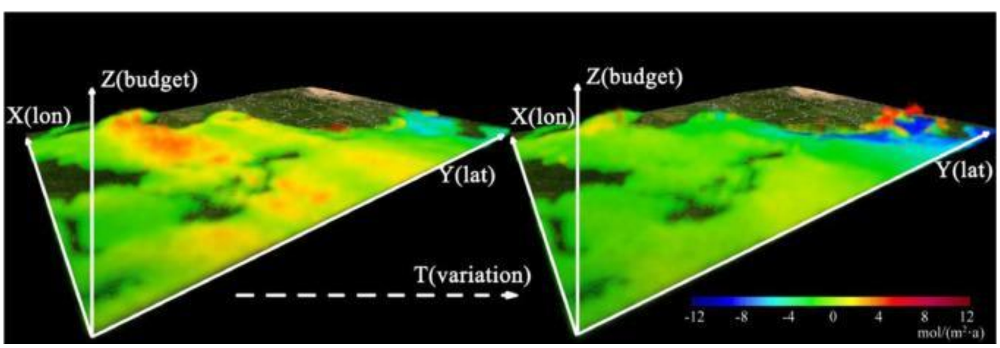


Fig. 6: *Simulation of CO2 flux levels of the ocean, with positive values indicating an upwards flux (CO2 leaving ocean) and negative values indicating a downwards flux (CO2 entering ocean) (Du et al., 2015).*

In this case, the color scheme allows the user to see that there is increased acidification (negative flux) over much of the ocean surface surveyed, which also increases in severity over time. This is certainly an improvement compared to two-dimensional charts, which cannot illustrate real-time changes at all.

As a whole, real-time globe environments like World Wind illustrate complex time series more realistically than do two-dimensional maps. However, like two-dimensional maps, these globes have only been used to visualize the effects of a single variable on the system, rather than multivariate interactions. This means that users can draw only incomplete conclusions from these visualization methods. For instance, while the methodology of Du and his colleagues can display CO2 flux, it is unclear what the effects of this would be on atmospheric or oceanic conditions. Likewise, while the methodology of Liu et al. effectively displays the path of a cyclone, it is difficult to gather details of the storm, such as its effects on the upper ocean or changes in its intensity, from their method of visualization. This presents a gap in literature, which could possibly be resolved by introducing a visualization method that displays multiple variables and their interactions with their surroundings. Such a method could also have an interactive component allowing users to focus on areas of interest, where different variables may appear to have a correlation, and this could be included as an analytical feature in its interface.

There is also a significant gap in literature in that no method of data visualization has been tested for its effectiveness in conveying the effects of climate data to technical and non-technical audiences, which means that improvements to these visualization methods are merely based on speculation and a general sense of inadequacy. It would be useful to test this new interactive method, as well as the older methods, to determine which method is the most effective for communicating these climate data to interested audiences.

<u>Section 1.3 - Storing and Processing Data</u>

When designing a data visualization platform to reveal trends and interactions between data sets, it is also important to consider how these data will be stored and processed effectively to create a smoother user experience. Some issues presented by large data sets, such as climate data, include interpreting numerous different file types, efficiently processing large quantities of data, and rendering the corresponding graphics onto a user’s machine. Researchers have addressed these problems by developing improved database management techniques, compressing data when possible, and outsourcing computations.

Climate data are recorded all over the world from a large variety of sources and in heterogeneous formats. Idreos et al. (2015) highlight the need for systems built for “data exploration,” where users may not be familiar with the details of how a certain data set is stored, but wish to query the system for data in an exploratory manner. This can be accomplished with “middleware,” a layer between the user interface and the database that improves the efficiency of searching for interactions between data sets (Idreos et al., 2015). According to this study, techniques such as predictive analysis to search for interesting correlations, or data caching to store data likely to be used, can streamline this process. An exploratory system such as this could therefore help users visualize and examine data from multiple unfamiliar sources more easily.

Users may also wish to have a more comprehensive visualization by compiling many different data sets from separate sources. However, these might be stored in different formats, making them more difficult to compare. To address this issue in one of its applications, Szlam et al. (1997) developed a system for call centers to automatically consolidate data about consumers from heterogeneous sources into a single presentation, allowing agents to quickly glean information from one source. A similar technique could be implemented to compile climate data into one format for ease of use in generating visualizations. Additionally, Sun et al. (2011) developed a PHP program called KML Generator to extract data fields from database sources so that a single file could be used to generate the final visualization, prior to rendering. Employing a combination of these strategies to compile requested data sources into a single format would save time when accessing data during the visualization rendering process.

Another component of animated data visualization is the efficiency with which frames are generated. Data scheduling tasks must be established to ensure that visualizations can be generated in time for the user to view them. A technique developed by Du et al. (2015) allows for external data to be read asynchronously, so that an entire data set does not need to be loaded at once. This technique employs a node-based strategy where frames are simultaneously generated and displayed so that the next frame is prepared as the current one plays, and ensures that loading data does not interfere with the process of rendering images since only two GPU buffers are in use at any given time (Du et al., 2015). When testing this model, Du et al. (2015) concluded that frame rate is not significantly affected by data set size, demonstrating that this is an efficient method for generating and displaying animated visualizations in real time.

No matter how efficient the rendering process may be, however, generating images from data still takes time and requires significant computational power. Two ways that researchers have tried to reduce computation times are by simplifying the data or by outsourcing processing power. One method for simplifying data was by developed by researchers from the National Center for Atmospheric Research (NCAR) during the development of their Visualization and Analysis Platform for Ocean, Atmosphere, and Solar Researchers (VAPOR) (Norton & Clyne, 2012). In order to render large data on normal desktop computers, VAPOR utilizes progressive data access, which means that it sacrifices accuracy to speed up computations (Norton & Clyne, 2012). The researchers found that for some data sets, especially those used for volume rendering, the progressive data access approximation is adequate for visualization purposes (Fig. 7), meaning that users can visualize this sort of data on regular desktop computers (Norton & Clyne, 2012).

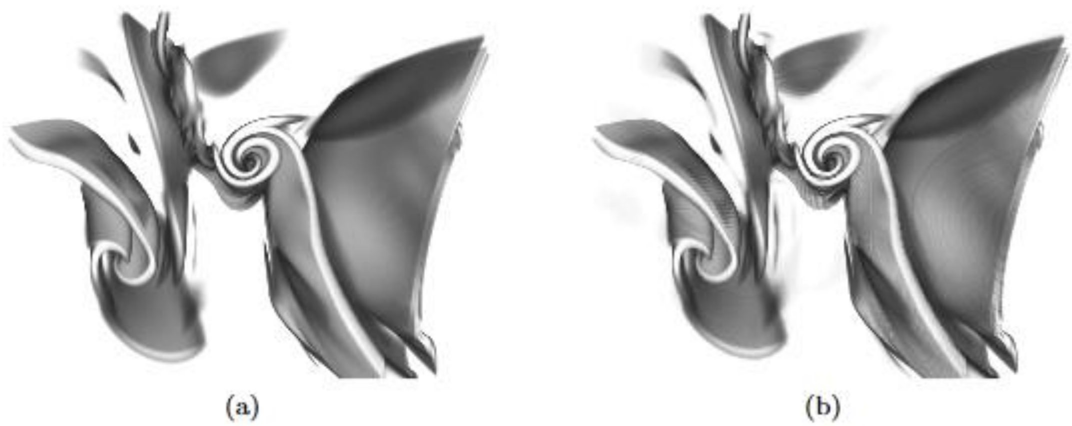


Fig. 7: *Close-up of VAPOR's volume rendering of a region reveals little difference between (a) the original, uncompressed data and (b) the compressed data (Norton & Clyne, 2012).*

In cases where data fidelity is very important, rather than relying on users to have sufficient resources, it is beneficial to outsource major computations to the cloud and simply serve clients the final product. Cloud platforms such as Amazon Web Services (AWS) can be used to gain access to remote computing power such as GPU clusters that share resources to quickly accomplish tasks (Zheng et al., 2015). This system, developed by Zheng et al., (2015), allows for customizability of visualization algorithms and takes advantage of AWS's auto scaling features so that the platform can be scaled up to include more remote GPUs if more computation power is needed. Employing a system like this would allow climate data visualization platforms to operate independently of client resources so that rendering images can be done in minimal time.

Section 2 - Virtual Reality (VR)

Previously discussed methods of climate data visualization, including maps and globe interfaces, suffer from a lack of interactivity. These methods can display variation in few variables at a time, but in general, it is difficult to gauge the combined effects on the surrounding environment, the oceans, and the atmosphere due to changes in one or more variables. Current methods also make it difficult to visualize the interaction between various climate variables, limiting the predictions they can make and the trends they can observe. One potential solution to this lack of interactivity would be to involve VR. This would allow users to more easily visualize the effects on the atmosphere and oceans previously mentioned. It could also allow them to choose specific areas of interest in a multivariate visualization, and focus on and analyze those areas for trends or correlations. Literature suggests that VR already has analogous technical applications in the military, medicine, and engineering, so it is plausible that the benefits of VR could be expanded to climate data visualization as well.

The concept of VR has existed since the mid-1990's. Over these two decades, the available technology has grown immensely, yet many challenges still remain for the developers. Even today there are no standardized tools to use or procedures to follow when working with VR (Ray, 2015). Beginning in the 1990's, developers attempted to create Virtual Environments (VEs) with various VR toolkits. One of the earliest toolkits developed is called CAVELib, seen as early as 1996. In fact, this toolkit is still present today, along with others developed in the early 2000's, including SVE, VRJuggler, DIVERSE, and Avocado.

Unfortunately, researchers and developers have had numerous issues when working with these toolkits. Existing toolkits are rarely reused when developing VEs, as they are often device- and use-specific. As a result, developers will often create their own toolkit from scratch.

However, time is an issue when developing a new toolkit, because one often takes years to create, as seen by the large gap between the creation of CAVELib and those from the toolkit wave of the early 2000’s. Instead, some developers learn to use existing toolkits and modify them as needed to satisfy the requirements of their project.

Andrew Ray blames the lack of publications about VR studies as the root cause of having no standard toolkit or procedure (2015). He suggests that researchers publish their findings, so that a standard can be developed over time. Ray also provides guidelines for those attempting to create such a standard. A toolkit must be able to work by default, stay out of the developer’s way, and be easy to use. Working by default entails having interoperability between different pieces of hardware. In addition, the architecture should consist of a modular design, looking to augment instead of replace existing work.

Section 2.1 - Current State and Limitations of Virtual Reality

In order to better understand the potential of visualizing climate data with VR, it is important to evaluate the device that we plan to use for its strengths and weaknesses. Currently, the most popular and widely used VR device is the Oculus Rift by Oculus VR, so we plan to use it to develop our visualization tool. The most current model is the Oculus Rift DK2. It has a very high display resolution of 960 pixels by 1080 pixels, 100 degrees’ field of view, and a refresh rate of up to 75 Hz, making Oculus Rift a truly immersive and life-like experience for the users (Desai et al., 2014). With regards to the sensor system, the Oculus Rift has a gyroscope to measure angular velocity, an accelerometer to measure acceleration, and a magnetometer to measure direction which transfers data at 1000 Hz, making the headset ultra-responsive to head movements and improving the overall user experience (Desai et al., 2014). Other capabilities of the Oculus Rift that we can take advantage of are head and positional tracking, which can be used as controls for our visualization tool (LaValle, 2014).

Despite the Oculus Rift's many strengths, it shares many of the same drawbacks with other VR devices. One weakness is the screen door effect, which is the empty black spaces that user sees between each pixel on the screen (LaValle, 2014). The screen door effect can distract users and make the visuals seem less life-like. Another limitation of Oculus Rift is ghosting, which is the trailing image left behind any moving object on the screen caused by low pixel switching frequencies (Desai et al., 2014). The ghosting effect produces a blurring effect and decreases the apparent resolution of the images. This means that objects on the screen have a maximum speed at which they can move without producing the ghosting effect. Another disadvantage of the Oculus Rift is that some subjects involved with VR studies have reported motion sickness. This was so pertinent of an issue that a question on motion sickness appeared on a survey to participants involved in a study on using VR to help autistic children learn words (Winoto et al., 2016). Lastly, another drawback of using VR as a visualization tool is that, unlike a TV monitor, only one user can see and experience the VR, which makes using VR ineffective at reaching large audiences at one time.

Section 2.2 - Modern Day Applications

VR technology has a variety of applications ranging from everyday uses in home entertainment to more technical uses in medicine and engineering. Perhaps the most well-known application for VR is in the entertainment industry. Especially in the video game industry, consumers are eager to have a more immersive experience that puts them right in the center of all the action. The desire for a 3D gaming experience can readily be seen in the early boom of 3D video games in the 90's; however, the technology at the time was not sufficient for generating satisfactory graphics (Goldman Sachs, 2016). With new advancements in technology since then, VR can now be applied to the entertainment industry.

Apart from just providing entertainment, VR also has military uses. The United States military currently utilizes advanced simulation to provide soldiers with combat and flight trainings. With VR technology, more advanced simulations can be incorporated to train soldier to ensure their combat readiness without expensive live combat training. VR is also commonly used by engineers. Computer Assisted Design (CAD) has become a popular method for prototyping new designs in a professional and aesthetically pleasing manner. VR technology can allow engineers to visualize their design in a way that increases productivity and offers key insights into possible design flaws.

Just as VR technology presents new possibilities for engineers to visualize their design better, it also presents new ways for people to visualize data. Effective data visualization is especially useful for scientists trying to analyze their data as well as to present their results and findings. New methods of data visualization can be developed to capitalize on VR platform to help increase understanding of certain data set, which is what we aim to accomplish with our research.

VR technology is currently widely used in the area of medicine. For example, VR medical training was used to substitute traditional medical training in the field in one study done by Mathur (2015). This can significantly decrease the cost of training upcoming doctors and physicians and increase the accessibility of this training as they don’t have to physically come to a hospital to receive training.

Section 2.3 - The Future of Virtual Reality

According to a Goldman Sachs research report (Goldman Sachs, 2016), the development and growth of VR technology will likely be comparable to the growth of PC, smartphones, and tablets. Following the trend that PCs have taken over the past three decades, VR will surely benefit from the economy of scale, driving the price of VR product down. Goldman Sachs also describes the VR platform as a new potential computing platform that offers a new level of interaction with computers; just as the tablet introduced the concept of touchscreen interaction. In that sense, VR can be seen as an extension to existing general purpose computing technologies. This huge potential VR technology presents does not go unnoticed by tech companies as over $3.5 billion of investment have been poured into VR and Augmented Reality technologies in just the past two years (Goldman Sachs, 2016). Given the massive potential growth for VR in the future, we believe that VR is the best platform on which to develop our new and modern climate data visualization tool.

Section 3 - Human Factors

Emotional appeal and user perceptions of models and visualizations are becoming increasingly important, especially for communicating data to technical audiences outside of the field and to the general public. Currently, data models tend to be extremely complex and pay little attention to human perception, but studies on emotional aspects of data visualization suggest that human perception plays an important role in how audiences understand data (Grinstein & Levkowitz, 2013).

Data sets tend to be influential when presented emotionally, as they make the data more relatable to users (Herring et al., 2015). Two important factors that appeal to emotions are spatial and temporal proximity. Spatial proximity refers to how close the user is to the data being described, while temporal proximity refers to how immediate the data are, i.e., how close the data set is to the user in terms of space and time. Studies have found data that are modeling the near past or near future are far more impactful to the user than data that are too far into the future or too far into the past (Kostelnick, 2016). Also, people find models that are changing with time more interesting than multiple snapshots (Kostelnick, 2016). This is known as temporal fluidity, which can help enhance temporal proximity by making the user feel closer to the data. Through the use of VR, the users' spatial and temporal proximity could be heightened much further by bringing them closer to the time and location of the data being presented.

Another factor in appealing to the emotions of the user is making the method of data visualization more user-friendly and interactive. One simple technique is the manipulation of color. Color creates visual stimuli that physiologically, aesthetically, and culturally arouse the user's emotion (Elliot et al., 2014)**.** Colors have been proven to enhance both user engagement and excitement when used in data models. Since data are so content specific, colors become far more important (Elliot et al., 2014). For example, when a user wants to model a specific data set, he or she may want to add emphasis on an aspect through colors to evoke an emotional or physical reaction.

Visualization techniques such as dense pixel displays and iconic displays improve visual designs for climate data. Dense pixel displays use single pixels to represent each data value with color, which allows the user to see mass data (Keim, 2002). This allows the users to see detailed information on local correlations, dependencies, and hot spots and compare data trends (Keim, 2002)**.** Iconic display allows the user to see data more clearly and can vary depending on the data being shown. Often times, combining aesthetically pleasing visuals with other techniques can further enhance the user experience. An example of a technique that can be combined with visual aspects is the use of haptic icons (HI). HI are brief signals conveying an object's or event's state, function or content which are often combined with haptic feedback. This allows the user to use hand gestures to interact with a system (MacLean & Enriquez, 2003). Utilizing haptic techniques in conjunction with aesthetically pleasing visual design may improve emotional appeal and understanding of the data more than using any one of the technique by itself.

Conclusion

While current methods of climate data visualization and analysis can effectively display a single variable, they are generally not able to represent interactions in data. This prevents researchers and other interested individuals from grasping the full effects of variations in the data, since these interactions are what allow researchers to understand climate phenomena in the first place. For instance, global temperature distributions are connected to wind patterns in the atmosphere and the surface temperature of the ocean, which are in turn connected to global precipitation patterns, but current methods do not allow users to see this sort of relationship. Current two-dimensional maps are almost completely restricted to univariate or bivariate data visualization, while three-dimensional globe interfaces have not yet been implemented to allow users this sort of control or interactivity.

A potential means of improving this lack of interactivity between the user and variables with the display would be to integrate virtual reality technology, such as Oculus Rift, into these methods. VR has already been used in medical, military, engineering and educational applications in order to give users a better understanding of important tasks. In the area of climate data visualization, VR could allow users to visualize multiple data sets simultaneously, and focus on the trends of interest. It could also help depict the effects of changes of these variables on oceans and the atmosphere, a key component missing in current methods.

Furthermore, psychological studies suggest that spatial proximity and suitable color schemes help users better perceive the significance of data; VR would help incorporate both of those features. Together, these features would create an experience in which climate researchers and other interested individuals can view in real-time how large sets of climate data interact to produce many of the oceanic and atmospheric patterns we observe today.

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Assignment 2

Describe research problem

- Current visualization techniques are awful
- These methods are outdated
- No techniques use VR currently
- Difficult for general public to understand
- If scientists have a tool to better communicate their findings that would be good

Refine general idea into research question

- How can we visualize climate data?
- How can VR be used to better improve the understanding of scientists and the general public?
- How can we design better techniques to visualize climate data through VR?
    - What algorithms are most efficient for parsing and displaying?
- How can we better present climate data to help people visualize better?
- How can current weather models be better modified to?
- How can we develop a VR tool to make it readable and relatable to the general public?
- How does virtual reality affect the public's perception of climate data?
- How does such a tool affect people's use and perception of climate data?

1. How can we build a tool that works well?
2. How does this tool affect people?
3. How does virtual reality help present data to researcher/general public?
4. How efficiently can we generate data?

Q1: In terms of computation time, power, feature selection, and storage, how can we most effectively implement a Virtual Reality climate data visualization tool?

Q2: What are the most user-friendly and aesthetically pleasing ways for scientists and the general public to visualize climate data through VR?

Qualitative, quantitative, or mixed methodology? Applied or basic research?

- Mixed methodology
    - Quantitative
    - Qualitative
- Applied research
    - Generally proving something for a purpose

Theories used?

- Psychology
- Graphical design
- VR will be a more effective method
- Weather patterns

Variables? How measured? Nominal, ordinal, interval, ratio?

Nominal = qualitative; ordinal = qualitative: good, bad, ugly; interval = distance between data points has meaning; ratio = distance between measurements, also has absolute zero

- Independent variable: code, methodology
- Dependent variable:
  Phase 1: quantitative, interval/ratio
  Phase 2: emotional response from surveys, nominal/ordinal

Logistical concerns

- Powerful enough computer
- Keeping code updated for everyone
- Time-line
- Communication

Scientific method?
Applicable: second half, predict if people will prefer certain features over the others