Earth Mission Control: A Virtual Reality Platform for Bridging the Climate Science Communication Gap

by

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Abstract

Data visualizations are incredibly powerful tools for engaging users with increasingly complex and unfamiliar information about the Earth's changing climate, yet scientists often use only one tool or modality to communicate their ideas about climate data, such as two-dimensional figures and graphs. With the rise of commercially available virtual reality (VR), we can leverage the affordances of the immersive technology to help integrate multiple modalities into a cohesive experience. In this thesis, I will present the design and implementation of the Earth Mission Control (EMC), an immersive multi-user VR data visualization platform designed to enable scientists and educators to more effectively communicate their data-driven stories of climate impacts to policymakers and community members to help them deepen their understanding of their community and the climate impacts that they are facing. The EMC combines existing visualization modalities such as NASA's Hyperwalls, spherical projections (e.g., NOAA's Science on a Sphere), map tables, virtual environments, 360 video, and human scale immersive experiences into an engaging and highly interactive VR environment, leveraging each of the modalities' unique strengths. The design and creation of an AI-powered virtual assistant is also described as a way to add increased immersion, more natural interactions, and increased presence. Initial testing of potential effectiveness of the platform in providing a deeper understanding of localized climate issues and available adaptation strategies and personal actions are also discussed.

Thesis Supervisor: Dava J. Newman
Title: Director, MIT Media Lab, Apollo Professor of Aeronautics and Astronautics

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Chapter 1

Introduction

> *If you want to teach people a new way of thinking, don't bother trying to teach them. Instead, give them a tool, the use of which will lead to new ways of thinking.*
>
> —R. Buckminster Fuller

The climate crisis is one of the most pressing issues of our time that we have faced on Earth. While there is a lot of research currently being performed to better understand the changing climate and how best to address it, there still remains a gap between understanding and action. Leaders across the world are dealing with increasingly complex and challenging policy decisions on mitigating and adapting to the impacts of climate change.

There is a need for helping people better understand climate data and think about our planet in a whole new way. So far, we have relied on the same tools we have used for decades to convey climate stories, using charts and graphs for most of our communication. Despite their popularity, these tools can be hard to interpret for anyone other than the researchers themselves[42]. Though we have begun using other techniques such as animations to convey information on a more emotional level, there has not been as much focus on developing other tools that can communicate these issues on a more personal and understandable level.

Buckinster Fuller, a sustainability architect and futurist renowned for his comprehensive perspective on the world's problems, believed us all to be astronauts on our Spaceship Earth. He believed that, like a spaceship, our planet can be seen as a mechanical vehicle that needs to be studied and serviced as a whole. He viewed all humans as being passengers on Spaceship Earth, and, much like the crew of a massive ship, we all have to work together in order to keep the planet functioning properly[38].

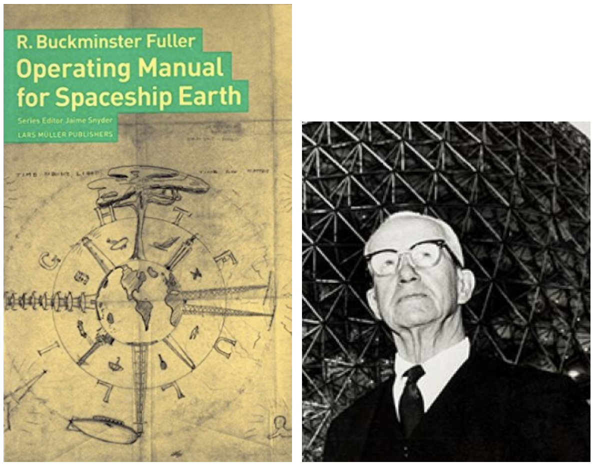


Figure 1-1: Operating Manual For Spaceship Earth (left), by Buckminster Fuller (right)

Historically, we have seen our world as being made up of many separate pieces, divided by regional and social borders. Though this can help focus our views on local issues, it prevents us from seeing the interconnectedness of our issues and how they can be addressed together. Taking on the new perspective of being astronauts together on a single spaceship gives us a path towards addressing the issues of disconnectedness mentioned above and moving towards a sustainable future.

“Since most decisions in the U.S. about land use, infrastructure, hazard mitigation, and water resources are made at the local level, it is imperative that local communities find ways to integrate climate considerations into their planning and management activities (Berke et al., 2015, Betsill, 2001)” [89]. Though there are some effective tools for climate communication and education, they are rarely geared to the needs of policy makers.

In its 2014 report, and again in the latest report in 2023, the Intergovernmental Panel on Climate Change (IPCC) confirmed that the global climate is changing [1, 19].

These changes bring with them associated impacts that are felt most strongly at the local level[5]. “A survey conducted by Brody et al. (2010) looking at both efforts to reduce greenhouse gas emissions (mitigation) and to prepare for climate impacts (adaptation) at the sub-national level found that decision-makers across sectors have low to extremely low concern about climate change. This translated into little to no climate action in their sample...”[89] While it is local departments that are responsible for climate action, they are also the least equipped to deal with these issues.

In order to significantly decrease the human effects on the climate, drastic changes are essential in economics, governance, and personal behaviors [88]. Even though people usually express general concerns about climate change, they often hesitate to practice environmentally friendly behaviors. This discrepancy between concern and action may be explained by several factors, including people’s tendency to view climate change as a far off issue that doesn’t affect them[73].

It is crucial to bring community members and decision makers together to explore issues relevant to them to ensure that all voices are heard. Through combined action, policymakers are able to enter a space/dialogue that supports them (with scientists, data, etc) in understanding the why and what of the problems being faced by their community, as well as explore and accelerate solutions for their specific community needs (mitigation).

To address the need for this sort of communal platform for connection and exploration, this thesis introduces novel a Virtual Reality (VR) platform for climate science communication focused on policy and decision makers to bridge the communication gap that exists, and that can also be leveraged with general public audiences for educational and awareness efforts. The goal of the research is to develop a platform to help decision makers better understand the causes of climate impacts in their local areas and enable them to explore the data in a more informative and understandable way. The issues facing decision makers today are becoming increasingly more complex, involving larger amounts of data that cut across disciplines. By leveraging the affordances of multiple data visualization modalities, this project aims to lessen the burden on data understanding and communication, enabling scientists to more effectively support policymakers in data-driven explorations and decisions. It will allow users to explore across a range of types and formats to understand the environmental impact of climate change from a global to a local scale. The work from this thesis can also be expanded to a larger initiative that aims to develop a comprehensive multi-user immersive physical visualization environment that can deliver these climate stories to a broader audience.

1.1 Thesis Contributions

The goal of this work is to create a virtual platform that is focused on helping users view Earth's "vital signs" to explore and understand the impact of climate change by combining different visualization modalities together. Moreover, the platform aims to reduce the need for new ad-hoc virtual experiences to be created for each new research exploration. The system is called Earth Mission control (EMC), and is a reusable and modular multi-user virtual reality data visualization platform. It serves as an initial step towards creating a connected virtual environment for studying and understanding Earth's vital signals. The EMC platform enables groups of users to interactively and collaboratively explore climate data together in VR, supporting science data communication for education and decision making. This work does not present a final solution on how to best present climate data, but rather it acts as a starting point to explore these questions in a systematic way.

While there has been work in recent years reviewing existing VR experiences and understanding some underlying principles[76], there remains a need for a platform for facilitating new research in these areas. We have developed a tool to be able to rapidly deploy and test various climate data visualization techniques in a multi-user space in order to develop best practices for virtual data visualization and communication. The work presented in this paper attempts to address this gap by providing a novel virtual reality and augmented reality sandbox to develop and test various visualization techniques and tools.

The summary of the contributions in this thesis are:

- A VR platform for developing virtual climate data experiences
- Novel multi-modal methods of interacting with multi-dimensional data combining gaze, voice, and hand-tracking
- Explored novel designs of scientific communication and visualization using spatial computing
- Unique combination of popular display modalities to highlight multi-dimensional connections
- An AI virtual assistant to aid in the navigation of the virtual environment and data

1.2 Thesis Overview

This thesis will walk through the design and development of the Earth Mission Control platform. In Chapter 2 I provide an overview of the challenges of climate data communication, with some background on cognitive load and how it affects data understanding. I then explore the current state of solutions available for communicating climate stories and their limitations. Finally, after reviewing other projects that leverage immersive technologies and the insights that these projects brought, I discuss the research motivating the use of virtual reality, covering its benefits for climate data visualization and communication.

Following this, in Chapter 3 I go over the system design of EMC. I review the overall architecture of the system and the tools used to build the platform, covering libraries used, the different data visualization modalities, and available tools. Next, in Chapter 4 I discuss the user interaction design, reviewing the guiding design principles and system implementation. In Chapter 5, I introduce EarthBot, a virtual AI-powered assistant that was added to the platform and extends the capabilities of EMC. I review the design, development, and benefits of the virtual bot and reflect on possible performance improvements to create a better user experience. In Chapter

6 I introduce the working prototype and review feedback that was collected during informal user testing. This chapter also discusses a couple of example demo scenarios that were created to illustrate the potential use cases of EMC as an education and decision-making platform. Lastly, in Chapter 7 I conclude the major findings and summarize the contributions of this thesis, highlighting future work that can help expand the capabilities and reach of the platform, moving us towards a more sustainable future.

Chapter 2

Literature Review

2.1 Localization of Climate Challenges

The repercussions of climate change, including droughts, heatwaves, floods, and vector-borne diseases, have been, and are projected to continue affecting communities most at a local level[9]. This means that it is crucial for local leaders and community members to include climate considerations into their management and planning, since most decisions in the U.S. about land use, infrastructure, hazard mitigation, and water resources are made at the local level[8, 23]. Despite the clear need for expertise and guidance, most local governments lack the capabilities and understanding required to be able to take into consideration all of the added complexity of climate change[9].

While climate change is most strongly affected by local action, it's a global issue where the local actions of policy makers and community members have a direct effect back on the larger global system. This multi-scale connected nature of climate change highlights the need for the global-to-local-to-global (GLG) paradigm[6]. Understanding these interconnected relationships is a major key in being able to take informed actions to mitigate and adapt to our changing climate. Studies have shown how important it can be to view climate change through the GLG lens when considering policy responses[47, 46].

The ability to access and understand this interconnected climate information

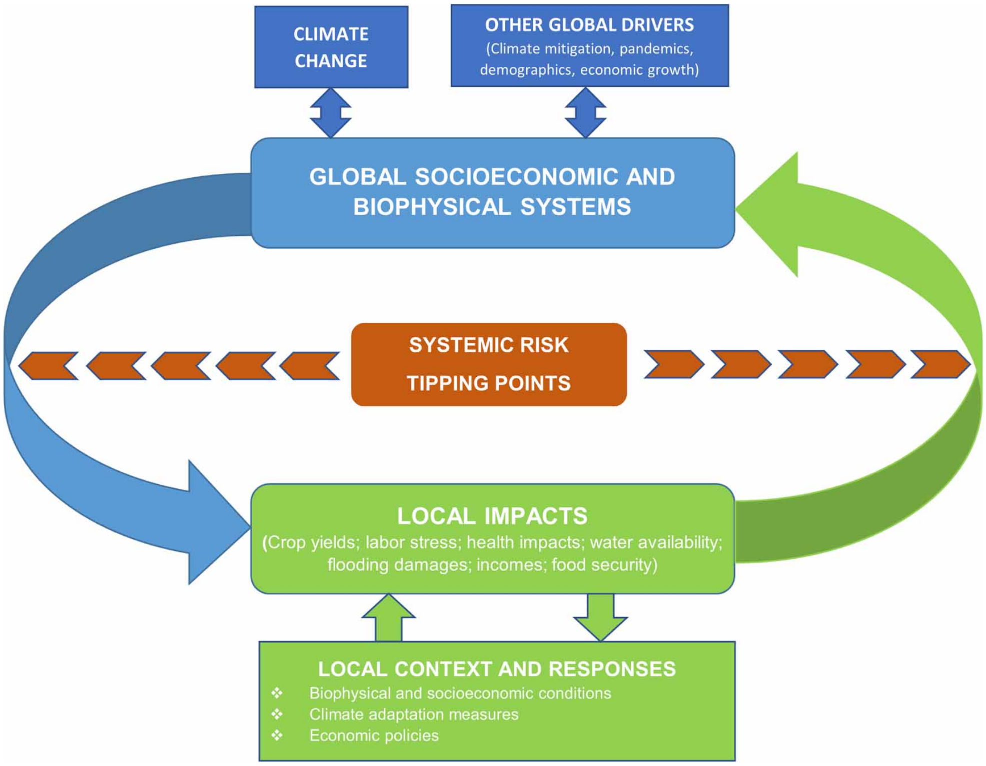


Figure 2-1: Flowchart of the GLG connections as related to climate change. Image Credit [6]

plays a key role in enabling society to leverage scientific insights for climate change adaptation[51]. One of the major issues for climate service providers historically has been to effectively communicate climate-related data and the corresponding uncertainty in a way that is easily understood by users with different levels of expertise[58, 72]. To address this, climate service providers often turn to using visualizations custom made for each users' needs to provide the climate knowledge required for effective decision-making[39, 120].

2.2 Complexity of Climate Data Communication

Standard visualization techniques like time and bar charts, box plots, scatter plots, probability distribution functions, and different types of maps (such as flood maps, heat maps, choropleth maps) have traditionally been the preferred methods for the scientific community to represent climate data[49, 3]. While these formats are commonly used when discussing climate data, they tend to cater more to expert audiences who have the necessary background knowledge. They neglect the broader audiences such as policy makers and community members who, despite their growing involvement in climate adaptation processes, may not be as familiar with these conventional ways of displaying climate data. Even for those familiar with these visualizations, the data is always limited to a single visualization modality at a time.

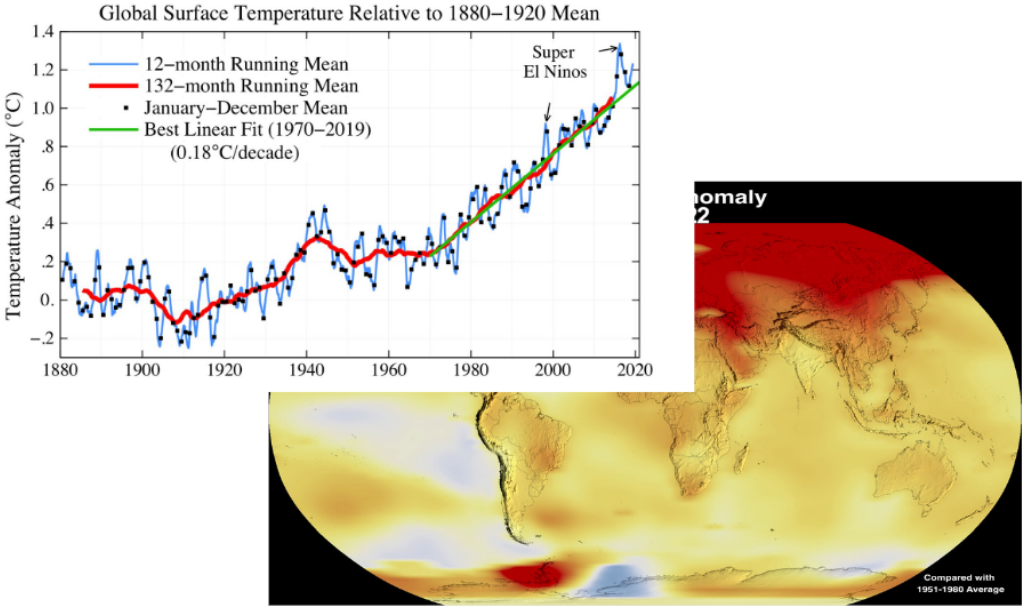


Figure 2-2: Graph of Earth's surface temperatures (top) and a still from an animation showing global temperature increases (bottom). Credit: NASA Scientific Visualisation Studio (SVS)

Because the process and consequences of climate change are often unclear to the general public [48, 35], scientists aim to make their research psychologically closer and more relatable to participants[31].

Similarly, previous studies have shown that experiencing climate change effects firsthand (such as heatwaves, floods, etc.) tends to increase people's perception of climate change as a risk, which in turn is associated with an increase in pro-environmental behavioral intentions[15, 114, 122].

According to research, the perceived psychological distance, including aspects such as spatial, social, temporal, and hypothetical distance, plays a crucial role in fostering behavioral change related to the environment [57, 74]. The psychological distance related to climate change is considered one of the main causes for climate-inaction. The larger the social (it happens to others, not me), temporal (it happens later, not now), spatial (it happens somewhere else, not here), and hypothetical psychological distance (the effects are uncertain, not certain), the lower the likelihood of action [84].

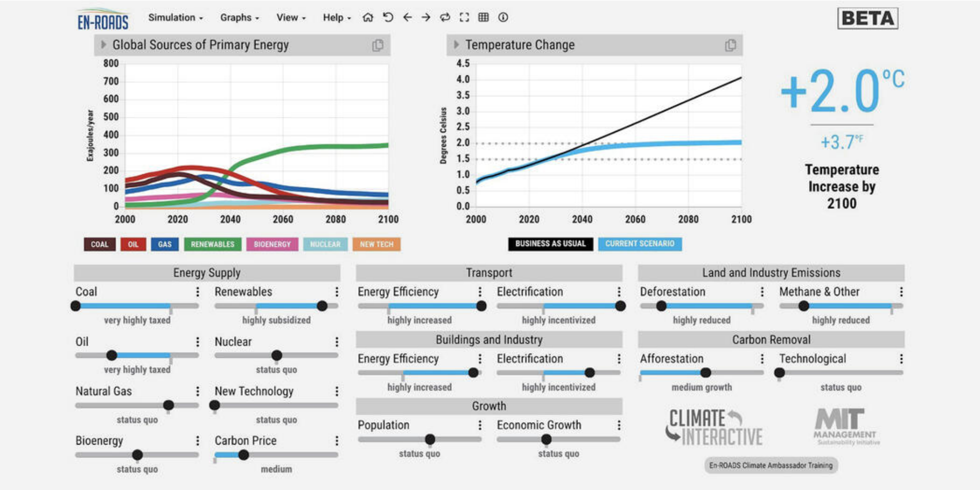
Interestingly, this issue of psychological distance that drives climate inaction is the same concept that is often cited as a reason for the effectiveness of virtual reality. By making the "invisible visible"[31], virtual reality (VR) has been proposed as a powerful tool to amplify awareness around climate change. Virtual reality has the ability to facilitate deeply immersive experiences that parallel real-life scenarios[82]. This means people can safely encounter the effects of climate change, such as a wildfires and flooding first hand, decreasing the psychological distance [84]

Beyond just the issue of psychological distance, the complexity of climate data creates a need to balance the cognitive load of users to ensure they are not overwhelmed and are able to process the information. Cognitive load is defined as the amount of effort that is exerted or required while reasoning and thinking. Cognitive Load Theory (CLT), was first proposed by Sweller in late 80s, and builds upon the model of human cognition presented by Atkinson and Shiffron in 1968 which defines memory as having 3 distinct parts, a sensory register, short term memory (STM), and long-term memory (LTM)[4]. The theory was proposed as a framework "to provide guidelines intended to assist in the presentation of information in a manner that encourages learner activities that optimize intellectual performance"[118]. This theory points out the limitations of our working memory and highlights the importance of preventing overload to improve information understanding.

The CLT identifies properties that can make information more or less digestible based on how it's presented. Cognitive load can be divided into intrinsic and extrinsic categories. Intrinsic load relates to the inherent challenges involved in understanding content, whereas extrinsic load pertains to its presentation. When considering climate data communication and the complexity involved, there are a couple of ways that current data visualization methods add to extrinsic cognitive load due to their limitations. One example of this is split attention, which is when different data is displayed across multiple screens. Working on multiple displays, across multiple programs or other inconveniences like this can quickly add up the limited slots in the STM and overload the user[44]. Another example is dimension mapping where geo-spatial data is presented in 2D, forcing users to create a mental mapping to 3D.

Climate Simulators

One common tool to explore the impact of different actions on future climate projections are climate simulation tools. For example, a couple of these simulators are En-ROADS[116] and C-ROADS[115], developed by Climate Interactive, the MIT Sloan Sustainability Initiative, and Ventana Systems, have been used to educate over 200,00 peoples on the importance of the climate issue and how different global and regional actions can affect the future climate projections.



Energy Supply
Coal: very highly taxed
Renewables: highly subsidized
Oil: very highly taxed
Nuclear: status quo
Natural Gas: status quo
New Technology: status quo
Bioenergy: status quo
Carbon Price: medium

Transport
Energy Efficiency: highly increased
Electrification: highly incentivized

Buildings and Industry
Energy Efficiency: highly increased
Electrification: highly incentivized

Growth
Population: status quo
Economic Growth: status quo

Land and Industry Emissions
Deforestation: highly reduced
Methane & Other: highly reduced

Carbon Removal
Afforestation: medium growth
Technological: status quo

Figure 2-3: Screenshot of En-ROADS climate simulator[116]

While effective, these tools have a major limitation in that they mainly focus on near global scale events. En-ROADS only shows the impact of global action, which is not a reliable metric and would be unevenly distributed based on region. The C-ROADS emulator shows how certain country level actions can impact the environment, but doesn't allow for granular enough control or allow for exploring actions across the energy sector, which are crucial for accurate projections.

Other approaches to climate simulation and visualization have also been explored.

One of the challenges in climate research right now is getting accurate climate projections that are granular enough and predictive enough to be useful for informed decision making at a local level. There are models that exist that can predict the future climate for an area, but in order to get even just a single year projection of the world's climate at a 1 km2 resolution, it takes a supercomputer cluster with 5000 GPUs running for ten days, which uses the same amount of energy that a coal power plant can produce in an hour [37]. For this data to be useful, it needs to be able to forecast not just a single year, but rather over one hundred years. In order to solve this challenge, the Climate Pocket research being performed by Dr. Bjorn Lütjens[78, 77, 18], aims to leverage the use of generative artificial networks (GANs) in order to create more efficient, accurate predictions. The work is "a climate education simulation that leverages fast machine learning (ML)-based climate models to illustrate local science-based flood impacts of global climate policy decisions"[79].

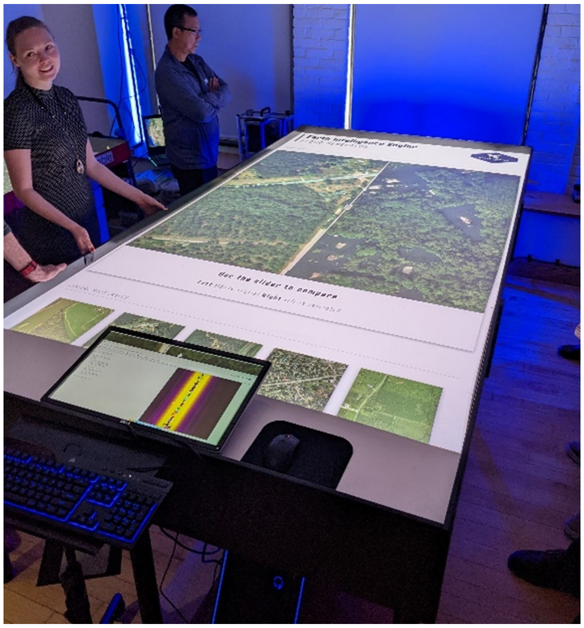


Figure 2-4: Photo of the Earth Intelligence Engine projected onto an interactive table[78]. Source: https://climate-viz.github.io/

2.3 Virtual Reality

Thanks to a culmination of advances in computer science, the accessibility of VR has come a long way since its humble beginnings. In the last half-decade since the introduction of the Oculus Rift, and more importantly, the Oculus Quest, VR became a medium accessible to the average person. Over the last few years, the cost and barrier for entry into VR has come down so much that VR can be considered a common technology. This has led to an unprecedented boom in the use of virtual reality for non-commercial (personal) use that has helped drive further development in the field. With this continued investment into VR, the technology has been able to go through an incredible revolution, improving its sense of presence.

With this rise in accessibility, VR has been explored as a potentially promising tool in many contexts and for a variety of topics and aims: for professionals and stakeholders [63, 64, 61], in education [82, 7, 104], and on various subjects including plastic pollution[22] to building design[63], sustainable mobility [100], tourism[104] and water management[64], among others. Additionally, different virtual modalities have been explored, including immersive experiences[22, 16], mobile applications [100, 32], computer games [104, 32], simulations [7, 59], games [32, 36, 20], and single- [22, 16, 123] and multi-user [64, 20] applications. Given all of these different possibilities, VR developers have a huge amount options available when creating virtual experiences, and with that, the ability to manipulate and change features depending on the specific content and audience. This ability to tailor experiences depending on the user and their learning styles can be a great advantage in education [70].

This emergence of commercially available augmented and virtual reality (AR/VR) technology has provided a way for researchers to engage with climate data beyond just the traditional methods of charts and graphs, which have been shown to be difficult to use for complex data[42]. By immersing user in the data, these technologies attempt to address the limitations of current visualization methods and studies have shown that these new approaches have statistically significant improvements in data understanding [82, 33].

Beyond data visualization, VR has the ability to connect data to intuitive virtual representations, leading to the even more powerful concept of data visceralization. First proposed in 2020 by researchers at Microsoft, data visceralization combines data visualization abstractions with their original units and measures to create a complimentary experience that can lead to a deeper understanding of the information [65]. The quantitative and analytical understanding that is often gained from visualizations is complemented nicely by the qualitative aspects of the measure. For example, instead of just showing the relative heights of tall buildings on a chart, it's possible to place virtual copies of them next to each other in a VR environment, as seen in Fig. 2-5. This allows users to intuit the physical relations between the measurements and the visual representations.

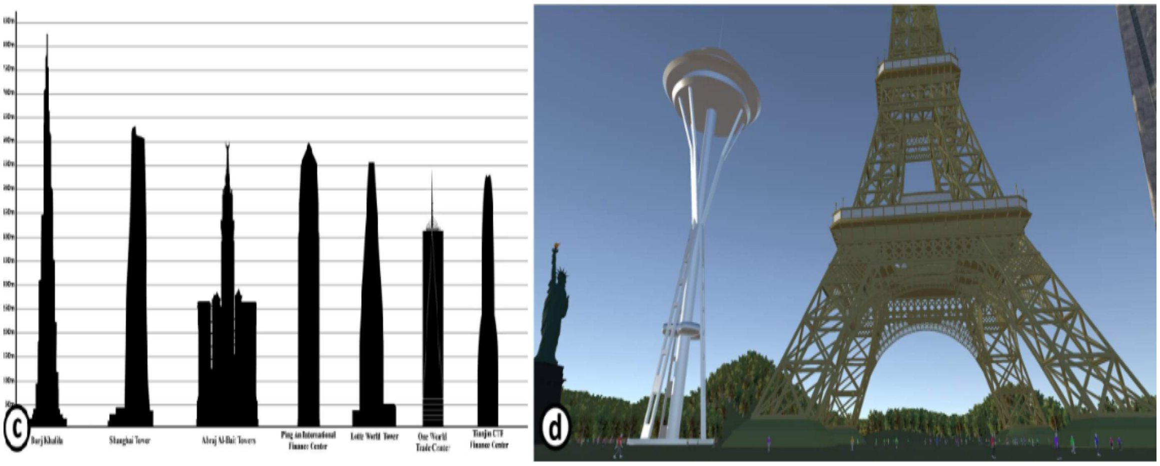


Figure 2-5: Data visceralization prototypes compared to their common representations, showing a comparison diagram for the world's tallest buildings (left) vs an immersive 1-to-1 scale VR experience visualizing the relative heights (right). Image Credit: Lee et. al. 2020[65]

Additionally, over the past twenty years, advances in virtual reality research have highlighted the technology's ability to be a powerful tool for transforming beliefs and attitudes, and to a more limited degree, influencing behavior[110]. Multiple studies have shown that virtual reality significantly is better at eliciting a sense of spatial presence as compared to traditional videos[17, 34].

Earlier studies have explored ways in which VR can have a unique impact on human behavior and decision making, finding five main ways [106]:

- Summing behaviors' effects: displaying collective and long-term consequences
- Providing a journey in space and time
- Creating a symbolic and concrete representation
- Presenting and evaluating future solutions
- Testing future solutions with users

There is growing evidence that leveraging these opportunities is very important, since exposing individuals to the potential impacts of climate change through immersive virtual reality could underscore the urgency of the problem and kick-start action[84]. Studies have shown that people feel closer to the environment and consequently perceive higher risks related to its pollution through the use of virtual experiences. [36].

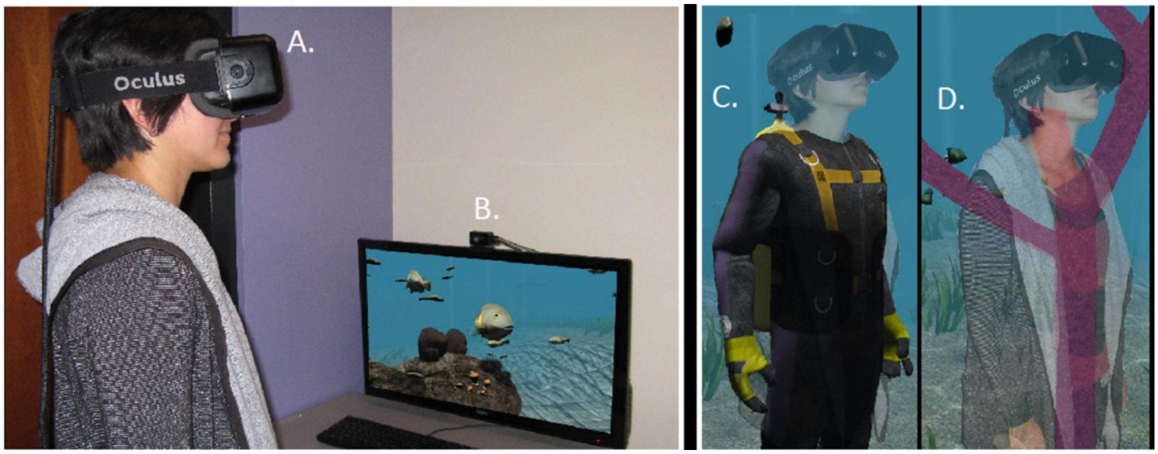


Figure 2-6: Participants from study by Markowitz et al., 2018, exploring use of VR to teach about ocean acidification, with the participant wearing an Oculus rift headset (A,B) and experiencing the underwater environment from the perspective of a diver (C) and of a coral (D). Image Credit: Markowitz et al.,2018[82]

Virtual reality has the ability to create powerful psychological experiences thanks to its 3 primary affordances: presence, immersion, and embodiment[108]. Here, presence refers to the psychological feeling of "being there" in a virtual environment[52] and has been called the "illusion of non-mediation"[71]. Users are able suspend their belief that the virtual world they are in is artificial when a VR experience is well executed[66] While presence is the feeling of being there, immersion refers to how well the users' movements and actions translate to the virtual world. Specifically, immersion refers to the medium's technological quality, which is gauged by how accurately the VR hardware interprets human movements [26]. To be able to talk about experiencing something virtually, the immersive quality of the medium and the subsequent illusion of spatial presence ("being there") in the virtual surroundings are important[82]. Research shows that virtual reality is better suited to elicit a sense of spatial presence compared to regular videos [17, 34]. Lastly, embodiment provides the ability for users to take on the form or perspective of another character [109, 10]. While embodiment has commonly been considered a feature of virtual experiences for years, it is particularly pronounced in VR experiences where the effects of immersion and presence are combined [13]. For example, in a recent interview-based study exploring responses to ocean acidification showed that the majority of participants felt the problem seemed psychologically closer, triggering negative emotions when experienced in virtual reality [98]. This is significant as negative emotions have been found to be an effective way to influence action, intentions, and attitude change [119].

Other studies have explored the effectiveness of bringing existing display modalities into VR. Using tools such as map tables in VR shows very comparable engagement and learning results when compared to their physical counterparts[117]. Other tools such as Science on a Sphere have had a VR extension for years and have been used for educating a lot of people across the world. These tools illustrate how using VR can lead to a much deeper understanding of more complicated data and a greater ability to see complex patterns.

2.4 Summary

With the growing complexity of our climate issues, it's becoming crucial that local policy makers and community members are able to leverage current scientific data for more data informed climate actions. As the complexity of the climate issues grows, so does the quantity of data required to address them. In order to manage and understand all of this complex data, scientists have often relied on visualizations to help contextualize the information.

One of the major limitations of the visualization approaches explored above however, is that they all have only focused on a single modality of data visualization at a time. In order to be able to see the complete story being told, it's important to look at the data from a global-local-global perspective. To be able to make connections to other regions experiencing similar issues and learning from each other's different approaches, leveraging the varying affordances of different display modalities is crucial.

"Virtual worlds are often built as a proof-of-concept to demonstrate climate change phenomena can be rendered in immersive VR."[81] As a result, there are many ad-hoc experiences that have been created for each study individually. These inconsistencies highlight a need to develop a common platform for enabling rapid development and testing of interactive, multi-user VR experiences that can be adjusted and reused in different settings.

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Chapter 3

System Design

3.1 Overview

The Earth Mission Control (EMC) is a novel, multi-user climate science data visualization development platform aimed at helping climate scientists tell their stories with data. It is an experimental platform to explore integrating multiple types of data visualization modalities such as NASA's Hyperwall, spherical projections (like NOAA's Science on a Sphere), map tables, virtual environments, 360 video, and human scale immersive experience, leveraging the affordances of VR for better data communication, understanding, and engagement. By bringing the different display modalities together, EMC can enable users to get a multi-dimensional view of Earth's vital signs, from the global to a local scale, helping visualize the global-to-local-to-global(GLG) connection. In this chapter, I describe the design requirements for EMC, its architecture, and its implementation. This project was designed and developed during the Fall 2022 and Spring 2023 semesters by me under the supervision of Professor Dava Newman. This work led to the creation of the first prototype version of EMC, and I will describe future directions and potential that this platform enables.

When considering the system design, it was important that the platform is able to create a collaborative environment, enabling visualisations of dynamic spatialized data, while still providing an intuitive interface. Additionally, because EMC is a tool aimed at helping educators and scientists better tell their climate data stories, keeping them at the center of the system design was key. To address this, the Technological Pedagogical Content Knowledge(TPACK) framework was used to guide some of the design decisions, first introduces by Mishra and Koehler in 2006[85]. This framework "attempts to identify the nature of knowledge required by teachers for technology integration in their teaching, while addressing the complex, multifaceted and situated nature of teacher knowledge." Specifically, within the TPACK framework, EMC aims to explore the technological content knowledge (TCK) combination. This combination focuses on building the "understanding of the manner in which technology and content influence and constrain one another[85]." EMC is a testbed for rapidly testing ideas about which modalities are best for which kinds of data and learning how this content influences the technology used, and vice-versa, a key aspect of this combination[62].

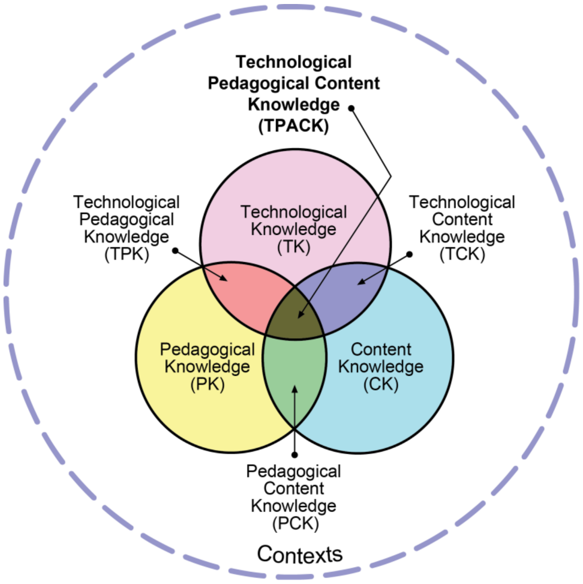


Figure 3-1: Diagram of TPACK framework[85]. Image Credit: http://tpack.org

3.2 Architecture

The EMC platform was built using the Unity game engine (Version 2021.3.20f1). Unity is one of the most popular game development engines that has a large community of developers. The other major game development engine is Unreal Engine. While both tools offer a great set of features, Unity was chosen for its ease of use and ability to quickly prototype interactive experiences. One of the main differences between the two platforms is that Unity code is written in the C# language, while Unreal uses C which is more complex, or blueprints, which is its built-in drag-and-drop scripting system. The blueprint system is great for helping non-coders get started with game development, but for this project, which involves integrating with multiple different services, ease of integration was a key factor.

Scale X 4.22536 Y 0.01999 Z 4.22535

Cylinder (Mesh Filter)

Mesh: Cylinder

Mesh Renderer ☑

Materials: 1

Element 0: Shiny

Lighting

Cast Shadows: On

Contribute Global Il ☐

Receive Global Illu: Light Probes

Probes

Light Probes: Blend Probes

Reflection Probes: Blend Probes

Anchor Override: None (Transform)

Additional Settings

Dynamic Occlusion ☑

Rendering Layer M: Layer1

Capsule Collider ☐

Edit Collider

Is Trigger ☐

Material: None (Physic Material)

Center X 5.96046 Y 0 Z -8.9406

Radius: 0.5000001

Height: 2

Direction: Y-Axis

Shiny (Material)

Shader: Universal Render Pipeline/Lit

Figure 3-2: Screenshot of EMC in Unity Editor

This project was designed primarily for the Meta Quest but was developed to be able to run across many VR devices. Both a Meta Quest 2 and a Meta Quest Pro were used during development. The Quest is a mobile VR headset which means that it is able to run without the need of a host PC but can also be connected to a computer to enable more high fidelity experiences. While not as powerful as other PCVR Head Mounted Displays such as the HTC Vive or the Valve Index, the Meta Quest was chosen because it allows for both a wired and un-tethered experience. This lowers the hardware requirement to get started with the experience and allows for more people to try it out without needing a powerful PC to run it. The higher quality experience is still possible when running the Quest using the Link cable, which is a USB-C cable that connects the headset to a PC for PCVR. Beyond the ease of use, the Quest headsets also provide a set of unique features such as hand tracking, which allow for a much richer and immersive user experience.

3.2.1 Networking

At its core, EMC is a collaboration tool so it's important that multiple groups of people are able to engage with the system at the same time in their own virtual spaces. Even though Unity is often used to create multiplayer games, it wasn't until this past year that they introduced their own, first-party networking solution. Because of this, there have been a lot of third-party solutions that have been developed by other companies over the years. While it is good to have multiple options, it can also cause confusion when choosing the best solution because of varying levels of documentation and support. Popular tools include Normcore, Photon, Mirror, and Unity's new Netcode for GameObjects (NGO).

For this project, I went with the Normcore platform as it is one of the best supported tools for adding multiplayer while also being fairly simple to integrate. It provides all of the main important features required for multiplayer including synchronizing data across clients, ensuring consistent connections, and providing support for live voice interaction through Voice-over-IP. Most multiplayer networking systems usually rely on Remote Procedure Call (RPC) messages to synchronize multiple users. These messages act as a way to tell the remote server what actions to perform, wait for them to execute, and then send the response back to the client. Created in the late 70's, this system required developers to create their own systems to synchronize the state of the application by sending messages directly to each client. This was notoriously difficult to implement correctly, and would often cause the application to fail unpredictably when not build properly. With multiple clients trying to update the server at once, managing all of these messages can be very challenging and developers spend most of their time solving these issues.

Normcore avoids this issue by using a concept called 'DataStores' to create a central source of truth for the application state. This state is stored on the remote server and when users update any of the state, the DataStore just needs to get updated and Normcore will synchronize the change to everyone else automatically. The DataStores can automatically detect changes and sends an update to all of the connected clients. Beyond ease-of-use, this system provides additional benefits such as making it easy for users to join mid-session and for the virtual spaces to be saved when a server shuts down so it can easily be brought back the next time users connect.

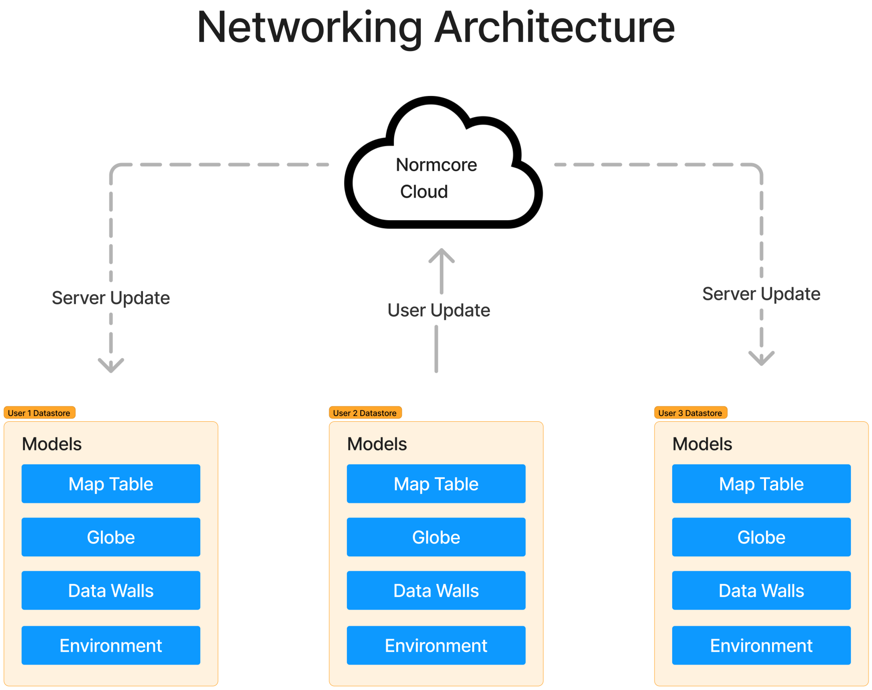


Figure 3-3: Networking Diagram of EMC components across multiple users.

Normcore is built on the concept of Model View Controllers (MVC), which is a common way for web and mobile apps to represent networked data. In this architecture, the DataStores store RealtimeModels, which are digital representations of the information required to be synced between users. To illustrate, EMC uses models to represent the state of each display module to ensure that all users are seeing the same data. For example, the model keeps track of the rotation, scale, and the data layer being displayed on the globe, the zoom level, data set and location being explored on the map table, and the different data being displayed on the Hyperwall. While there were default components for tracking basic information like position, rotation, and scale, keeping track of the other values such as map location required the creation of custom models. It's crucial to make sure all of this information is properly synchronized across users to ensure everyone is talking about the same thing and to make sure there isn't any confusion caused by incorrectly updated displays. These models are all in turn synchronized through RealtimeComponents, which keep track of the local state of each object and make sure they are up to date with the information in the DataStore. Each client maintains a view of the objects and whenever the view of an object is changed by the RealtimeComponent, an update is sent to the RealtimeModel which then updates the DataStore, as seen in Fig.3-3. The other client RealtimeComponents read the update from the DataStore and then update their local views accordingly.

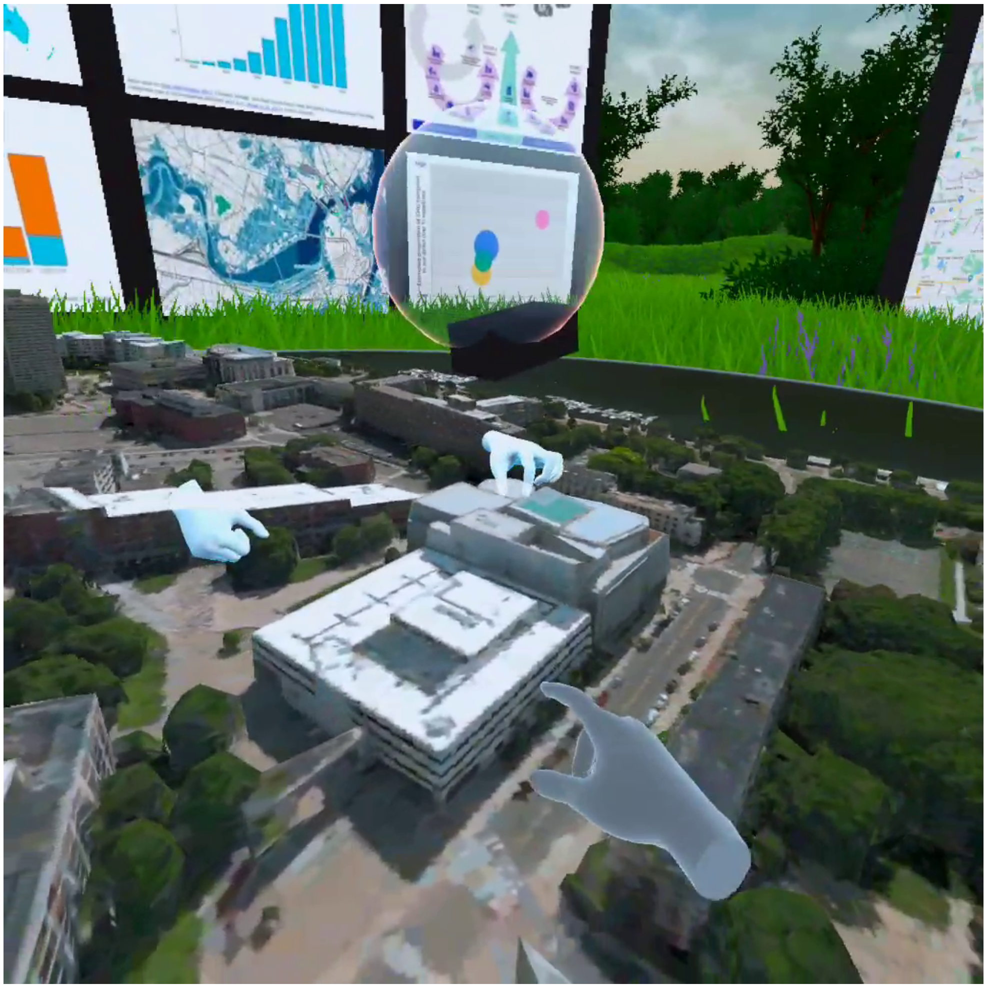


Figure 3-4: Screenshot of multiple users in EMC interacting with map table

One of the main benefits of using virtual reality and multiplayer together is the level of presence gained when users interact together. Body language is an incredibly important part of human communication and one that is lost when using remote video collaboration tools such as Zoom, which everyone became very familiar with during the COVID-19 pandemic. VR can address this by capturing the users natural head and body movements through the headset, making remote users are able to feel physically present with each other, even when miles apart [68].

Beyond synchronizing the state of the environment between players, Normcore also enables seamless real-time audio interaction through Voice-Over-IP. This lets users speak with each other naturally and adds a layer of immersion. These voice interactions, combined with the synchronized body movement make it feel like the remote users are actually present.

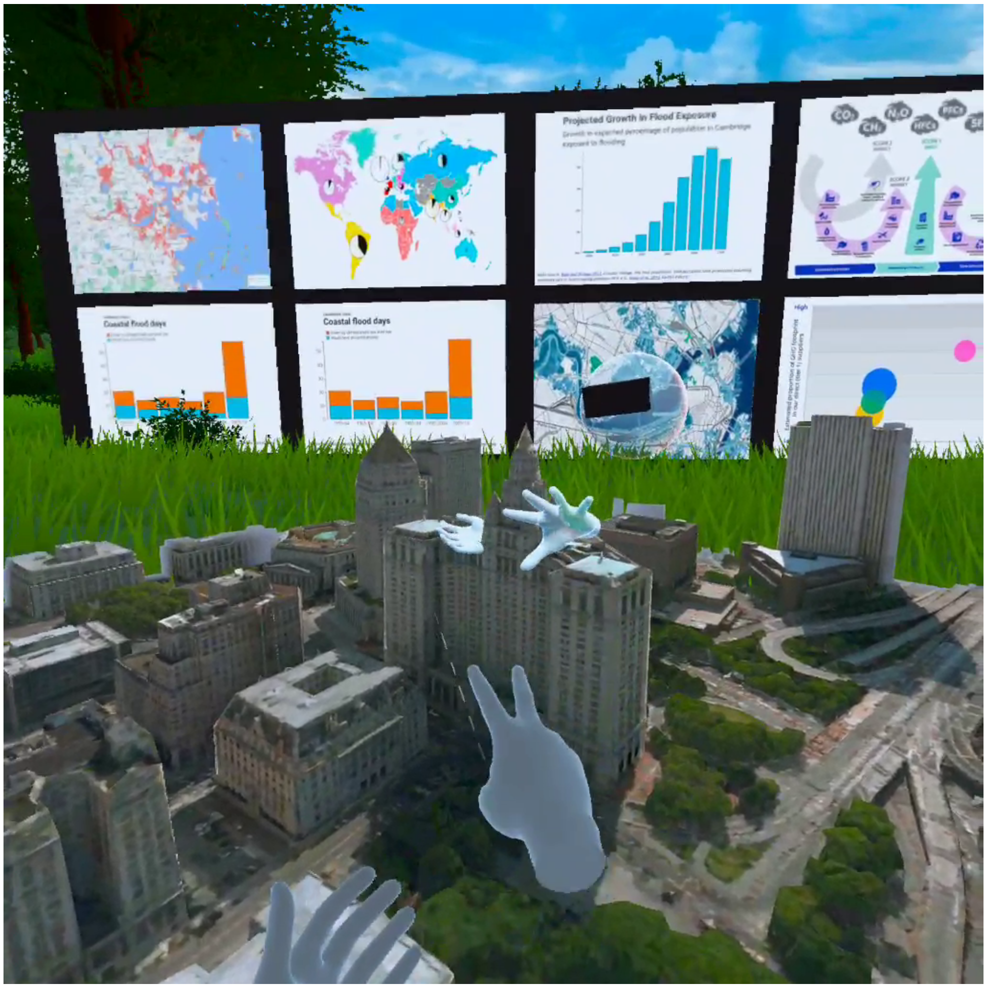


Figure 3-5: Screenshot of users in EMC communicating using spatial audio and hand gestures

Additionally, this audio is spatialized, which means that stereo speakers on the headset are able to replicate the direction, distance, and position of audio signals, creating a more realistic experience. This means that users are able to hear those near them loudest, while those far apart can't hear each other as well, just like in the real world. This audio drop-off and spatialization allows for even more natural and immersive interactions, where users are able to split off into different groups and have separate discussions about different topics or data.

3.2.2 Interaction Management

When creating graphical web applications, developers often leverage frameworks such as Vue, React, and Angular. These tools allow developers to more easily build user interfaces and make sure the applications feel consistent. Unlike 2D web development, virtual reality development does not have its design patterns and practices set yet. This means that there is a lot of flexibility when designing virtual reality experiences and it's important to be able to use a framework to keep the interactions consistent. While not as robust as the tools available for web development, there are a number of interaction tool-kits available for use in VR. These Software Development Kits (SDKs) are great tools and a way to easily integrate many pre-built and configured interactions in your XR project such as grabbing objects, interacting with UI, recognizing hand gestures, etc.

Popular toolkits include, Virtual Reality Toolkit (VRTK), the Windows Mixed Reality Toolkit (MRTK), Mixed Reality Toolkit (XRTK), Unity's XR Interaction toolkit, and the Oculus Interaction SDK. For this project I chose to go with the the Windows Mixed Reality Toolkit(MRTK) developed by Microsoft. This toolkit is cross-platform, based around the OpenXR API standard that allows for the app to run on multiple different kinds of VR headsets without needing to change the code. Specifically, OpenXR is "a royalty-free, open standard that provides high-performance access to Augmented Reality (AR) and Virtual Reality (VR)—collectively known as XR—platforms and devices[2]". Additionally, this toolkit is opensource, with an active base of users and contributors, giving it a more consistent update and support

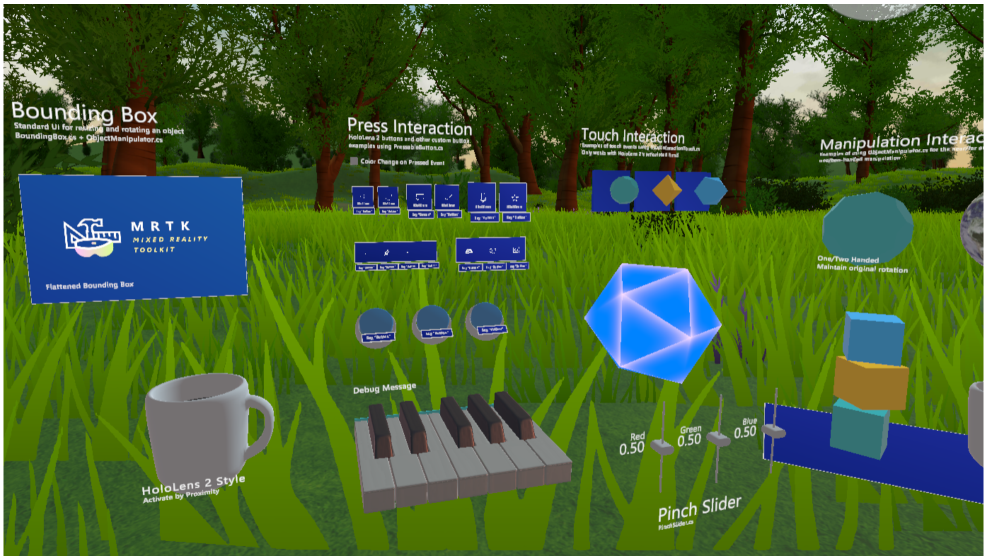


Figure 3-6: Screenshot of example interactable objects from MRKT in EMC environment, including buttons, sliders, and 3D shapes

schedule and ensuring that the tools will continue working well into the future. One issue with the rapid development of VR technologies is that many tools can become out of date quickly without consistent updates. Even though Microsoft is ending official internal development on the platform, they still support community efforts and are guiding the continued improvement of the platform.

Because MRTK isn't natively set up to support Normcore, which is used for networking, it was necessary to include additional components to ensure everything was properly synchronized. The components that made this possible were MRTK online and the Networked Manipulator, created by Eric Provoncher and available through GitHub as an extension of MRTK here.

3.2.3 Virtual Environment

> "We modern, civilised, indoors adults are so accustomed to looking at a page or a picture, or through a window, that we often lose the feeling of being surrounded by the environment, our sense of the ambient array of light. .. We live boxed up lives."
>
> Gibson, 1986 [41]

As mentioned before, one of the most powerful features of VR is its ability to create a sense of presence, a feeling of "being" in a virtual space. VR can serve as a tool for going beyond the traditional 2D ways of interaction. Because of their immersive nature, VR experiences rely heavily on their virtual environments. In order for it to be an approachable and engaging experience, not only does the interface need to be intuitive, but the whole environment should feel welcoming and comfortable. The design for the EMC virtual environment is inspired by the SolarPunk design movement which envisions “a sustainable future interconnected with nature and community”[99]

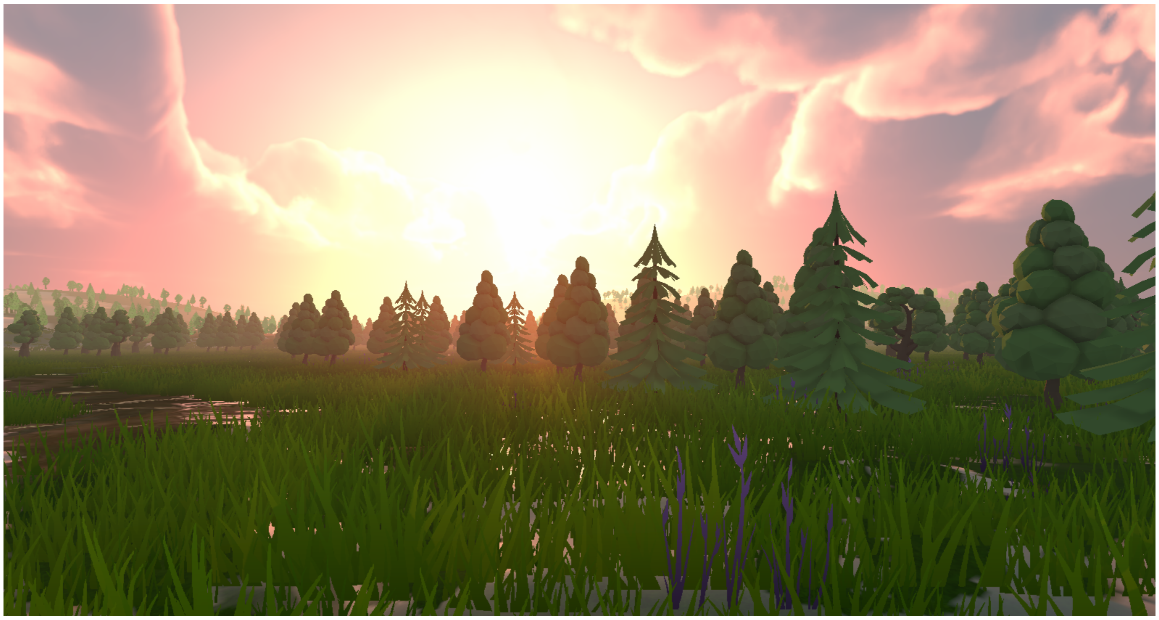


Figure 3-7: Screenshot of the natural virtual environment

This vision continues the theme of Spaceship Earth, as presented by Buckminster Fuller, and helps create a sense that the platform is connected to our planet.

By incorporating data visualization tools into a virtual outdoor environment, complete with vegetation and other environmental details, the space can convey a sense of connection with the Earth and allow for a more immersive experience. In order to make the environment feel more alive and immersive, extra attention was given to adding in subtle details such as nature sounds, trees and animated birds. By adding these little environmental cues, EMC immerses users in the virtual environment and adds a subtle sense of realism that helps connect users with experience.

Sound is one of the primary ways in which we perceive the world around us and it is equally important in VR. Multiple studies have shown that leveraging spacial audio that aligns with the visuals of the environment correlated with medium to large increases in the feeling of presence [111, 54, 96]. To ensure the EMC is as immersive as it can be, special attention was given to the sound design of the experience. When the user first enters the experience, they will be greeted with the calm sounds of nature, with quite bird songs, wind, and light ambient music. These added elements help immerse the users more deeply, leading to greater engagement. Not all users have the same reaction to sound stimuli so EMC has the option of controlling the volume of the ambient sounds and turning it off entirely if it is overstimulating or distracting.

Because the EMC will be used as a testbed to explore different visualization modality combinations, it's important that the environment can be easily reconfigured. By representing different visualization tools as reusable virtual components, we can rapidly experiment with different layouts and configurations for the EMC. The initial sample layout for EMC consisted of the main visualization modules arranged in a row near each other. This was useful for initial development since it allowed for a very simple layout to test the modules together for basic functionality.

Once the initial functionality was developed, I worked with Gui Trotti, an internationally recognized architect and industrial designer, to explore different layout arrangements. Combining various aspects of architectural design, a layout was chosen that arranged high Resolution display walls around the space, with the map table taking up most of the space in the center and the globe module floating above it, as seen in Fig. 3-9. This arrangement enables users to view the global data on the

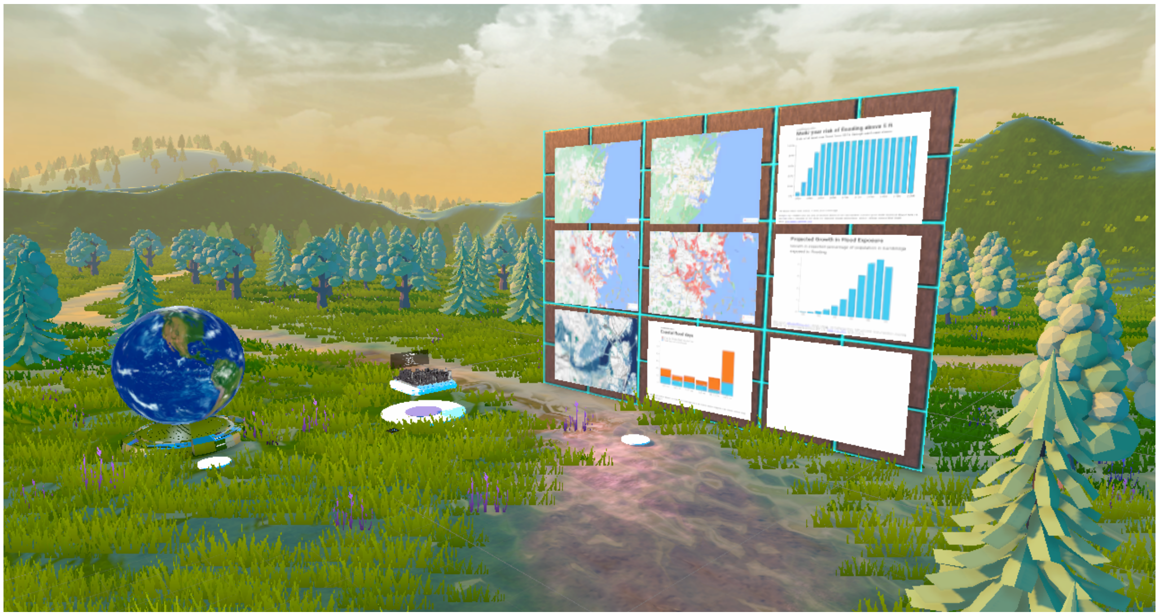


Figure 3-8: Screenshot of initial EMC layout

sphere and see the local connection at once, without having to move between screens or look around. Additional relevant data is presented on the surrounding walls, with each section corresponding to data on a different scale. This lets users see global, regional, and local data all at once and be able to go between each representation seamlessly.

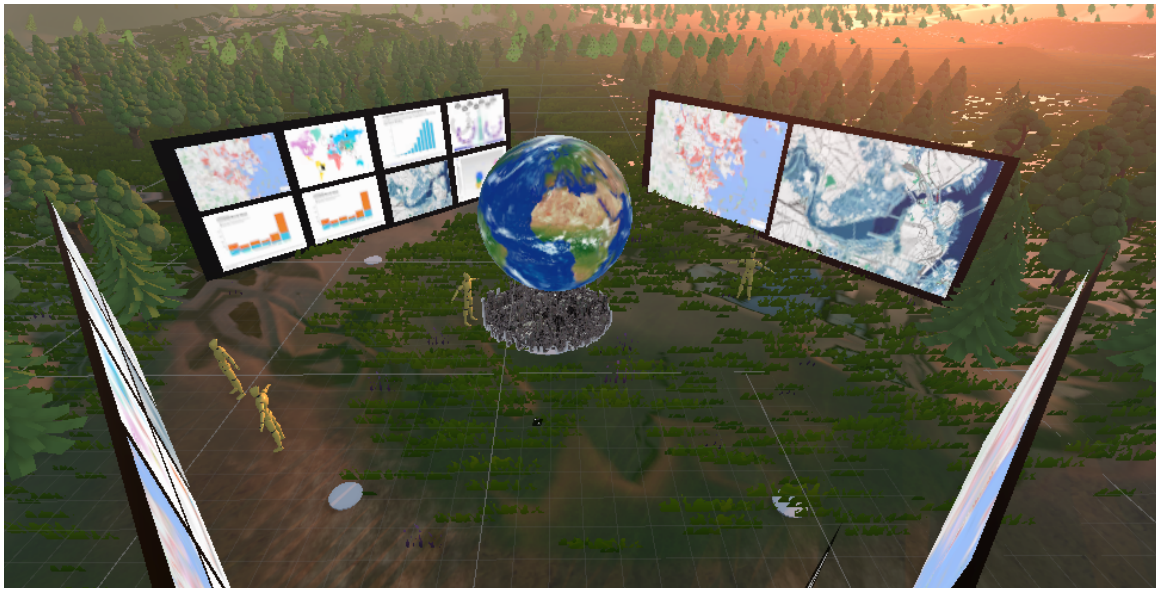


Figure 3-9: Screenshot of updated layout after working with Gui Trotti, with human-sized models for scale

The EMC environment was designed to support up to 10 concurrent users, though technically the networking can allow over 20 with the right optimizations. The interactive space is about 40x40 meters, with the nature environment stretching beyond that, providing a sense of depth. The central map table measures 6 meters in diameter, allowing multiple users to stand all around it and interact with the data together, viewing it from different angles.

Though not implemented in the scope of this project, future iterations of EMC will include the ability to move and resize the different modules while in VR to adjust the space to different needs. This will allow for even quicker prototyping and layout design, while also allowing users to tailor the experience to their personal preferences.

3.3 Data Integration

As we collect more and more climate data from different sources around the world, it is becoming more and more important that there is a simple and consistent way of accessing the data[91]. This is a much larger problem than the scope of this work allows for, so for this project, the focus was mainly on how to connect existing data sources to the system.

3.3.1 Bing Maps

One of the key aspects of EMC is being able to view map data of anywhere in the world. There are different tools that exist for interacting with geographic data. For this project, we needed a tool that would integrate well with the rest of the Unity application. A couple popular map SDKs are the ArcGIS Maps SDK from Esri and the Bing Maps SDK from Microsoft. They both have Unity compatible versions and both are able to work with geographic datasets that often come in the form of GeoJSON files and other traditional map data files.

For EMC, the Bing Maps SDK was chosen for its simple integration and extendable functionality. Unlike the ArcGIS software, the Bing Maps SDk doesn't reply on external data sources for the 3d models of the buildings and terrain. Instead, it is

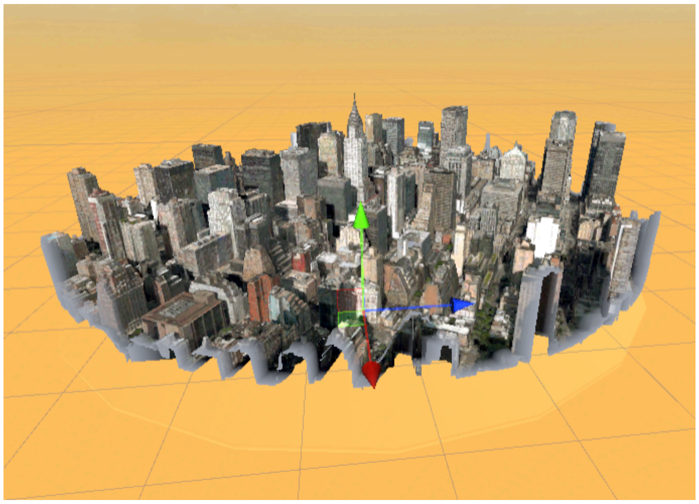


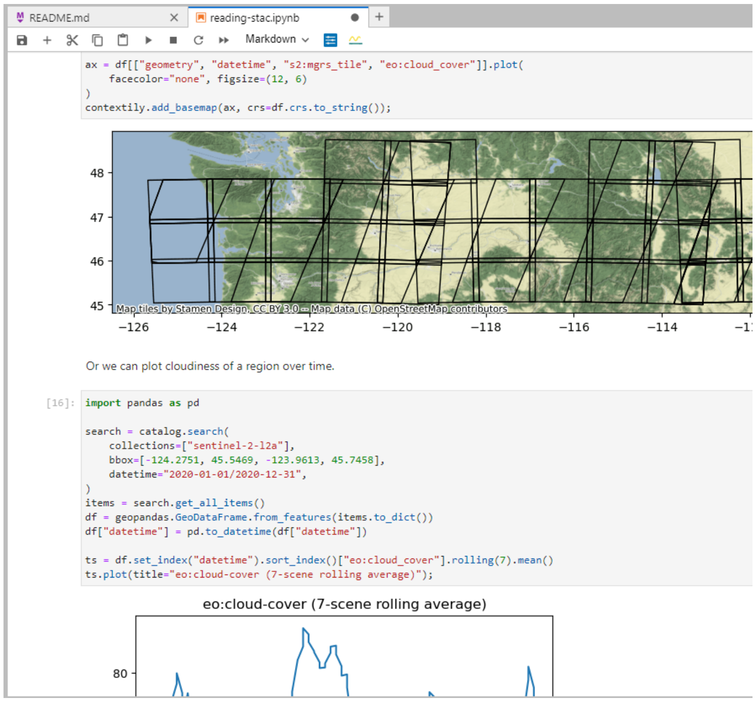
Figure 3-10: Screenshot of Bings Map 3D component showing a map of NY in Unity

able to leverage all of the data available through Bing Maps and makes set up much simpler. Additionally, the SDK comes with a set of features that make implementing additional visualizations more straightforward. For example, there is a concept of MapMarkers, which are points that can be placed around the map for additional location-specific information. Adding these points to the MapMarkerLayer automatically places them in the correct geolocation and allows for simple management of the data. The SDK not only allows the markers to be placed correctly on the map based on latitude/longitude coordinates, but it has the ability to automatically cluster points when too many of them are in a certain area, reducing visual clutter.

3.3.2 Microsoft Planetary Computer

Beyond just loading map data, we need the ability to be able to access some of the vast amounts of public data available through sources such as NASA and NOAA. Being public entities, all of their data is available for free online for everyone to access. The issue with all of this data being available is that there is not a simple way of accessing it all in a consistent way. In an attempt to address this problem, companies such as Google and Microsoft are working on creating large scale data management systems to help make this process easier. A couple of the most common solutions in the space right now are Google's Earth Engine and Microsoft's Planetary

Computer. They both work by combining the publicly accessible data into a single source that can be accessed through their managed API. For this project, I chose to use the Microsoft Planetary Computer. While not quite as mature as the Google Earth Engine, which has been around for about a decade, the Planetary Computer is actively integrating open-source technology, which gives this service interoperability with many other tools that climate researchers are already using. This, coupled with the fact that the planetary computer integrates very well with other Microsoft services running on Azure, Microsoft's cloud service, which are also used in this project, made it a good fit.



```
ax = df[["geometry", "datetime", "s2:mgrs_tile", "eo:cloud_cover"]].plot(
    facecolor="none", figsize=(12, 6)
)
contextily.add_basemap(ax, crs=df.crs.to_string());
```

Or we can plot cloudiness of a region over time.

```
[16]: import pandas as pd

search = catalog.search(
    collections=["sentinel-2-l2a"],
    bbox=[-124.2751, 45.5469, -123.9613, 45.7458],
    datetime="2020-01-01/2020-12-31",
)
items = search.get_all_items()
df = geopandas.GeoDataFrame.from_features(items.to_dict())
df["datetime"] = pd.to_datetime(df["datetime"])

ts = df.set_index("datetime").sort_index()["eo:cloud_cover"].rolling(7).mean()
ts.plot(title="eo:cloud-cover (7-scene rolling average)");
```

Figure 3-11: Screenshot of sample Jupyter notebook using Microsoft Planetary Computer to access and plot data

The Planetary Computer provides a way to access the data that is stored on Azure either through direct queries, or by using the Python API. In order to create endpoints that are callable that can process requests and generate responses based on the Planetary Computer's API, a wrapper was created around the API using Azure Functions. This wrapper allowed us to host the logic to access specific map data based on simple queries passed in the message request. By using this sort of distributed system, we are able to create a growing library of functions that can be added to EMC to provide just-in-time relevant data to users inside the system.

3.3.3 Azure Storage

In addition to being able to access the vast amounts of public data available through groups like NASA and NOAA, EMC also supports users adding any of their own content that can be viewed on the Hyperwall. To accomplish this, a back-end was created using the Azure Storage platform. Azure is Microsoft's cloud offering and provides many managed services that are very reliable and easy to set up. For this project, Azure Blob storage was used specifically, which is Microsoft's object storage solution for the cloud. It is optimized for storing massive amounts of unstructured data, which is data that doesn't adhere to a particular data model or definition, such as text or binary data. This type of data storage is great for serving documents and images directly to applications and streaming audio and video, which are the main types of uses in EMC. To make it easier for users to add data into the system, there is the Azure Storage Explorer which is a tool that allows users to access their storage through a simple file manager. The files are stored in 'Containers' which are essentially folders, and the containers are organized so that different types of data are stored together, such as 360 videos, animated charts, static images, etc. Though this system is currently designed to support one data upload user, this could be extended to have different containers for different users.

3.4 Virtual Display Modalities

3.4.1 High Resolution Display Wall

Overview

Since its introduction in 2003, NASA's Hyperwall, an advanced visualization tool, has been used as a cutting-edge means to communicate complex scientific concepts[53]. Consisting of an array of high-definition screens functioning in unison, the Hyperwall serves as a platform for the simultaneous representation of multiple datasets.

Figure 3-12: Photo of Hyperwall in use at NASA to deliver a presentation on climate data

One of the key strengths of the Hyperwall is its ability to present multiple datasets concurrently, facilitating an understanding of the relationships between different types of data. This multi-dataset representation not only fosters an integrated perspective of diverse data streams, but also enables researchers to identify patterns, correlations, and anomalies that might be less evident when datasets are viewed separately. The inherent visual nature of the Hyperwall "encourages people to scan the displays looking for trends, relationships, and anomalies."[53]

And while this is a very useful tool for individual data exploration, it is even more powerful in a group context. When it was first created, researchers found that when using the Hyperwall, "scientists want to walk right up to the wall of screens, look closer, and point out observational curiosities to co-investigators making it inherently collaborative in nature."[53] This collaborative nature, as well as high resolution visualization capabilities, makes the Hyperwall an integral part of climate science communication.

Implementation

One of the key ways to interact with data in the EMC will be through the high resolution display wall(HRDW) interface. Similar to the real life Hyperwalls at NASA, the virtual HRDW component will act as a large connected display that can display data on a very large surface and be split up into multiple sections. By scaling up the resolution of data, we can see smaller patterns that would be otherwise very difficult to detect. At the same time, we can use the extra screen real-estate to display various sets of data side by side. Different dashboard configurations can be used to organize the data, making it possible to explore the best way to configure different climate information.

Figure 3-13: Screenshot of virtual High Resolution Display Wall (HRDW) with 8 data panels

3.4.2 Map Table

Overview

Map tables are historically significant tools for the visualization of geographic data, and have served as communal communication platforms for centuries.

Climate data is inherently geographical and multidimensional in nature, covering a wide range of variables such as temperature, precipitation, wind patterns, and more.

The spatial component of climate data, when visualized through map tables, allows for the simultaneous analysis of diverse climate factors across different geographical areas. This helps users gain a comprehensive understanding of global and regional climate patterns and the various factors influencing them.

In recent years, new technologies such as large touchscreen displays have enabled this traditional tool to be updated for the digital age. The Digital Map Table (digLT) is the most popular example of this virtual table. The digLT is a broad table surface screen, allowing interaction with the presented map data and other interactive features using gestures from multiple hands and fingers.[6] Multiple studies have found it to be a very effective collaboration tool and a useful way to explore and analyse geographic data[55, 56].

Figure 3-14: Photo of children using an interactive map table. Image Credit: D Finnin, American Museum of Natural History

Moreover, visualizing climate data on map tables can promote collective problem-solving and action planning. As climate change is a global issue affecting various sectors - from agriculture and water resources to human health and biodiversity - it requires the concerted effort of multiple stakeholders. By facilitating a collective understanding of climate patterns, map tables can foster interdisciplinary collaboration and informed decision-making.

Implementation

Drawing inspiration from map tables such as the ones from the Tangible Media Group at the MIT Media Lab and the Harvard Visualization Lab, the EMC will include a virtual map table component that will allow users to load in GIS (Geographic Information System) data and overlay various datasets in a horizontal tabletop display. This modality allows multiple users to gather around the table and interact collaboratively with the data. This encourages dialogue and enables controlled viewing from different angles, which can lead to novel insights.

The map table module uses the Bing Maps SDK mentioned above to display 3D maps on a large table. The map shows a selected region and users are able to control the zoom level of the map and pan around the map to explore different regions. Additionally, the users are able to visualize data as overlays on the map. For example, users can visualize the projected water level rise of regions by raising the water level in the virtual city, as seen in Fig. 3-15. This provides a clear visual approximation of the extent of flood risk and lets users feel the difference between possible future climate scenarios. Another example is that users can turn on the CO2 emissions visualization, as seen in Fig. 6-3 in Section 6. This visualization which show creates green-yellow particles representing the emissions, with the particle density determined by the emissions concentrations of the area. This provides a very simple yet visceral understanding of the data, easily showing the relative amounts of emissions across different regions. Another example is Integrating more visualizations like this can help provide a local understanding of climate impacts and see how various communities may be affected differently.

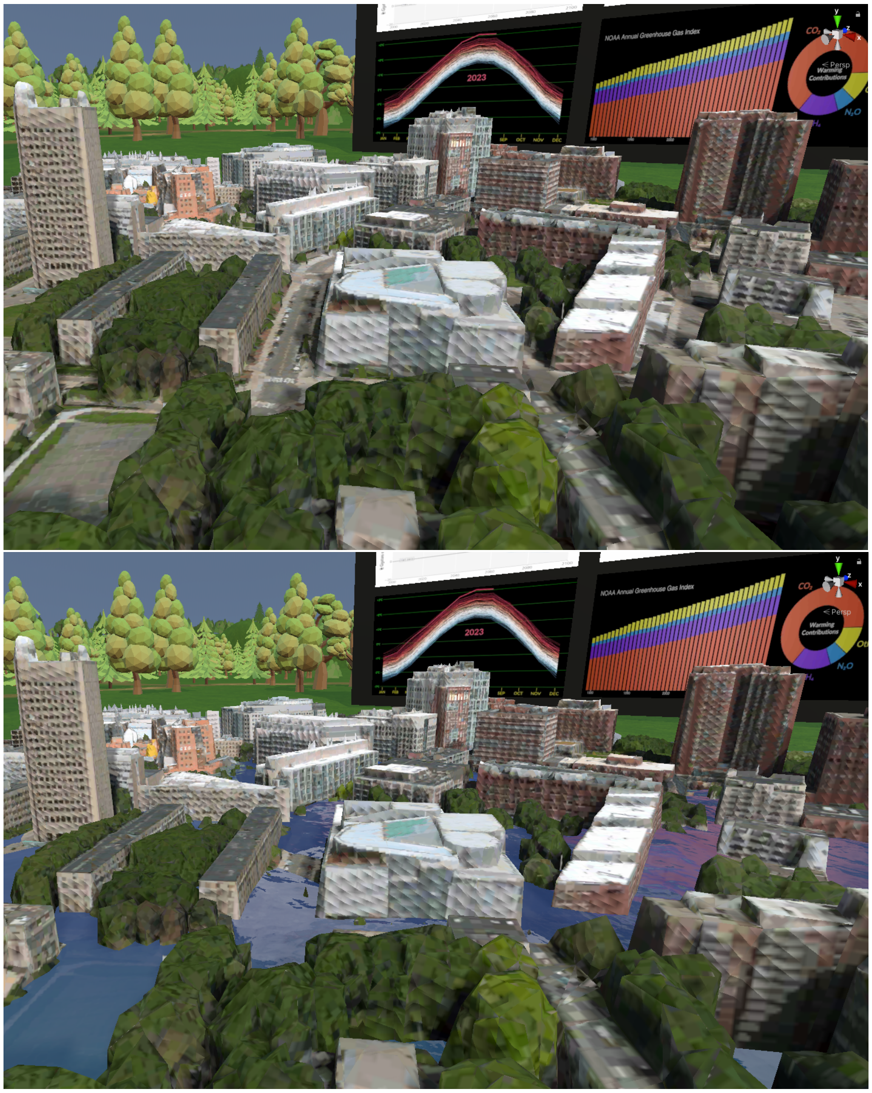


Figure 3-15: Screenshots of the map table showing the MIT Media Lab current water levels (top) and potential water levels given a 3 degree Celsius rise in average global temperature (bottom)

3.4.3 Globe Module

Overview

Another data visualization modality that has been shown to be very effective at communicating global impact is the spherical projection. By projecting data onto a spherical display, it's possible to see how climate change can impact interactions of planetary-scale systems. Developed in 1995 and patented in 2005 by Dr. Sandy MacDonald at the National Oceanic and Atmospheric Administration (NOAA), Science on a Sphere (SOS) is a spherical projection system that displays high resolution data and videos on a large sphere using projectors. It enables users to see global data visualizations more naturally and, through a connected system of institutions using the Spheres, allows scientists, teachers, and visualization experts to collaborate in new ways [43]. With over 33 million visitors across over 100 sites viewing the Spheres each year, this tool has an incredible reach. Through guided videos and presentations, Science on a Sphere has been effectively used to teach many people about the global impacts of climate change and it has been shown that student not only retained the scientific understanding gained during the SOS presentations but also seemed to build a deeper understanding of the Earth's interconnected systems [103].

Figure 3-16: Photo of a Science on a Sphere guided presentation at a museum

Implementation

The EMC includes a virtual sphere projection, inspired by the Science on a Sphere platform. Using content from the Science on a Sphere catalog, EMC is able to visualize global scale information, such as greenhouse gas emissions, ocean currents, and temperature anomalies in an intuitive and easy to understand way. By overlaying this data onto the sphere, it's possible to see large scale global patterns and understand the connections between different regional phenomenon.[103]

In addition to just graphic overlays on the sphere, the globe module is able to load in data from a CSV file and represent the datapoints around the globe. When the system loads the data points, they are colored based on their values being outside of a given threshold. For example, it is possible to load a dataset of CO2 emissions from factories around the world, and the points would appear around the globe, colored according to their emission levels. Users are then able to select points of interest and learn more about them.

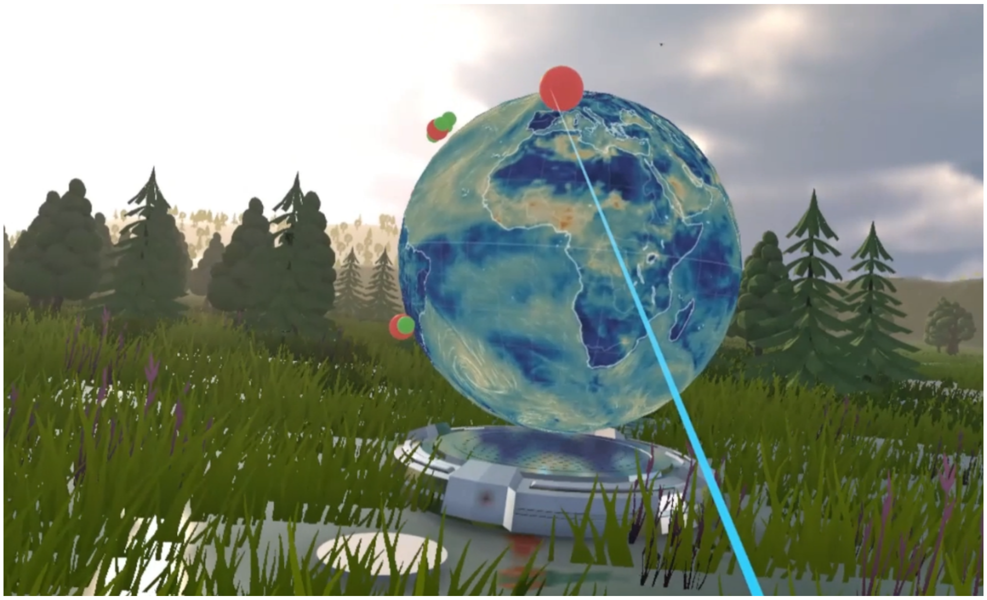


Figure 3-17: Screenshot of the globe module, showing the CO2 emissions overlay and a ray pointing at a red data-point around the sphere which is being selected for further inspection.

The globe is able to be rotated and resized using grab mechanics. This lets users explore global data from different angles and perspectives, with the added benefit that the data is dynamic and can be changed. This lowers cognitive load for users and can help them visualize how different global regions are connected. By not having to perform the mental transformation of mapping the 3D data from a 2D screen back into a 3D representation, users are able to gain a better understanding of the geo-spatial data.[103]

3.4.4 360 Video

360 video is created using either a multi-camera setup or an omni-directional cameras such as the GoPro Max and the Insta360. These cameras capture the data and then, through specialized software, are able to stitch the videos together into a single spherical field of view. These videos have been shown to greatly increase immersion and engagement of users, especially in academic settings [127, 95, 112, 16].

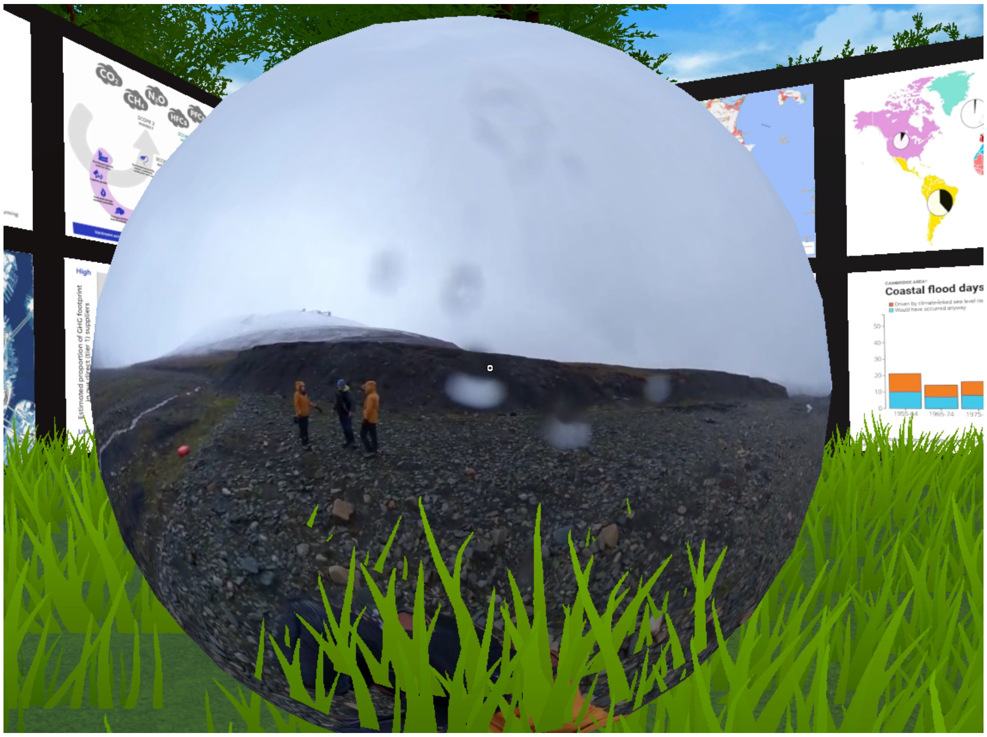


Figure 3-18: Screenshot of 360 video on inverted sphere in EMC

Though a natural fit for VR, there are not currently any built-in ways of adding 360 video content into a virtual Unity scene. In order to add this functionality into EMC, we needed to employ a small hack to be able to get the video content to display as expected. To do this, we added a custom 3D object called an inverted sphere. This object is similar to a regular sphere except for the fact that it projects the inside of the sphere outside, and the outside in. What this means is that if we apply a 360 video to the sphere, when users step into the middle of the sphere, they will be surrounded by the video. By adding in this layer of immersion, users are able to get a much more personal view and connection with the location they are exploring. By being able to "step" into the location, they are able to see the environment in a realistic way.

3.4.5 Dynamic Environment

While environments can be integral in creating a sense of presence and place making in virtual reality, it can also be used to visualize data as well. In virtual reality, the environment is fully controllable and this allows us to convey information in ways that otherwise are not possible. For example, EMC has the option of showing the projected water-level rise in the environment, creating a plane of water that viscerally shows the data. By immersing users within the data itself, it's possible to give added context and create a much more emotional connection to the data. As seen in the literature review from before, there are great benefits to learning and retention when immersive environments are used [50]. Specifically, when the environment is connected to the information users are learning, learning outcomes are greatly improved [21].

The environment is also able to change various features, such as time of day, latitude/longitude, precipitation, cloud coverage, and more, allowing users to experience the conditions of the real location they are learning about. This was achieved using the Enviro3 asset from the Unity asset store.

3.5 Passthrough AR Mode

While being immersed in a virtual environment comes with many benefits, there are also times where being in a more familiar setting can create a more comfortable experience. Especially for users not as familiar with virtual reality, having the ability to see the real world around them can help make the experience more enjoyable and less overwhelming.

To address this, adding an Augmented Reality Passthrough mode to EMC was explored. Unlike virtual reality, which immerses the user in a completely artificial virtual world, augmented reality instead adds or "augments" the real world with digital objects. Headsets like the Microsoft Hololens and the Magic Leap are able to accomplish this by projecting light onto specialized glass that is able to overlay the

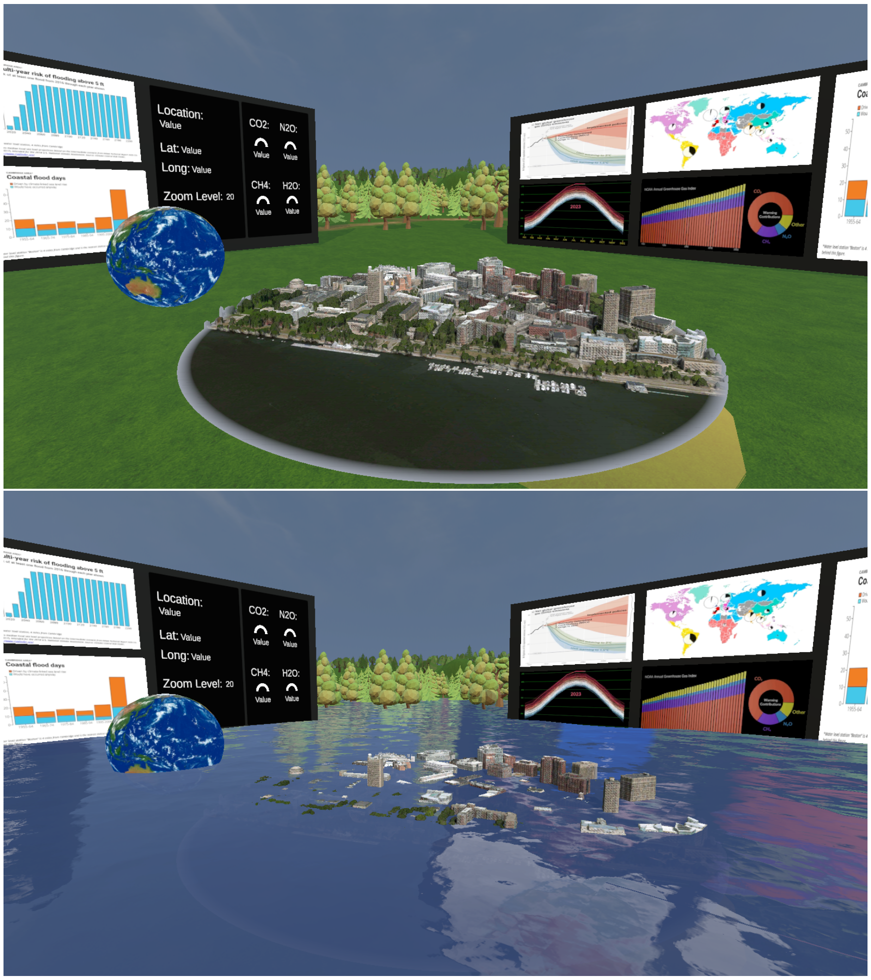


Figure 3-19: Screenshots of the virtual environment of EMC visualizing different flooding conditions, including current levels(top) and possible future levels (bottom)

digital information directly onto the user's visual field. Another method to achieve this effect is by using cameras to feed video of the external world into an immersive headset. In this mode, the virtual environment is removed and instead replaced with a live feed "passing through" from the outward facing cameras of the head mounted display(HMD).

The Meta Quest headsets support passthrough, with the Meta Quest 1 and 2 having black and white passthrough from the IR cameras on the headset, while the Quest Pro enables full color passthrough with dedicated RGB cameras on the front. Instead of the the display modules being in a nature-based environment, they are now part of the real world environment, appearing in the room with the users. The one

Figure 3-20: Screenshot of EMC in passthrough mode

limitation of this implementation is that currently, the virtual objects aren't mapped to the physical space so some immersion is lost. In future iterations of this work, the passthrough mode would allow users to move and resize the modules to better line up with the space that they are in, creating a more immersive experience. Additionally, while remote multiplayer is still supported in this mode, co-located multiplayer, which is when multiple users are in the same physical space, was out of scope of this phase of the project.

3.6 Desktop Application

Though primarily developed for virtual and augmented reality, EMC also has a desktop mode which allows users to explore the EMC environment from their computers without the need for additional hardware. Because AR and VR are still new developing technologies, it was important to ensure that as many people can access the platform as possible. The desktop version of the application connects to the same virtual environment and provides users with a limited set of controls to explore the environment and interact with the data. In the current form, the desktop application is meant to be a guided experience, with either a live or pre-recorded expert guiding users through by highlighting relevant data across each display modality.

Because the desktop application connects with the VR and AR instances and allows users to interact together in the space regardless of device being used. This feature is incredibly important in increasing the reach of EMC and allowing a larger audience to engage with the experience.

Figure 3-21: Photo of user testing EMC using the desktop application

In addition to providing more features for users, the desktop application also acts a way for us to test the effectiveness of EMC as an immersive platform compared to a traditional 2D desktop tool. While more work still needs to be done to run a full user study to understand the effectiveness of each platform, initial user tests have shown that while users have similar levels of understanding when presented data in both platforms (in line with previous work), users in the VR condition reported a much higher emotional response when seeing the data in context of the 3D map table and better retention of the experience and information. Additionally, users in the VR condition reported feeling much more connected with the other users in the experience as compared to the desktop condition.

3.7 Visualization Space

Figure 3-22: Photo of EMC running in the MIT Media Lab Visualization Space

Beyond allowing individuals to connect to EMC using their computers, the desktop mode also enables groups of users to experience EMC together in the same physical space. The desktop application can be opened on a computer and then projected for a whole classroom or auditorium. At the MIT Media Lab, a custom visualization space was created to explore immersive experiences and EMC was tested its the large display wall. Consisting of 3 ultra-short throw projectors blended together, the large display wall in the visualization space acted as a "portal" into the virtual EMC environment. Users in the space are able to follow along as a guide using a VR headset controlled the experience for everyone. In addition to allowing experts to present their work in a more compelling format to live audiences, this feature also enables them to record themselves giving the presentation and share the video more broadly, using EMC as a virtual production studio.

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Chapter 4

Human User Interaction (UI) Design

Despite the fact that many industries and organizations are very interested in designing for behavior change with a focus on sustainability targets, designers don't have the tools or education to be able to do it[24]. "Specifically, when it comes to VR, there is a lack of guidelines, tools, and models that designers can use to create compelling VR experiences."[105]

While user interaction has been explored in 2D context for decades, the design of interactive 3D experiences still remains underdeveloped. There is a significantly larger design space with the addition of the 3rd dimension, and as such, many more design considerations must be taken into account. EMC builds off of interaction design principles developed over the years for 2D interfaces and applies them to a 3D context. Taking inspiration from the work of Nielson [87], Dumas[29], Blair-Early[11], and other interaction design researchers, the design principles used in the creation of EMC include: consistent logic, observing conventions, providing clear feedback to users, clear visual landmarks, interaction proximity, interface adaptation, accessible help/guidance, and using interfaces as content.

It is important that each element of EMC was able to be interacted with, ideally in a natural and intuitive way. The focus was to allow educators to facilitate group learning experiences where they could guide learners through the important data stories, or allow users to engage in guided self exploration. Ensuring that users have a sense of agency is crucial for creating experiences that are impactful and immersive.

Agency has been linked to both immersion [83] and presence [101], and studies have shown that users also expressed a strong preference for the ability to interact with and influence the narrative [102].

Following the principle of clear feedback to users, visual and audio cues were integrated into all of the interfaces. The interactable elements, such as buttons, that the MRTK input system provides all have multiple forms of feedback enabled such as color or size changes, glow effects, and audio responses. To ensure the platform stayed consistent across all interactions, any interactions created outside of MRTK also needed to provide similar levels of feedback. For example, data points on the globe would grow in size when they were hovered over, shrink back down when no longer being hovered over, and play a small confirmation sound when selected.

Figure 4-1: Screenshots of visual feedback when hovering in EMC, with color changing menu buttons (left) and enlarged data points (right)

4.1 Control Panel

Given the multiple display modalities available in Earth Mission Control, it is necessary to have a consistent and simple method for interacting with the displays and controlling what content is being presented. To accomplish this, Earth Mission Control has a virtual Control Panel that acts as a sort of universal remote, allowing users to interact with all of the modules through a single interface. The control panel follows the model of a hand menu that is popular in AR/VR development. A hand menu is a type of menu that is attached to the user's hand and brings up an interactive display when the user raises their hand and looks at their palm. The users are then able to interact with the menu with their other hand. It is also possible to unpin the menu from the hand if desired in order to be able to use both hands to interact with the menu. This allows for all of the necessary controls to always be within reach when needed, following the 'proximity' design principle mentioned above. When the user isn't looking at their hand, the menu disappears to remove unnecessary visual clutter.

Figure 4-2: Screenshot of Control Panel showing different tabs including the globe module (left) and mapt table (right)

The control panel is made up of a central content panel with tabs at the top to select which aspect of the EMC the user wants to control. Selecting the tabs changes the page on the panel and brings up the controls specific to that display modality. Although VR allows for a range of creative interaction options, a more traditional 2D display format for the control panel was chosen to provide a more familiar feeling interface for those users who have limited experience with VR.

4.2 Hand Tracking

Studies have shown that accurately representing the user's hand in the virtual environment is crucial to create a sense of immersion[80, 45]. Like most virtual reality applications, Earth Mission Control was initially designed for use with controllers, which is the most standard way of interacting in VR. These tracked motion controllers provide a relatively intuitive way of interacting with the virtual environment and through the use of buttons, provide extra functionality for the user. While a convenient way to interact with the 3D environment, there is a bit of a learning curve for users who haven't used virtual reality or gamepads before.

In order to make the interaction feel more intuitive and natural, hand tracking support was added to EMC. The Meta Quest headsets support native hand tracking by using the infrared(IR) cameras located around the perimeters of the headset. The cameras, which are normally used for position tracking of the headset and controllers, are able to process the IR camera feed and track the users hand movements, as long as they are within view of the cameras. This allows for each finger on both hands to be individually tracked and this opens up a wide range of possibilities for interaction and immersion.

Figure 4-3: Screenshot of handtracking in EMC with different hand pose examples

By bringing the users actual hands into VR, the sense of presence is greatly increased. Users are able to interact with menus using their fingers, pressing buttons and using sliders as if they were physically there.

Additionally, since EMC is a multi-user experience, hand-tracking adds a new level of virtual communication by enabling even more natural body language interaction between users. Being able to use your hands to communicate makes interacting with others much more intuitive. Additionally, seeing the virtual hands of other users moving in very natural ways makes the sense of actually 'being' around the other person much stronger.

Beyond regular communication using hand gestures, hand-tracking also greatly improves accessibility both for those with mobility issues using controllers, and for users who are hard of hearing and rely on the use of sign language in order to communicate. This allows for an even greater number of users to be able to experience EMC and benefit from the shared learning experiences.

When using hand tracking to interact with items at a distance, a virtual cursor is displayed emanating out of the hands. This is represented graphically as a 3D dotted line with a cursor. The line and cursor use dynamic ray-casting to project into the environment, landing on top of objects when hovered over. This prevents the cursor from going through objects and provides additional visual feedback for users to make interactions more intuitive.

While providing many benefits, hand-tracking also does have some limitations. One limitation is that unlike controllers, our hands don't have extra buttons that can be used for additional interactions. In most virtual reality experiences, controllers are used to perform a variety of tasks using the help of the controller buttons, including opening menus, grabbing objects, teleporting around the environment, to name a few. Without these buttons, it's necessary to be able to replicate these interactions using just your hands. To accomplish this, designers of virtual experiences have begin exploring using hand gestures as another form of control. In the case of EMC, the Windows Mixed Reality Toolkit(MRTK) supports hand tracking and includes some pre-defined gestures. One example of this is when users are able to select menu items by pressing them, or using the pinch gesture, common to hand-tracking tools. Additionally, the MRTK implementation of hand tracking allows users to move around the virtual space using teleportation. This is done by mapping the teleport action to the gesture of pointing to where you want to go with a finger and then pulling the finger down to move there. This is illustrated in Fig. 4-4 below.

Figure 4-4: Screenshot of handtracking teleportation mechanics

Research has shown that user preference for hand tracking vs motion controllers was primarily based on the task being performed[60]. As a result, EMC was designed to support both hand tracking and controllers. This way, users can choose which mode of interaction they prefer and also allows for the option of switching modality during the experience depending on the task being performed.

4.3 Tooltips

In order to help users get started with the platform, it was important to add some guidance into the experience for first time users. This was done through the help of 3D tooltips, which are common UI elements that hover over different parts of EMC and give more information about them. The tooltips are essentially information screens that are open by default for users when they enter the application for the first time. They label what each module is, and have a question mark button that users can select to learn more about each module. These tooltips use a concept called 'billboarding' which is often used in 3D video game development to make information panels always face the user, ensuring they are always readable. Once users are familiar with the layout, they can dismiss the tooltips to remove visual clutter. If they ever need to remember anything about the modules, the tooltip can also be toggled back on at any time through the control panel UI.

In our initial user testing, most users were able to become familiar with the environment and modules within 5 minutes and would dismiss the tooltips. This time would vary depending on users' familiarity with virtual reality and experience with 3D gaming.

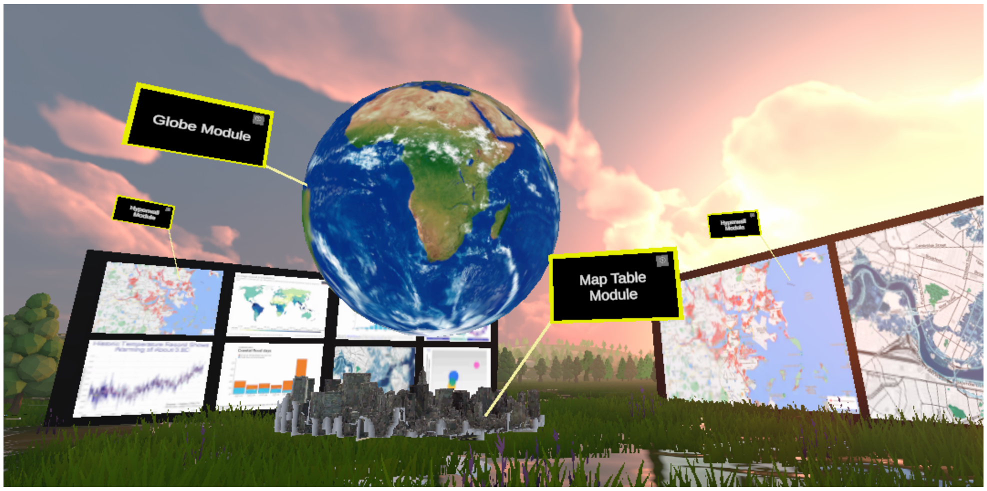

Figure 4-5: Screenshot with tooltips visible for each display

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Chapter 5

EarthBot

5.1 Background

As mentioned earlier, our world is filled with increasingly complex data, and understanding and navigating it all can present significant challenges. Tools such as the EMC demonstrate the potential of AR/VR technology in facilitating advanced visualization and immersive experiences, enabling scientists, engineers, and local communities to better understand complex climate data. However, despite the numerous benefits of AR and VR in this application, challenges persist in navigating the virtual environments and managing the intricate data involved, especially for users unfamiliar with VR controllers or facing accessibility issues[28].

In parallel with the rapid growth of AR/VR technology, artificial intelligence (AI) has been experiencing significant advancements, particularly in the field of natural language processing. Large language models, such as ChatGPT, have showcased their ability to understand and generate human-like text, providing a wide range of applications across various fields from medicine[67], to academics[75], and beyond[126]. The convergence of AI and AR/VR technologies offers a unique opportunity to address the challenges encountered in virtual environments.

To address the interaction issues and to incorporate the recent advancements in AI, EarthBot, a voice-controlled AI powered chatbot, is being developed for EMC. By providing users with a natural language interface, EarthBot can help answer questions users may have related to the data they are exploring, navigate the environment, and even assist with action planning and communication with teams that are often made up of people from all over the world.

EarthBot

Hi, I'm EarthBot and I'm here to help you navigate Earth Mission Control

Figure 5-1: Screenshot of Earthbot

Inspired by some early work in human computer interaction, including the "Put That There" paper[12], which demonstrate voice and gesture interactions for graphical interface, the chat assistant leverages multimodal user interactions to create a more natural user experience. There is current research being done into the effectiveness of using voice agents in virtual environments to help users navigate and complete complex tasks[97, 125]. Voice commands have also been shown to help explore large datasets more easily, helping users search through more information faster[113]. Now, with the advancement of large language models (LLMs) such as BERT[27], LLaMA[121], and GPT-4[90], and the commercialization/open sourcing of the projects, natural language input is quickly becoming more accessible than ever before. By leveraging the capabilities of these language models, combined with speech recognition and natural language processing, it is possible to create very powerful chat agents[107].

While the chatbot assistant is being designed specifically for the EMC project, it can easily be adapted to other virtual environments to help navigate the platform, interact with data, and learn more through natural language input.

5.2 Chat Assistant

5.2.1 Architecture

The basic architecture for this project involves using a VR headset which collects input from the user including the user's gaze based on the direction a person is facing and their voice using the built-in microphone. The system uses the Meta Voice SDK for transcription and speech recognition to turn the spoken words into actionable text using the wit.ai service. The ChatGPT API from OpenAI, using the GPT-3.5-turbo model, facilitates the chat interaction, taking in the user's questions and responding accordingly. It also keeps a running log of the conversation from the session so that users can reference earlier messages and explore multiple conversation paths. To ensure that the assistant responds in a consistent, clear, and friendly manner, there is a starting system prompt that gets sent to the chat service first and defines how the bot should behave.

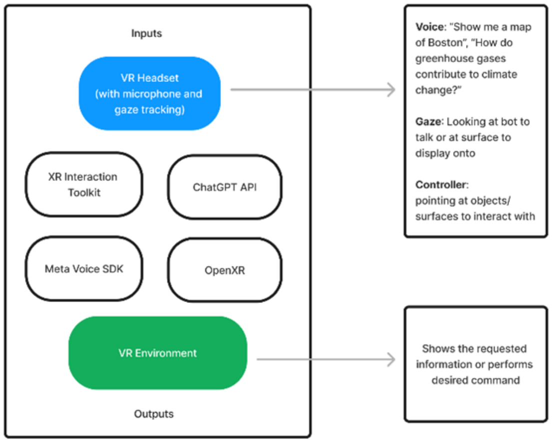


Figure 5-2: Chatbot Architecture Outline

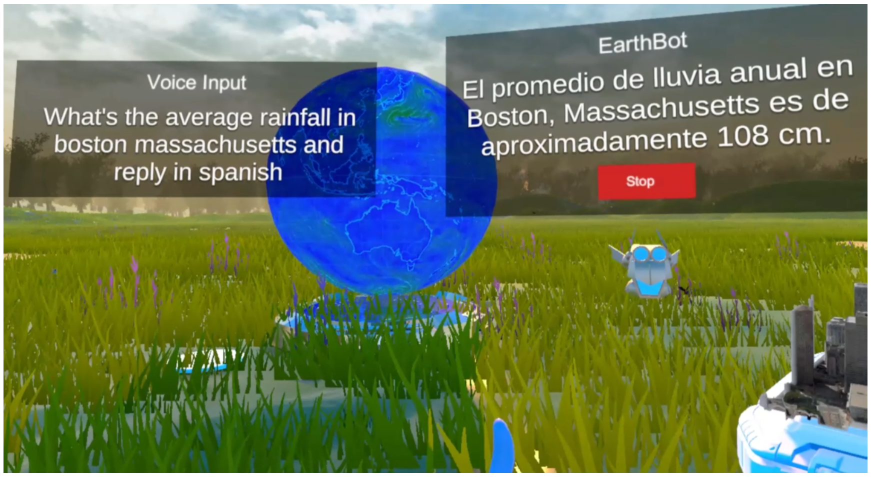
5.2.2 Interaction Design

To create a sense of presence and connection, the chat assistant is represented as a friendly floating robot with a dialog box above to provide a transcription for the responses. The system uses gaze detection to turn on the microphone when the user is looking at the bot, providing a more natural interaction. Gaze interaction has been used on other AR/VR applications and has been seen to enhance useability[94], especially when combined with other modalities of input such as voice[25]. Additionally, a gaze trigger can be added to any interactable object to enable voice control through the assistant. To prevent unwanted messages being sent to the bot, users will have to confirm their intent, either by starting their inquiry with the word “Question”, using a specific confirmation word, or confirming with a thumbs up if they are using hand tracking or controllers.

5.2.3 Benefits of EarthBot

The AI chatbot assistant for Earth Mission Control has many benefits beyond just making navigating the environment and the complex data easier, which make it an important addition to the platform. One of the most significant benefits is that it can provide translation assistance, which is especially useful for communication between teams that are made up of people from all over the world. By using natural language input, the chatbot can help facilitate better communication between team members who may speak different languages or have different cultural backgrounds. This can help to reduce misunderstandings and improve collaboration, ultimately leading to more effective decision making.

Another benefit of the chatbot is that it can provide just-in-time information to users. As users navigate the data and interact with different visualization modalities, they may have questions or want to explore a particular aspect of the data further. The chatbot can help to answer these questions and provide additional insights, allowing users to gain a deeper understanding of the data. By providing this type of assistance in real-time, the chatbot can help users make more informed decisions and



What's the average rainfall in boston massachusetts and reply in spanish

El promedio de lluvia anual en Boston, Massachusetts es de aproximadamente 108 cm.

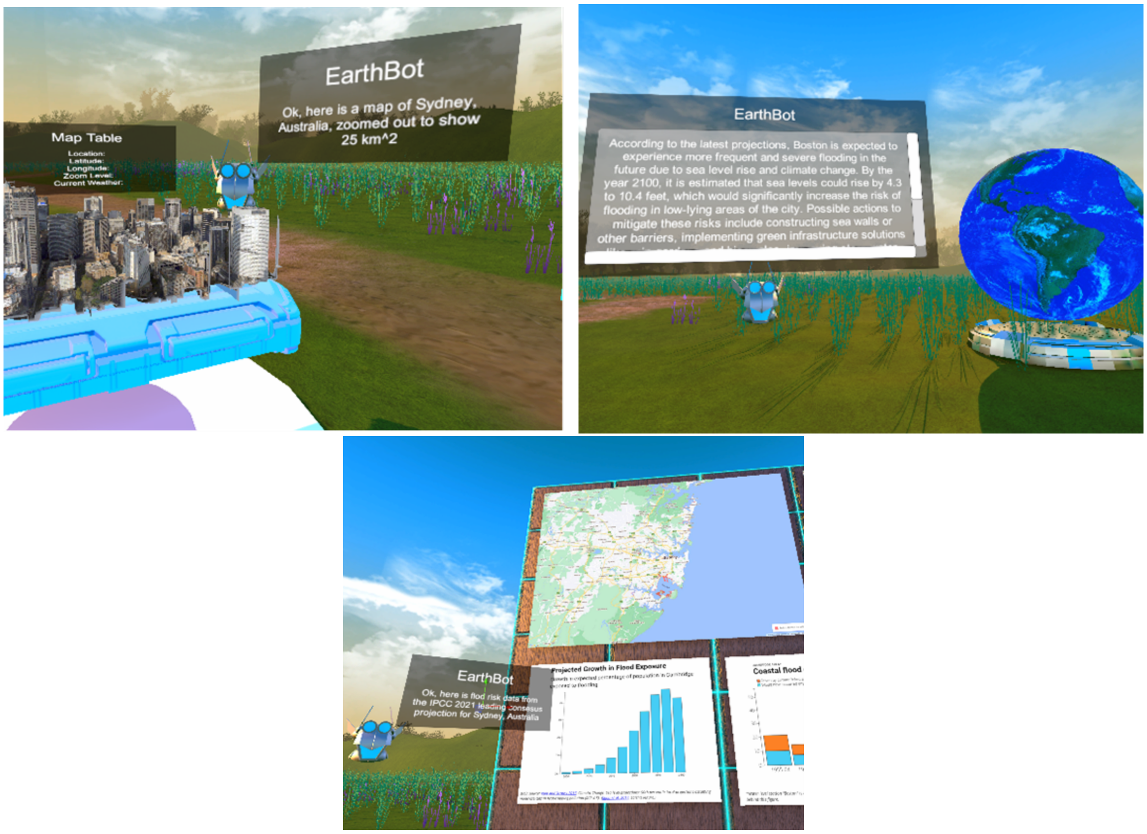
Figure 5-3: Screenshot of Earthbot replying to a user in Spanish

better understand the implications of the data they are exploring.

In addition to providing assistance with translation and just-in-time information, the chatbot can also act as another user or companion that users can interact with. This can help reduce feelings of isolation and enhance user engagement, particularly in solo exploration sessions. The chatbot's presence can also inspire more creative and dynamic discussions as users can bounce ideas off the AI assistant, fostering a more collaborative atmosphere. By creating a conversational interface, the chatbot can help to make the platform feel more welcoming and engaging, ultimately leading to greater user engagement and satisfaction. This is particularly important for platforms like the Earth Mission Control, which are designed to be immersive and engaging. This can be expanded further by allowing users to select different avatar models for the chatbot that best suit their preferences, which can help enhance learning through personalization[93].

Beyond being just a virtual companion for making exploring the virtual environment and data more engaging, the bot is also able to act as a guide, lightly moving the users along a path of exploration that can lead to new insights. Since the message logs that are send to the system are maintained through our system, we are able to also insert pre-defined messages for the bot to help lead users in interesting directions. These messages can act as a set of 'speaker notes' for the chat bot, ensuring that important takeaways are seen, even when the educators are not able to facilitate the experiences in person.

Finally, the voice-controlled AI chatbot assistant improves accessibility for users who may face challenges using traditional controllers or hand-tracking input methods. For users who may have mobility issues or difficulty using traditional input devices, the chatbot can provide an alternative input mechanism that is more accessible and easier to use. By enabling users to interact with the virtual environment and data through voice commands, the chatbot ensures a more inclusive and user-friendly experience.



Ok, here is a map of Sydney, Australia, zoomed out to show 25 km^2

According to the latest projections, Boston is expected to experience more frequent and severe flooding in the future due to sea level rise and climate change. By the year 2100, it is estimated that sea levels could rise by 4.3 to 10.4 feet, which would significantly increase the risk of flooding in low-lying areas of the city. Possible actions to mitigate these risks include constructing sea walls or other barriers, implementing green infrastructure solutions

Ok, here is flod risk data from the IPCC 2021 leading consesus projection for Sydney, Australia

Figure 5-4: EarthBot prototype assisting with various tasks, including map navigation(left), question answering(center), and data loading(right).

Chapter 6

Prototype and Feedback

The completed design and architecture previously described in this thesis come together in the EMC working prototype. This foundational work opens the door for the future development of the virtual data visualization platform. The robust architecture outlined in Chapter 3 was intentionally designed with further expansion in mind, since the goal of this work was to create a platform for exploring virtual data visualization, as opposed to creating a single, one-off experience. The tools were designed to be cross-platform, thanks to the OpenXR API, making it possible to port the experience to other VR and AR headsets to expand the number of users able to interact with the platform. The system also uses a networking infrastructure capable of supporting many more concurrent users than EMC is designed for currently. Additionally, the interface follows an intuitive visual design leveraging generalized components and interactions that are becoming standard in 3D environments to create a consistent experience. All of these features are able to be expanded and added to through future work.

Due to the very visual nature of VR, it can be difficult to visualize the layout and functionality of EMC without the help of animated visuals. To help readers form a clearer picture of the final prototype, a video demonstration and accompanying storyboard are available. This demonstration showcases the features of EMC, including the interfaces, interactions, data viewer systems, and EarthBot.

The demo video of EMC can be viewed by following this link: Earth Mission

Control Demo Video

Hello and welcome to Earth Mission Control. I am EarthBot and I am here to help you navigate this virtual space, load data, and answer any questions you have about our planet and its climate.

Latitude: -33.865143
Longitude: 151.2099
Zoom Level: 17

Latitude: 42.3584289550781
Longitude: -71.0597686767578
Zoom Level: 17

According to data from the National Oceanic and Atmospheric Administration (NOAA), the average annual precipitation in Boston, Massachusetts has increased by about 10% over the last 40 years. This trend is consistent with rising global temperatures and is associated with an

Figure 6-1: Storyboard of a basic user flow in EMC, beginning with loading into the virtual environment and being greeted by EarthBot who introduces themselves and EMC (top-left). The user then tell the robot to teleport to the map table (top-right). Next the user asks EarthBot to load a map of Boston onto the map table along with its corresponding information (bottom-left). Finally, the user asks EarthBot about the average rainfall in Boston, to which EarthBot replies with information from NOAA (bottoom-right).

6.1 Preliminary User Feedback

The design and development process of EMC was heavily influenced by frequent user testing, with various milestones set for users to test features and offer feedback. Though conducting formal experiments with user groups was outside the scope of this thesis, informal feedback and user testing drove the iterative design process of EMC. For future work and further development, full-scale user studies and experiments are highly recommended. When testing the platform's usability, many users noted that they intuitively understood and discovered the buttons, panels, and other input systems. They found the design discoverable, although minor adjustments were required when the application didn't operate as predicted in some instances.

An example of this is when users gave feedback on the globe module for the first time. It was initially designed to be controlled using a sphere connected to the control panel. Though this model made sense for some users, many users expected to be able to rotate the globe with their hands, which initially wasn't supported. After receiving this feedback, the ability to directly manipulate the globe was added.

Figure 6-2: Images from user testing, showing user in Meta Quest Pro headset exploring EMC

Another example was when designing the EarthBot assistant, users quickly pointed out the need to be able to stop the bot while it was speaking when it would either provide too long of a response, or respond to an incorrect query that was sent by accident. Through this feedback, a stop button was added and a "stop" voice command was also included to provide users with more control when interacting with the assistant.

6.2 Demo Scenarios

One of the guiding principles when designing the EMC platform was to ensure it was able to be a platform that was easily built upon and could be adapted to a variety of use cases. To illustrate the capabilities and flexible nature of the platform, two different demo use cases were explored, one for industry emissions tracking, and another for capturing and sharing remote scientific field work.

Industry Emissions Demo

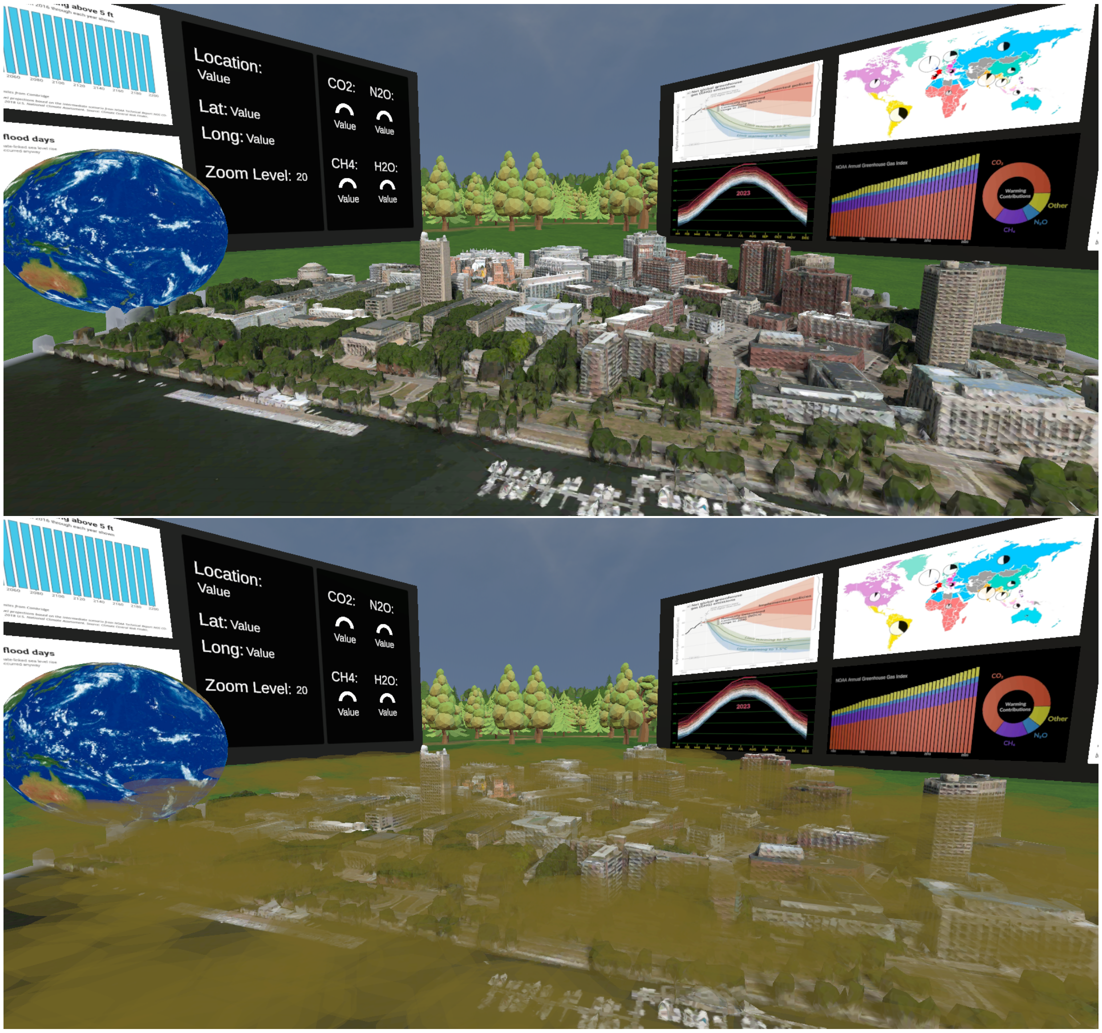


Figure 6-3: Screenshot of map table module in industry example (top), with the CO2 emissions visualization as an overlay (bottom)

One of the example use cases explored was using the platform to visualize CO2 emissions from factories world wide from an industry perspective. This was a demo to illustrate how a multi-user virtual platform like EMC could be used by industry leaders and decision makers to better understand the global flow of resources and local impacts of the work. In this example, sample data was used to represent different factories across the world. This sample data was stored as a CSV file and use sample emissions data from the Environmental Protection Agency (EPA) to represent CO2, N2O, and CH4 emissions and track water usage. This data would be loaded by the globe module and represented as colored dots spread along the surface. This allowed users to view the global data overlays such as global CO2 emissions in context with the factory locations. Each dot was a different size and color, depending on the CO2 emissions of that sample factory. If the emissions were within a safe range, the dot would be small and green. If, on the other hand, the emissions were outside of the safe operating rage, the dot would be larger and red, clearly denoting an issue that should be investigated further. Users can then select these dots, which loads the corresponding location onto the map table and pulls up additional related data on the surrounding hyperwall displays. Users are then able to explore each individual site further, seeing the 3D map of the area of interest. They can toggle an overlay visualization of the emissions, which appears as dark green particles over the city or region, with their density determined by the CO2 emission levels of the area. By connecting all of the local and global data together, along with relevant supplemental information, decision makers are able to quickly get an overview of global operations and make strategic planning decisions based on how local actions can impact the global system.

Earth Mission Control: Destination Svalbard

Though Earth Mission Control can facilitate exploration and learning about topics around the world, this example focuses on the Arctic, specifically an area called Svalbard, in Norway. It is one of the northern most cities in the world and, more importantly, it is also currently one of the areas most strongly affected by climate change in the world, with the area warming at a rate up to 7 times the global average[40]. As such, it is an incredibly useful case-study when exploring the effects of climate change.

Over the summers of 2022 and 2023, two different research groups from MIT went to Svalbard to conduct a series of field experiments. Taking advantage of the unique geologic history preserved in Svalbard, Norway, the goal of this demo was to translate the raw, static data gathered by geologists and glaciologists into an immersive, interactive, and educational narrative. Leveraging the EMC platform and generative

Figure 6-4: Photo of Svalbard landscape (top) compared to the virtual Svalbard environment with EMC tools including a map table, globe, and HRDW (bottom)

AI, the sample aimed to propel these observations beyond academic publications, creating a space for robust climate change discussions and envisioning possible climate futures. Data gathered in these missions was used to create a geological exploration experience to explore multi-sensor 3D data visualization in VR for planetary science and mission operations [124, 92]. The arctic environment was digitally recreated using drone photogrammetry and LIDAR data. This virtual environment was able to be ported over into the EMC platform, replacing the default forest environment. This allowed for users to be immersed in this 3D reconstructed environment while still having access to all of data exploration tools and multi-user capabilities of EMC. Though just a proof-of-concept for now, this demo showed how it is possible to combine data collected during field work, including 360 video and sensor data, to create an immersive education experience. This lets educators bring students to remote areas to learn from the experts directly, and in the future could even facilitate remote meetings between researchers. By creating a digital representation of a real research site, remote experts are able to collaborate and share their findings directly with policy makers and the general public.

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Chapter 7

Conclusion

7.1 Contributions

In this thesis, I propose that virtual reality and immersive technology have the potential to enhance data visualization, especially for education and decision-making. I began by outlining the complexities surrounding climate data understanding and how it can lead to inaction at the local scale. Future policy decisions will have to contend with various challenges and complexities brought on by climate change, requiring a set of enhanced tools for researchers, educators and policymakers. Driven by this need, I assessed existing data visualization techniques and the means of communicating climate data, analyzed the current practices in data visualization and climate data communication, and reviewed existing climate data visualization communication strategies. Lastly, I highlighted the recent developments in VR technology and examined the application and advantages of VR in related industries.

Next, I introduced the EMC system architecture, a cooperative virtual data visualization and communication platform. My work brings together the different virtual display modalities explored in previous work by Strentzsch et al(2017)[117], Schollaert et al(2014)[103], Markowitz et al (2018)[82], and Markowitz and Bailenson (2021)[81], combining multiple display modalities and immersive environments into one experience. The EMC system integrates diverse data representations into a unified virtual environment for all data visualization. It provides a multi-user environment that encourages collaboration and exploratory data analysis. Finally, I touched on design considerations, interface implementation, and user experience, which are informed by the principles established by Schjerlund et al (2018)[102]. My approach enhances these principles by applying them specifically to the context of climate data visualization.

The working prototype presented in this thesis serves as a starting point upon which additional features and tools can be built, further exploring experimental data visualization and interaction designs.

Additionally, incorporating a voice-controlled AI chatbot assistant into virtual climate data exploration platforms like EMC can significantly enhance the user experience by providing real-time translation, just-in-time information, companionship, and improved accessibility. While the utility of AI chatbots in virtual environments has been explored by Shafeeg et al(2023)[107], my work specifically focuses on their role in enhancing understanding of complex climate data, a unique angle not covered in the more general applications. These assistants can help users navigate the virtual environment, interact with the data more easily, and gain a deeper understanding of issues and actions through natural language input. While currently being developed for EMC, this work has the potential to help improve other virtual environments. Though there is plenty of future work to improve the assistant, the AI chatbot already shows the potential to significantly enhance communication and understanding of complex data within virtual exploration platforms like EMC, ultimately leading to more effective and impactful actions.

7.2 Future Work

7.2.1 EMC

While there is a functioning prototype, there are still many improvements that can be made to the EMC platform. Some of the short-term work includes performing formal user studies, adding support for real-time data integration, and exploring novel user

Table 7.1: Future work summary table for EMC and EarthBot

EMC	EarthBot
- Designing and running user studies - Realtime data integration - Improved user interactions - Improved avatars - Incorporate additional senses	- Leveraging RAGs for more reliable responses - Additional language support - Improved transcription support - Automatic chart/graph generation - Visual question answering with GPT-Vision - Guided learning companion - Support topics beyond climate

interactions.

Due to time and resource constraints, formal user studies were not conducted as part of this thesis. While informal user testing helped guide the design and development of the platform, formal user studies are necessary to evaluate the effectiveness of the platform and guide further development. User studies should cover usability of the platform, effectiveness of the platform at conveying the desired data understanding, information layout feedback, and ability of the platform to effect behavior change. These user studies should cover a range of users, with a focus on climate researchers and educators as the guides, and policy makers, community members, and students as the explorers. Additionally, the datasets themselves should also be varied, as different datatypes require different affordances and bring with them unique constraints.

Currently, EMC supports viewing historical data through the Microsoft Planetary Computer integration and through uploading data to Azure Storage. The addition of real-time data, such as sensor data would enable users to track the current state of the Earth and monitor for any issues that may arise. This would allow for the system to send notifications when data indicated that conditions were outside of optimal range and help users address issues as they come up.

Given its nature of being a platform, EMC is a great experimental sandbox the quickly test out new user interactions to engage with the data. Spatial computing is still a developing field and by having a consistent testing environment, it is possible to compare different interaction methods to see which are best for different kinds of data.

The addition of customizable avatars is another possible improvement that would help create a more immersive experience. EMC uses simple avatars to convert the sense of presence, but allowing users to create unique avatars could increase engagement and make the remote discussions feel more real and connected.

There are also a number of ways this work can be expanded in the long term, including incorporating additional senses such as smell, temperature, and touch to further immerse users and create a deeper sense of presence. Platforms such as The Void and Dreamscape use custom physical environments to enable multi-sensory virtual experiences. EMC can be expanded to include these multi-sensory inputs to create an even stronger experience of data visceralization.

7.2.2 EarthBot

The chatbot assistant is a promising technology that can provide a variety of benefits to users; however, it is important to acknowledge that there are still challenges that need to be addressed to make it even more effective. One of these limitations is that Earthbot is currently trained on a generic ChatGPT model[90]. While this model can provide a solid foundation for the chatbot's natural language processing capabilities, it can struggle with some more domain specific knowledge. The system could be further improved by training a model on more specific datasets relevant to the topic that the assistant will be used for, which in the example of earth Mission Control would be climate science and data communication. This could be done by using an architecture called Retrieval Augmented Generation (RAG), which leverags embeddings[86] to create a data base of embedded articles and resources. When a user asks a question, the question first gets embedded and then using that embedding, related articles can be pulled and added in as context to the prompt that gets sent to ChatGPT. This technique allows the bot to find context relevant information before responding and provide references for the user to later explore the resources further.

This would enable the chatbot to better understand and respond to users' questions and requests, and provide more accurate and meaningful information.

Another limitation of the chatbot assistant is the variability in voice recognition accuracy based on different languages and accents. While the current implementation of the chat assistant is using a generic model from wit.ai, there is a need for more specialized models that can better recognize and transcribe specific accents and languages. This is particularly important for a platform like Earth Mission Control, which is designed to be used by a global community with a variety of different language backgrounds and accents. To address this limitation, future work could involve the development and training of more specialized language models that are tailored to the specific language and accent needs of the user.

In addition to the limitations mentioned above, another challenge for the virtual assistant is the accuracy of voice transcription. While the chatbot is designed to assist users in navigating virtual environments and interacting with data through natural language input, the current implementation uses a generic wit.ai model for voice transcription that may not be optimized for the specific vocabulary and terminology used in the context of climate science and data visualization. Additional training can be used to improve the performance of the transcriptions and address these issues.

As discussed earlier, any application that tries to leverage immersive environments for visualizing complex data and performing intricate tasks, both in augmented and in virtual reality, will run into similar issues with navigation and interaction. As such, the proposed AI powered chatbot system has the potential to apply to a much wider range of domains beyond just climate change. Future work could include exploring using these tools in an educational context, exploring their efficacy at acting as a learning companion as the students explore virtual environments to learn curriculum topics. Due to the flexible nature of these assistants, they could be trained on topics from biology, to physics, and even to art, immersing learners in the learning process and giving them the tools that they need for self-guided exploration. There is already research showing that VR has many positive benefits for education[14, 30, 69] and adding this assistant could further increase engagements and longer-term retention through making more accessible virtual experiences.

Additionally, another future direction would be to explore the ability of GPT4 to interpret images[90] and be able to give insights based on them. Though currently not publicly released, in the announcement of GPT4 a new visual question answering feature was introduced which allows the model to interpret images in combination with text. This would allow for users to be able to directly ask questions about the charts, graphs, maps, and other visualizations they are interacting with and get relevant just-in-time information about it. By connecting both the visual and textual context into the chat prompts, it would be possible to gain deeper insights on the data and add another layer of natural interaction to the assistant, making it an even more useful companion.

Future work can build on the foundation of EMC to help us better understand and navigate our Spaceship Earth together towards a more sustainable tomorrow.

7.3 Final Conclusion

This thesis has presented Earth Mission Control (EMC), a novel virtual reality (VR) data visualization platform, which stands at the intersection of immersive technology and climate science communication. The creation and implementation of EMC is a necessary step in exploring how we engage with and comprehend the multifaceted narrative of Earth's changing climate.

The research underscored the limitations of traditional, unimodal approaches in conveying complex climate data. EMC effectively combines various established visualization modalities within a VR context and has proven to be more than an aesthetic advancement; it is a functional improvement in enhancing user engagement and understanding.

A significant achievement of this thesis is the design and integration of an AI-powered virtual assistant within EMC. This development not only enriches the immersive experience but also facilitates more natural interactions and a heightened sense of presence. This is crucial in translating complex climate data into an accessible and engaging format for a diverse audience, including scientists, educators, policymakers, and community members.

Preliminary testing and evaluations of EMC indicate its potential effectiveness in deepening the understanding of localized climate issues. Users have reported an enhanced comprehension of climate impacts specific to their communities, which suggests that EMC can serve as a useful tool in climate science communication, bridging the gap between scientific data and community-level awareness and action.

In conclusion, Earth Mission Control platform emerges as a promising development in the realm of data visualization and climate communication. By leveraging VR's immersive capabilities and integrating various visualization modalities, EMC has set a path for future explorations in scientific communication. It is hoped that the insights and methodologies developed in this thesis will inspire further innovations in the field, contributing to more informed and proactive global responses to climate change.

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