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Teaching, Visualizing, and Interacting with Very Large Climate Models

Yannick Gloster, Computer Science

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Integrated Master of Science in Computer Science

Supervisor: Brendan Tangney

Co-Supervisor: Silvia Caldararu

April 2023

Declaration

I, the undersigned, declare that this work has not previously been submitted as an exercise for a degree at this, or any other University, and that unless otherwise stated, is my own work.

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Yannick Gloster, Integrated Master of Science in Computer Science
University of Dublin, Trinity College, 2023

Supervisor: Brendan Tangney
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Climate change is arguably the biggest challenge facing humanity to date. Its effects are already being felt globally as we see the devastating impacts of increasingly frequent and intense natural disasters, extreme temperatures, food and water shortages, and the displacement of millions of people. Addressing an issue of this size requires a coordinated effort from countries and regions across the globe.

Organizations worldwide have produced a large amount of data modeling and predictions. Still, there does not often exist a way for non-specialists to interact with this data in a guided manner. As education plays a crucial role in informing people about the causes and consequences of climate change and encouraging individuals to take action to mitigate its effects, it is essential that climate data is made available to people in a useful and engaging way.

The aim of this dissertation is to design, build, and evaluate the effectiveness of a tool to teach about existing climate scenarios. In particular, the project aims to allow learners to interact with the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report predictions in a way that makes the implications of the choices made at a global level explicit. Using the tool, learners address climate change by making a series of policy decisions for their assigned world region. Using the cumulative decisions made by all of the users, an algorithm generates one of the scenarios presented by the IPCC, allowing the user to get a glimpse into a potential future using real-world climate predictions.

A particular goal is to surface the importance of collaboration to tackle climate change while leveraging and visualizing data from the IPCC and the Coupled Model Intercomparison Project (CMIP). The tool is designed for use by Transition Year students (ages

15-16) in secondary school.

The tool was built as a multiplayer web application using Typescript, Next.js (a full stack React-based framework), and Socket.IO (a performant WebSocket-based communication protocol). A subset (1.09 GB) of the data (10s of gigabytes) provided alongside the IPCC Sixth Assessment Report was preprocessed in Python and stored on a PostgreSQL server for access by the tool. The interactive visualizations of this data were built using Recharts, react-simple-maps, and D3.js.

The tool was first tested and evaluated by educators (N=7) and then by students (N=26) in a workshop-based setting. Over the course of 2 days, students participated in multiple different workshops focusing on different elements of climate change, finishing with a 3-hour learning workshop based in the tool presented in this dissertation. A survey was conducted to investigate the usability and effectiveness of the learning experience. While the collected data is not statistically significant, the feedback indicates that the tool successfully engaged these students with the issues and should be rolled out to a larger audience.

In loving memory of my brother Declan Gloster.

His dedication to the things that impassioned him has been a source of inspiration for my life and work. I would not work nearly as hard if it wasn't for him.

Acknowledgments

First I would like to thank my supervisor, Dr. Brendan Tangey for his support and guidance, not only for this project but also through college as my tutor. His advice and encouragement were steadfast in transforming the tool from an idea to something that real students engaged with and benefited from.

I would like to thank my co-supervisor on the project, Dr. Silvia Caldararu, who provided immense insight into climate change and data from the IPCC.

I'm very grateful to my family for their support and for ensuring that I could dedicate myself to my education. Without them, none of this would be possible.

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I am also very appreciative of all of my friends, who have not only supported me academically but have made the entire university experience all the more enjoyable. Specifically, thank you to Simonas and Paula, who have been incredibly thoughtful and kind.

And finally, I would like to thank my high school video production teacher, John Dent. At a stage of my life where I found myself frustrated, lost, and confused, I always knew that I had the unwavering support from Mr. Dent. His program gave me a purpose and reason and laid the foundations for who I became as a person.

Yannick Gloster

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Chapter 1

Introduction

1.1 Motivation

Climate change is the most critical issue facing the planet. Its effects are increasingly intense and will have severe consequences if substantial action is not taken [1]. Addressing climate change requires a coordinated effort between not only individuals but, more importantly, between governments and regions of the world. Yet, educating individuals on the causes and consequences of climate change and encouraging them to take action or get politically engaged is very challenging. In order to predict what may be in store for us, modeling and analysis of existing climate data have been conducted by numerous organizations worldwide [2] [3]. While this data is essential for both planning and education, the data is often difficult to interact with, especially for anyone who is not an expert.

The United Nations Intergovernmental Panel on Climate Change (IPCC) is among the organizations that have conducted and synthesized a large amount of climate research. The IPCC is tasked to prepare an exhaustive report detailing the latest scientific, technical, and socioeconomic knowledge on climate change and its likely impact [4]. The group is also tasked with producing a list of options for reducing the rate at which climate change is taking place. The IPCC, alongside other researchers in the field, have identified a range of plausible scenarios for the future based on different assumptions on the socioeconomic decisions made by countries and regions. These Shared Socioeconomic Pathways (SSPs) were developed in response to the need for a more systematic and consistent approach to studying climate data and predicting change.

In 2016, the IPCC released its Sixth Assessment Report consisting of over a thousand pages of research and synthesis alongside the Coupled Model Intercomparison Project (CMIP6) [2], which consists of tens of gigabytes of data, describing more than fifty variables concerning the earth, such as maximum temperature and ocean sea level for the next 100 years for all of the different SSPs. Alongside the report, they developed the Interactive Atlas, a tool to visualize a large portion of the data [5]. While the Atlas allows informed users to manipulate and learn about the data, it does not provide a guided learning experience to directly teach the strategies needed to tackle climate change.

As will be described in §2.4, others have developed structured learning environments that aim to help people become more informed on the topic [5] [6]; however, many of these tools are built without a clear connection to climate research and are typically designed for a single learner rather than multiple learners. These tools are beneficial; nonetheless, climate change is not a challenge that will be solved through individual action but rather through significant collaborative action, specifically focusing on the highest pollution emitters, such as countries, large regions, and organizations.

1.2 Goal

The dissertation aims to create an interactive learning tool based on the IPCC Sixth Assessment Report and the CMIP6 data. The target learners for the tool are Transition Year (TY) students (ages 15-16). The tool aims to help that cohort learn about potential future climate scenarios and what countries and regions can do to achieve the best scenarios and what they can do to help make the change happen.

The tool should allow learners to select different regions of the world and make climate-related policy decisions for their region. The available regions in the tool should be selected based on the criteria of either having a significant impact on climate change (for example, high pollution emitters [7]) or by being disproportionately affected by the effects of climate change (for example, the Amazonian rain forests [8]). After all the learners have made their policy decision (by answering a series of questions), they should be presented with the SSP that is most likely to result from those decisions. They should then be presented with a series of interactive visualizations of the data for that SSP. These should be built with state-of-the-art data visualization techniques and technologies and should be interactive, allowing users to change the variables, scenarios, regions, and timeframe in real time. Through the visualization section, the user should be able to develop their own understanding of the impact of decisions made by them and others in their simulated world and should draw connections to how these decisions resulted in the SSP. The overarching learning goal for the tool is to show that it will require close coordination and cooperation between regions to achieve the best scenario or even to have an impact.

Educational experts should first evaluate the tool to understand its benefits and drawbacks. Then, following the input of these experts, the tool should be updated and tested in a workshop-based learning activity with TY students. Finally, in the interest of getting qualitative and quantitative feedback from the learners, a questionnaire about the usability and learnings from the tool should be conducted after the activity.

The learners who will be given the opportunity to test and use the tool will be participating in Trinity's Bridge2College (B2C) program. Bridge2College is an education outreach program designed to teach TY students key skills such as digital media literacy, communication, collaboration, leadership, and more [9]. Ethical approval for researching different aspects of the Bridge2College program has been granted by the School of Computer Science & Statistics.

1.3 Road Map

The author will first introduce an overview of the necessary research already done in the fields of environmental science, climate change, education, visualization, and computing. Then, the design and requirements of the tool alongside the decisions made regarding the technology and requirements of the project will be outlined. The implementation process, the challenges faced during the implementation stage and how they were addressed will be presented in details followed by the testing process and results. Finally, the author will conclude the dissertation with a summary and personal reflection on the tool and the process.

Chapter 2

Background

This chapter details the background research the author conducted in preparation for the design and implementation of this tool. The chapter is divided into four sections: climate change research, pedagogical theory, data visualization techniques, and similar applications.

2.1 Climate Change

Climate change has been linked to several environmental problems, such as rising sea levels, melting glaciers, and more frequent natural disasters such as hurricanes, tornadoes, forest fires, and more. Moreover, according to numerous sources, human activities, such as burning fossil fuels and deforestation, directly cause climate change [10]. Climate change has also been linked directly to health problems as it impacts access to clean air, safe drinking water, sufficient food, and access to shelter. Because of this, a conservative estimate of climate change is expected to cause an additional 250,000 deaths per year between 2030 and 2050 from malnutrition, malaria, diarrhea, and heat stress [1]. These numbers were calculated using an optimistic scenario regarding development and adaptations and only cover four direct impacts of climate change on health. At the same time, climate change impacts human health in many more direct and indirect ways.

The United Nations recognized the importance of climate change when it endorsed the Intergovernmental Panel on Climate Change (IPCC) in 1989, only one year after its founding by the World Meteorological Organization and the United Nations Environmental Program [11]. The goal of the IPCC is to provide scientific information for all levels of government so that it can be used to create climate policies that will protect the environment that humanity depends on [4]. The IPCC, governed by its 195 member states, elects a committee of scientists to serve through an "assessment cycle" of six to seven years. These elected scientists work alongside other experts in the field to prepare IPCC reports.

Alongside these reports, the data used for the findings are made accessible through the IPCC Data Website [12] and EU Copernicus website [13].

The IPCC began its sixth assessment cycle in 2015 and completed it in early 2023 [4]. They released the “Climate Change 2021, The Physical Science Basis” report in 2021, which compiled the most up-to-date physical understanding of climate change [14]. It concludes that it is indisputable that “human influence has warmed the atmosphere, ocean, and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere, and biosphere have occurred” [14]. Due to human actions, the climate has warmed at a rate, unlike anything in the last 2000 years [14]. This change has already been observed to impact the climate across every region of the world. The report ties usage of greenhouse gasses, most significantly, CO_2, to this change.

The report details five different climate scenarios based on different socioeconomic assumptions resulting in different levels of greenhouse gas emissions [14]. These Share Socioeconomic Pathways (SSPs) were created to standardize research into climate science and different climate models [15] and are a core component of the Coupled Model Intercomparison Project Phase 6 (CMIP6), which is used to assess potential climate futures.

The Coupled Model Intercomparison Project (CMIP) is a separate international effort to assess and compare the effectiveness of climate models. CMIP6 is the sixth phase of the project that aims to provide more robust projections for future climate change. Based on different SSPs, different models have been created that predict over fifty climate change variables [2]. This data underpins a large amount of climate research and specifically supports the IPCC report.

The IPCC report concludes that from a physical science perspective, the way to limit human-induced climate change is to reduce CO_2 emissions to, at a minimum, net zero CO_2 emissions with significant reductions in other greenhouse gases [14]. In the best case scenario, the temperature is estimated to increase by 1.4°C [14]. In the worst scenario, the increase is estimated to be 4.4°C [14].

While this is very worrisome, it is not a hopeless situation, as the planet has previously shown that it can successfully address global issues related to our climate. In the 1980s, it was discovered that there was a hole in the ozone layer, a region of the Earth’s stratosphere containing a significant concentration of ozone molecules [16]. Research showed that chlorofluorocarbons (CFCs) which were being released into the air through aerosols, refrigerants, and other industrial processes, were the primary cause of this hole [17]. The ozone layer is essential in absorbing harmful UV radiation from the sun, which can cause skin cancer, cataracts, and other health issues alongside damage to marine and terrestrial ecosystems [18]. The international community acted to address this through the Montreal Protocol on Substances that Deplete the Ozone Layer treaty signed in 1987, which reduced and phased out the production and consumption of ozone-depleting substances, including CFCs [16]. This effort has been seen as hugely successful, and data shows that the ozone layer hole has been shrinking ever since [19].

Similar to the Montreal Protocol on Substances that Deplete the Ozone Layer, the international community signed a landmark international treaty called the Paris Climate Agreement (also referred to as the Paris Agreement) in 2015 [20]. The Paris Agreement commits countries to collectively tackle climate change while promoting sustainable development by setting a goal to reduce the increase of global temperature to 2°C [21]. In addition, the agreement establishes a framework for countries to communicate regularly and enhance their efforts to reduce greenhouse gas emissions [21]. While the agreement has been widely ratified and hailed as a historic milestone, its effectiveness in achieving its goals is an ongoing debate [7]. Additional efforts are needed to ensure its implementation and, more broadly, to tackle climate change.

As highlighted by the current research, climate change is arguably the most critical challenge that needs solving, as it has been and will continue to affect the entire planet.

2.2 Education with Technology

As technology has become more accessible and powerful, leveraging technology to create better teaching environments has become increasingly popular. Specifically, web-based learning environments have become a powerful tool in classrooms and, more generally, online [22] [23]. Using web or technology-based experiences, students can learn about subjects that would be too complex, dangerous, or costly [24].

Many technology-based tools that have been built for use by children use a combination of methods to teach through the tool [25]. This allows the learners to view the problems from different angles to glean a more complete understanding of the problem, allowing the learners to "gain deeper insights" [26]. These different methods can be divided into two major categories: direct and indirect [27]. Direct teaching methods are methods with a long history, such as a lecture on a subject [27]. These methods can be viewed as teacher-centered or instructivist models [28]. Conversely, indirect teaching methods include problem-based learning, the project method [29], guided discovery learning [30], and other similar methods. These methods are also referred to as student-centered learning [28]. In technology-based learning, traditional methods have been seen to have little impact on learning [27]. In contrast, technology-based tools that use a mix of indirect teaching methods significantly affect the acquisition of knowledge [27].

Research has shown that programs built around sustainability and environmental education positively impact students' behavior regarding supporting sustainability. Thus dedicated education on climate change can directly reduce and change behavior that harms the environment [31].

Teaching key competencies regarding sustainability has become a widely discussed field due to the immediate need to solve the issues related to the climate crisis. These competencies can be boiled down to the idea that the learners should have “the skills, competencies, and knowledge to enact changes in economic, ecological and social behavior without such changes always being merely a reaction to pre-existing problems” [32]. Wiek et al. compiled a list of these competencies from select peer-review literature and broke them into eight categories: sustainability obligations of professional engineers, “Gestaltungskompetenz” (empathy, planning, participation, interdisciplinary work, and others), critical theory, “Globo sapiens” (global awareness and consciousness), problem-solving, change agent, head, hands, and heart, and values, knowing, skills, and understanding [33]. These serve as an explicit framework for developing competencies in learners that are effective tools when tackling climate change.

2.3 Data Visualization

The field of data visualization is an increasingly popular field looking to develop and understand the most effective ways to visualize data. When dealing with large amounts of data, it is challenging to draw any conclusions from tables alone; therefore, visualizations are needed to understand the data and its context. It is a very cross-disciplinary field, drawing on human perception, psychology, statistics, computer graphics, and graphics design. In this context, data visualization is essential to communicate and help users of all levels of expertise understand the presented climate data.

Effective data visualization is extremely powerful. When humans see (visual perception), they use the fast and efficient visual cortex located toward the rear of the brain. Conversely, thinking (cognition) is handled primarily by the cerebral cortex in the front of the brain and is much slower and less efficient. Therefore, compelling data visualizations allow the brain to use more of the visual perception part of the brain rather than cognition [34].

It is generally agreed that there are eight ways to encode information through visual means, referred to as visual encoding channels: position, mark, size, brightness, color, orientation, texture, and motion [35].

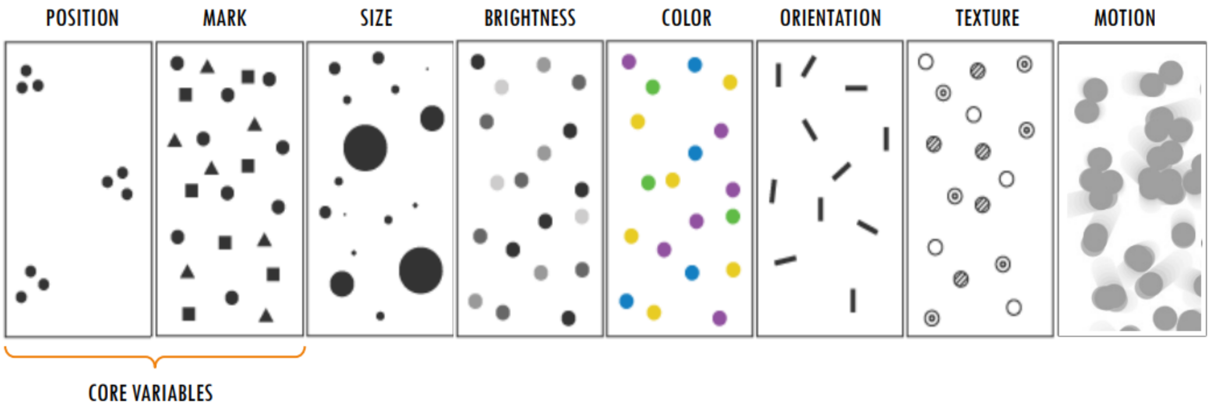

Figure 2.1: The eight visual encoding channels [36] [35]

The different channels can be combined to different levels of effectiveness to communicate multivariable and complex datasets. The use of position, placement of graphics within the visualization, is used in all visualizations in some fashion. It can be used to express values, categorize information, organize data for legibility, or position data in the case of spatial data. Using a mark or shape allows the representation of data attributes through that shape. This can be effective when dealing with categorical data, as multiple classes can be encoded. Using the shape alone only allows for ordering or grouping. Following this, size can be used to change how large or small a mark is drawn. This could be through a mark's length, area, or volume. It is easy to see the difference in size between marks, but it takes up more space on a screen. It is effective with continuous variables and can also be used for categorical data. Brightness, luminance, or intensity can also be used to encode quantitative or categorical data. It has a limited range as the human eye cannot recognize many different shades. Color, specifically hue and saturation, is a good choice when visualizing categorical attributes. Its effectiveness often depends on the choice of colors, as eye sensitivity differs from person to person. Orientation is a less common but still helpful encoding channel. The direction or angle can be rotated based on the data, but this channel is limited in precision and range as angles smaller than 45 degrees are hard to notice. Texture, also referred to as pattern, is another encoding channel that deals well with categorical data. It can, however, be considered a combination of mark, color, and orientation. The final channel is motion which can affect other visual variables. The data gets encoded through the degree of change displayed by the motion. For example, the speed or direction of a mark could be adjusted [35].

Given that these channels can be used together, it is crucial that there is as little interference between the channels as not to confuse the different variables being encoded. Different channels cause more significant interference than others. These channels will be specifically suited for specific types of information and goals of the visualization [35].

When designing compelling visualizations, it is important to remember the following visual separability issues. First, shapes affect the perception of color differences; conversely, color affects the perception of a shape. Shape significantly affects size perception, for example, a filled shape will be perceived as more significant than an unfilled one. Thin or small shapes will also affect texture visibility, brightness, and hue perspective [37].

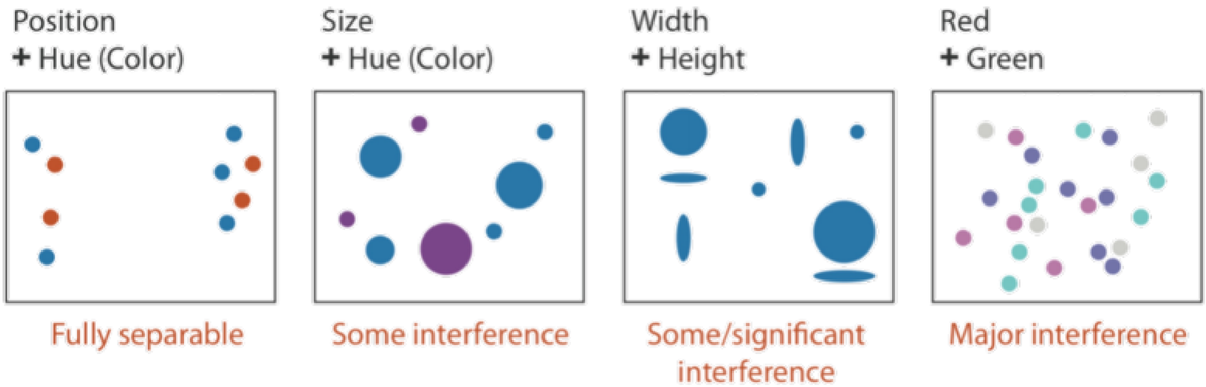

Figure 2.2: Visual Separability [38]

2.3.1 Climate Visualization

The climate data presented by the IPCC is continuous geospatial data over time. When dealing with geospatial data, the position is fundamentally intrinsic to the task [35]. By visualizing geospatial data, viewers can quickly interpret datasets and solve tasks by understanding trends and patterns that would be otherwise impossible to see with the raw data [39]. The following are ways that the data could be visualized.

Dot Distribution Map

A dot distribution map is one of the most basic examples of plotting geospatial data. A list of items with spatial positioning on a geographical map can be plotted with a point mark with a background map layer. It lets the viewer quickly understand the distribution, outlines, or clusters of data [40].

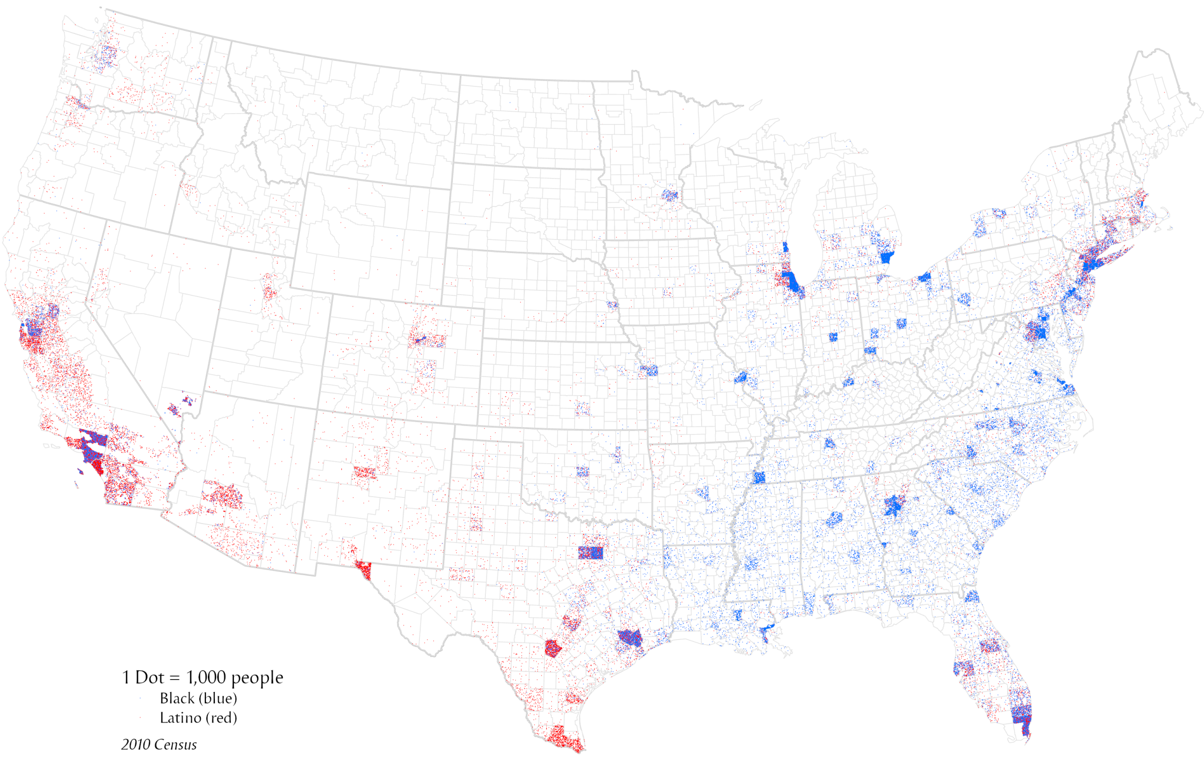

Figure 2.3: Dot Distribution Map of Concentrations of the Black and Hispanic Populations from the 2010 US Census [41]

Choropleth Map

Another way to encode geospatial data is through choropleth maps. In a choropleth map, regions are divided up by shape, and a quantitative or categorical attribute is encoded using the color for that region [40], see Figure 2.4. For example, when plotting something such as the maximum temperature in a region, temperature values could be mapped to a color scale, and the maximum temperature for a region could be plotted. Viewers can compare values between regions through choropleth maps and discover similarities, trends, or outliers. It is important to note that regions remain static.

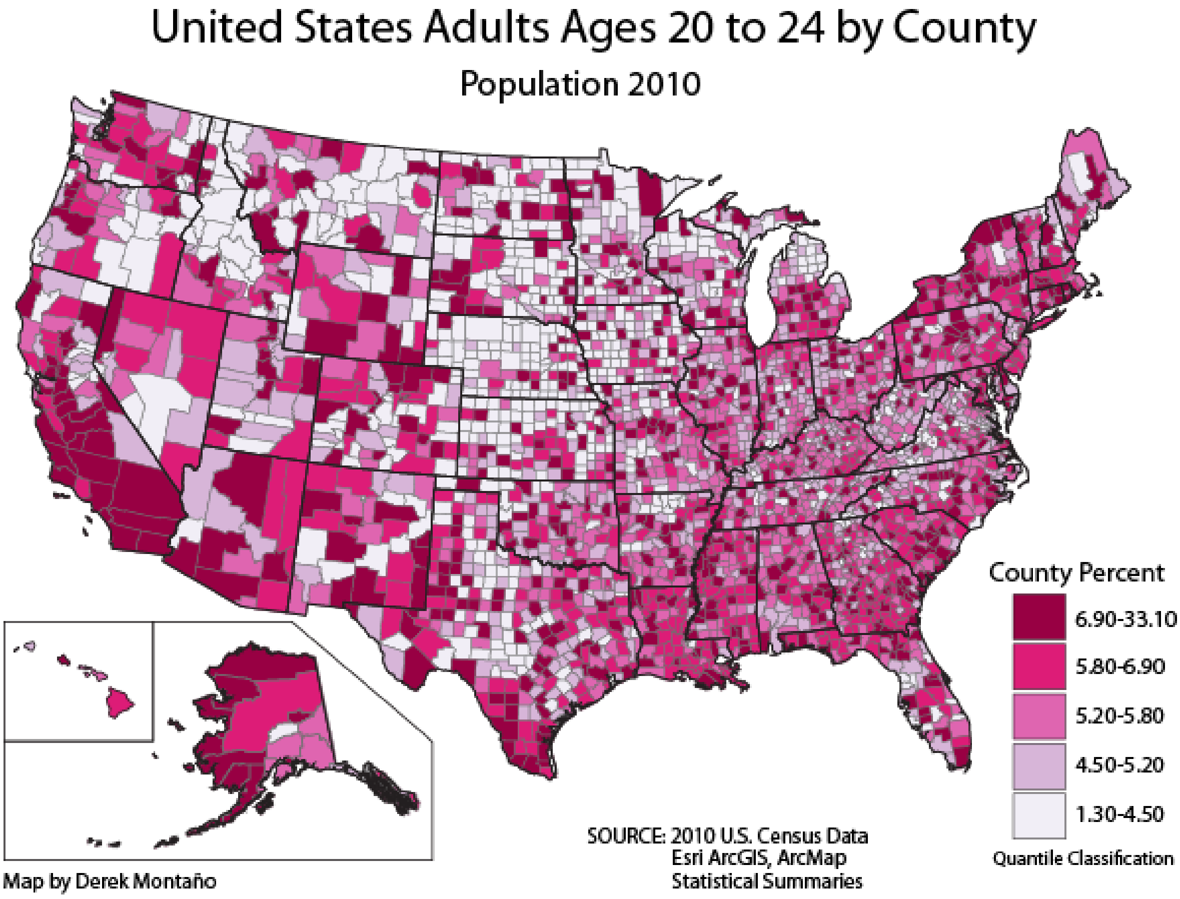

Figure 2.4: "Choropleth map showing United States adults ages 20 to 24 by county." [42]

Heatmap / Density Map

Heat maps are similar to dot distribution and choropleth maps in that data is plotted on top of a map layer, and color encodes the data. What distinguishes it from those map types is that the data is plotted with no relation to regions and instead to the granularity of the data itself [40].

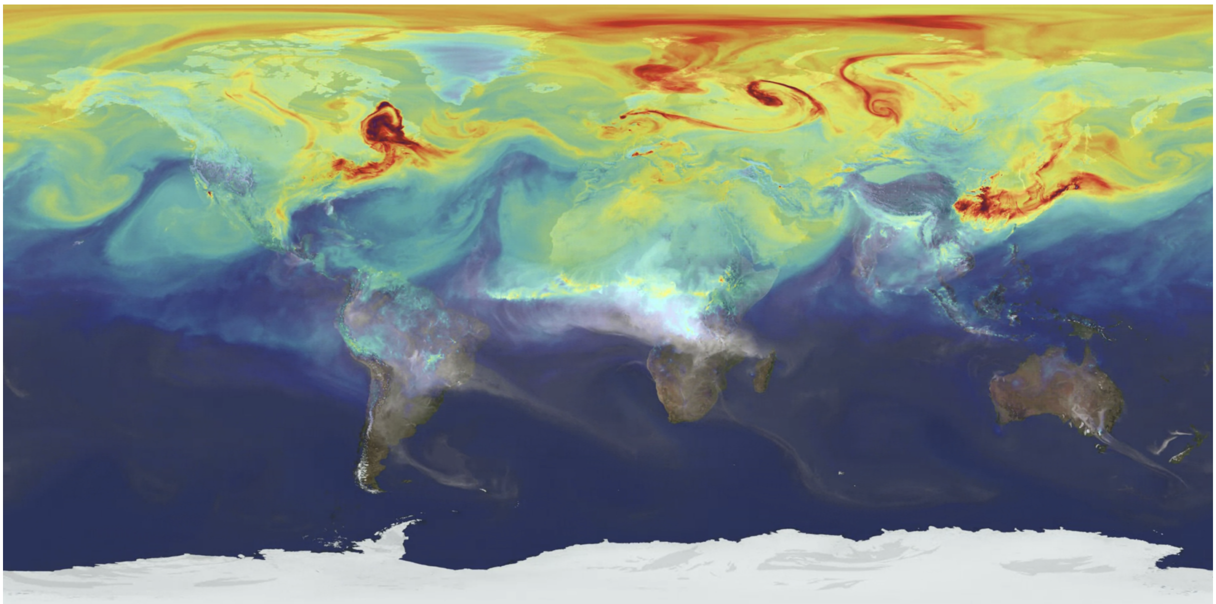

Figure 2.5: "Displays temperature across a world image with red being the highest and blue being the lowest degree in temperatures" [43]

Map Visualization Enhancements: Pop-ups / Tooltips

Pop-ups are often used in map visualization to display various information points. They provide an intuitive way for viewers to access more detailed information from a map. Typically, a viewer can click or hover over a data point, region, or color to get more precise information about that data point.

Figure 2.6: A European Map Showing a Tooltip [44]

All of the previous examples demonstrated how to plot geospatial data. However, a large portion of the data from the IPCC has a time element associated with it. This data can be plotted separately or integrated into the maps themselves.

Line Charts

The easiest way to plot data over time is to use a line chart. Time can be encoded through the position of the line or points. Typically this would be through the x-axis.

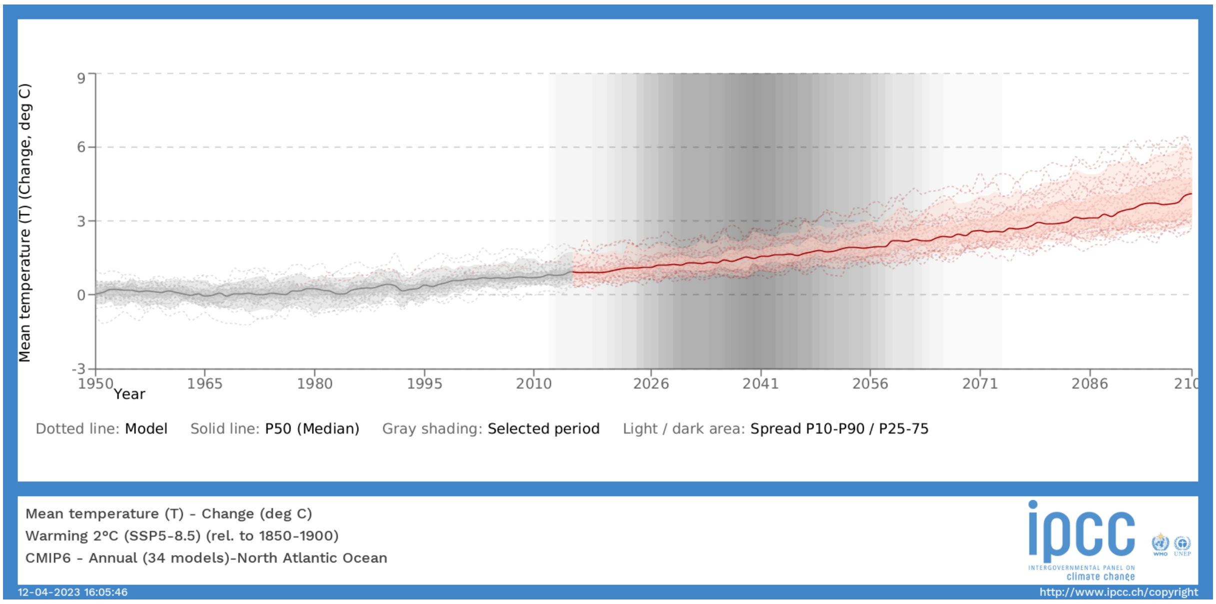

Figure 2.7: A time series plot for many models predicting mean temperature from the IPCC Interactive Atlas

Climate Stripes

Climate stripes are a relatively new data visualization technique that uses a series of colored stripes to minimalistically visualize long-term climate-related trends [45]. Each line represents a specific data point. While temperature data is what is commonly plotted, it has been used to visualize sea level rise [46], global glacier retreat [47], and other variables related to climate change.

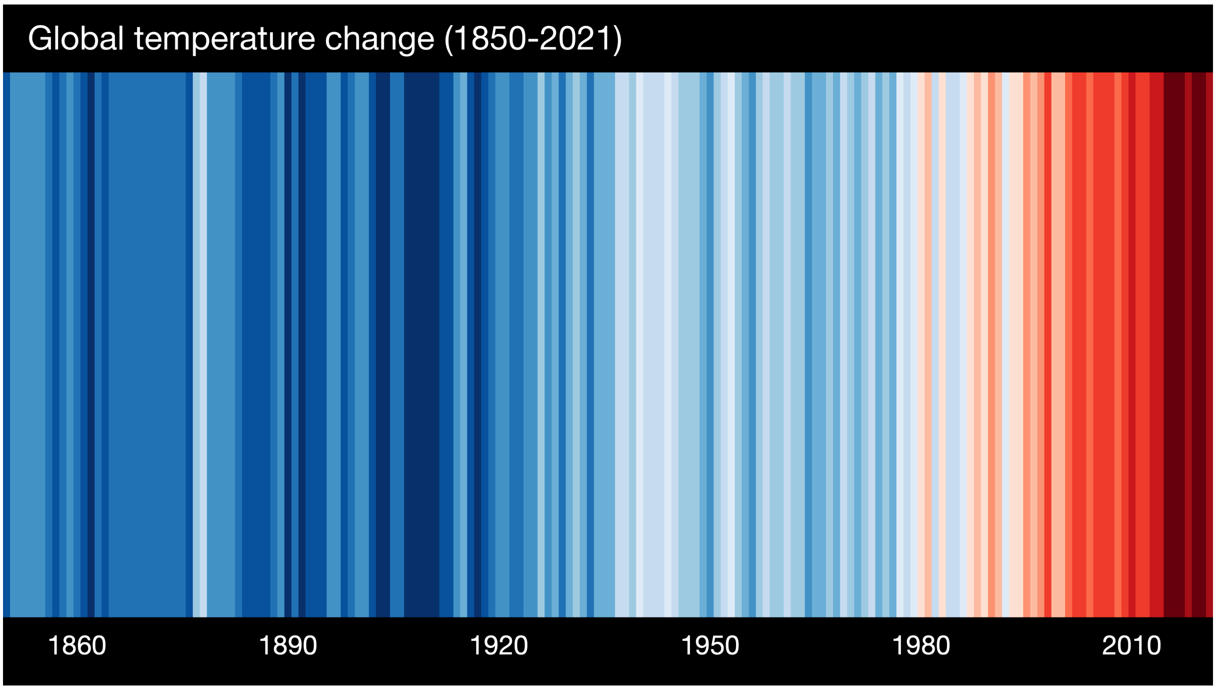

Figure 2.8: Climate Stripes showing Global Warming from 1850-2021 [45]

Animation/Motion

A more complex mechanism to demonstrate change over time is to transition other encoded variables over time. In the case of the different geospatial maps, the color would shift over time, allowing the user to understand the changing nature of the data. Because animation takes place over time, the viewer can naturally understand a shift of information through animation [48].

2.4 Closely-Related Projects

A limited number of similar applications have been built to teach users about climate change, and the research conducted by the IPCC and some of these are described below. However, there were none that could be identified which were designed to connect directly to real-world data modeling, cater to multiple users, and have specific learning outcomes.

2.4.1 IPCC WGI Interactive Atlas

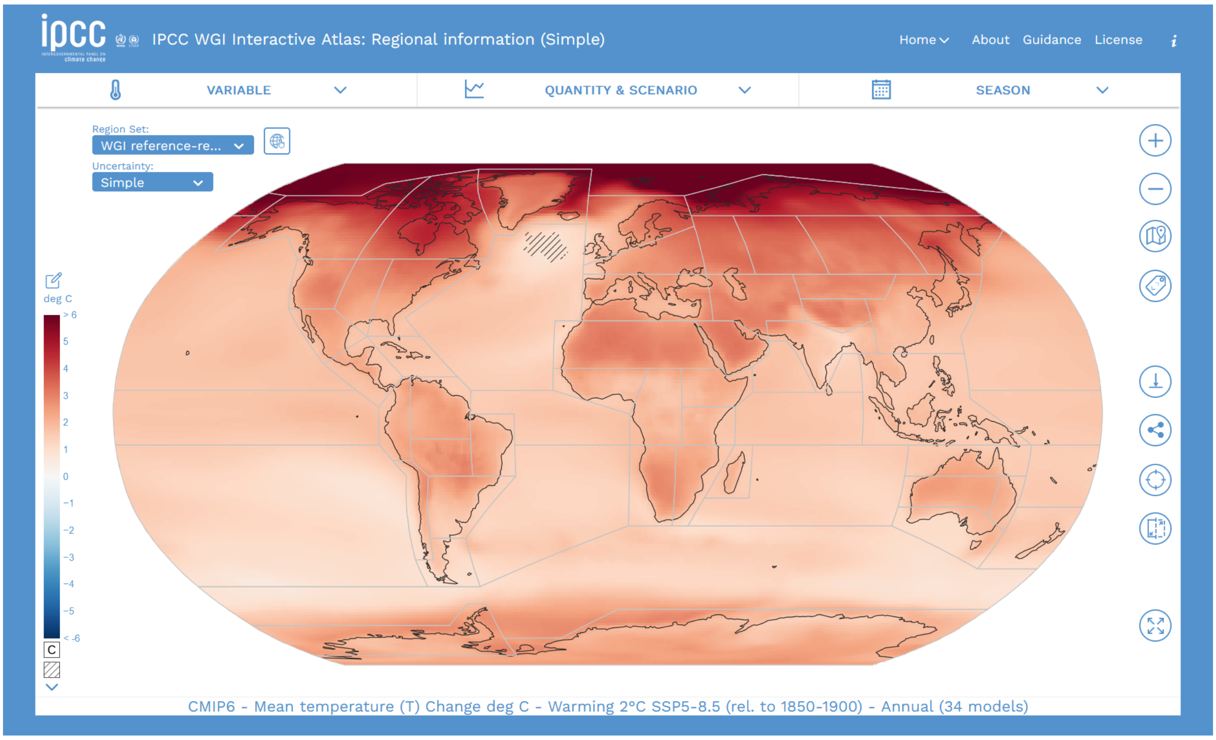

Figure 2.9: Interactive Atlas in Simple Mode [5]

The Interactive Atlas was built to accompany the IPCC Sixth Report and two other documents the IPCC produced: the Technical Summary and the Summary for Policy Makers [14]. The Atlas allows for spatial and temporal analysis of a large portion of the climate change data modeling and information used to create the reports. It allows users to analyze trends and changes in crucial atmospheric and oceanic variables through many global and regional observational and model-based datasets.

Users can select the variables they are visualizing, the scenarios, models, and the time frame, and interact with the data in real-time on an interactive heatmap. If a user clicks on the map, they can select one of the delineated regions to look at different subsets of the data more precisely through various charts, including a time series line chart, a scatter chart comparing different models, a line chart showing predicted yearly trends, a table summarizing the data as well as a stacked climate stripes chart, showing the change of data over time while comparing different models.

This tool lets the curious user click through different models and interact with much of the data. Unfortunately, there are 110 different parameters that the user can set, making it potentially overwhelming for the user. There are also no specific goals when using the tool; therefore, it is up to the user to glean whatever information they can from it.

2.4.2 The Climate Game by the Financial Times

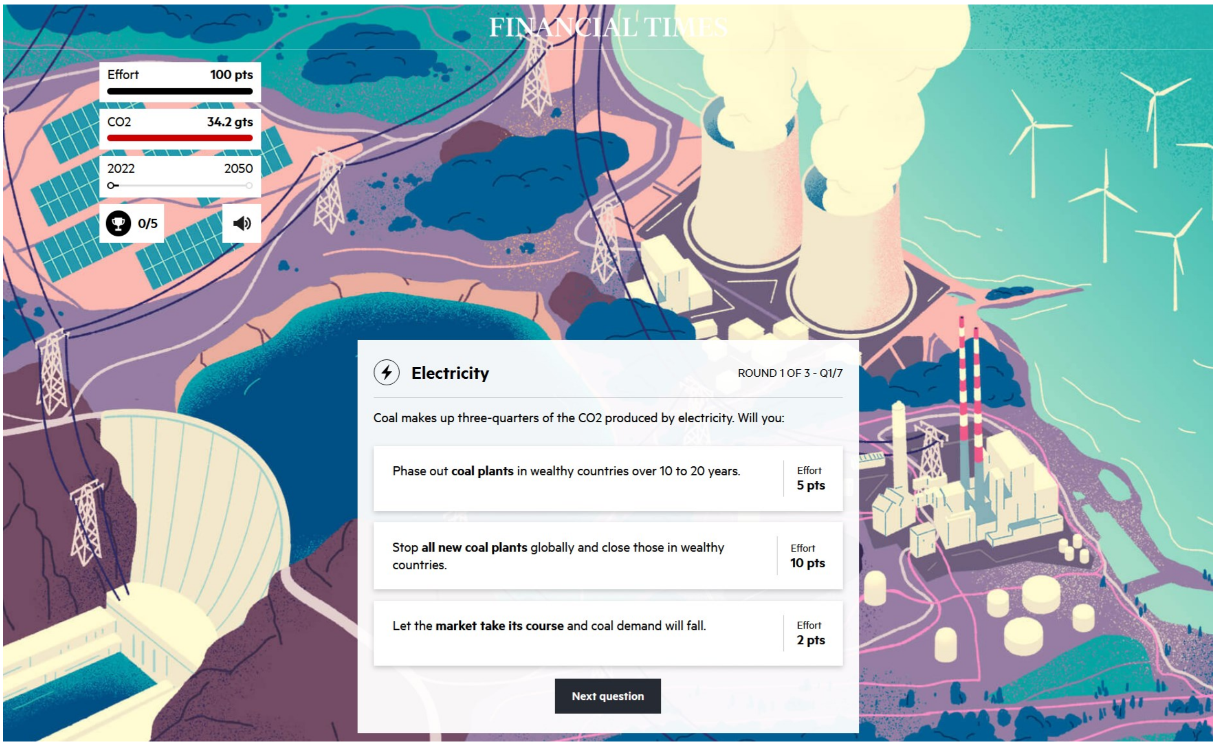

Figure 2.10: Question from The Climate Game [6]

The Financial Times (FT) created the Climate Game in partnership with Infosys, which gamifies the actions needed to tackle climate change. The game's purpose is to bring an opaque and highly complex process of causes and consequences into the light, making it easy and simple to understand [49]. While not a direct simulation of the future, it was built using the latest research at the time. The emission modeling was developed by the International Energy Agency (IEA), and scenarios were based on the "Net Zero by 2050" report [50]. To calculate the climate outcomes, they used IEA's World Energy Model and Energy Technology Perspectives model coupled with the Model for the Assessment of Greenhouse Gas Induced Climate Change V7+ [3].

The questions in the game, based on the 400 actions to reduce climate change in the "Net Zero By 2050" report, relate to four sectors linked to energy-related C02 emissions: electricity, transport, buildings, and industry. Players aim to limit global warming temperature to less than 1.5C and must decide the best choices for each sector to achieve that goal. Alongside different solutions proposed in the report, a few "wrong" answers were included, based on failed ideas to solve climate change, for example, solar panels on roads [49].

The modeling is not based on specific tracks that the players fall into, but instead, players explore their unique scenario based on the decisions they make in the game. Decisions are connected together, simulating the interconnectivity of the world.

Each question costs "effort points", and natural disasters can occur, reducing the number of points. Players get 100 points at the start and more after answering a group of questions. Over time, answers become more expensive to emphasize the importance of taking actions sooner rather than later.

At the beginning of the game, players elect an advisor, which is meant to highlight other factors that are important to reaching net zero: behavioral change, new technologies, green business practices, and policy change. In the game, the advisors earn the player 10 points for working hard in their specific sector.

The game also includes tipping points which are critical thresholds that, once passed, negatively affect the user by reducing their effort points. These tipping points are based on real-world scenarios.

At the end of the game, players are presented with Earth's median temperature for 2100, predicted using the MAGICC V7 model. Players also see plots and graphs showing their emission cuts, their progress to net zero, and how the world changed, all based on their decisions. Fundamentally, the goal is to educate users and help users think critically about how to approach and solve the climate crisis.

This simulation achieves a lot of the goals set out in this dissertation. It is very effective and engaging and connects back to real-world data. It lacks, however, a few key features. The game focuses on the player being a policy maker, making decisions for the entire planet. This is not representative of the real world, and different regions of the world only have different impacts. The game is also only designed for a single player, not a group of players.

2.5 Summary

It is clear that climate change is an important and complex issue that needs teaching at every level. But when taught well, information and data about climate change can significantly impact the learners' behavior. Connecting pedagogical theory and data visualization allows the creation of environments where learners can lead their own personalized learning experience and be more hands-on during the learning process. While a limited number of applications teach climate change through different mechanisms, these applications only cover some aspects of climate change that are important.

Chapter 3

Design

This chapter introduces the tool proposed by this dissertation. Building on the background research, climate change has been identified as a critical challenge that needs immediate solving. By combining research and modeling conducted by the IPCC and CMIP6 along with technological and pedagogical techniques, this section will describe the design of a tool that will educate users about the importance of climate change and collaboration as a mechanism to tackle it. The tool is influenced by the visualizations that were built for the Interactive Atlas but will focus more on a guided learning experience with specific goals. The tool is also influenced by the Climate Game learning experience and will ask similar questions. Diverging from the Climate Game, the tool will be built using a more complex dataset while simplifying the types of questions being asked to the user. The tool will also be focused on multiple users acting congruently in the environment.

3.1 Overarching Tool Design

Learners will join a lobby, a collection of users participating in a session together, and will each be assigned to different regions of the world. These learners will act as policymakers for their respective regions. They will be presented with a series of decisions they must make regarding actions relating to climate change and ecology. These decisions will impact the total amount of simulated emissions in the environment. Using the simulate emissions, an SSP scenario will be calculated, and the learners can then interact with a subset of the CMIP6 data for that scenario through a series of visualizations.

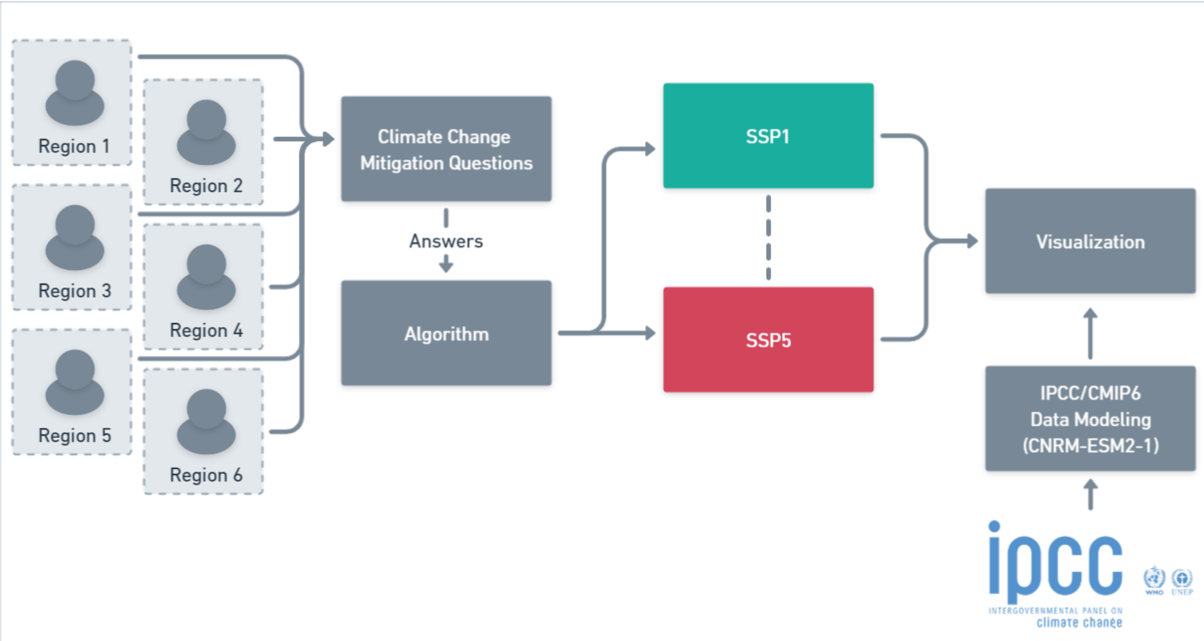

Figure 3.1: Tool Overview

3.2 Considerations

The tool is designed for Irish Transition Year students in secondary school, and the following considerations were taken for this target group.

Transition Year students will have studied sustainability as part of the science curriculum during their Junior Cycle. The students should have been taught to “illustrate how earth processes and human factors influence Earth’s climate, evaluate effects of climate change and initiatives that attempt to address those effects” [51]. As part of the modules they take during the Transition Year, they may have also completed the 45-hour transition unit teaching environmental studies [52]. The unit focuses on connecting how both global and local government issues affect their surrounding environment.

The tool will be built to accompany an educator leading a workshop for a group of students. Nonetheless, it should be accessible for the students to use as a group, independently of an educator.

Variations in technological literacy among students require the tool to be user-friendly and intuitive, including explanations for the different sections, features, and buttons.

While politics is naturally entangled with climate science, the tool should avoid making political statements and focus on actions regions or countries can focus on to reduce climate change’s effects, making learners more informed citizens.

3.2.1 Regions

While the entire planet contributes to the causes of climate change, some countries and regions have an outsized impact due to a considerable amount of pollution generated from that country or region [7]. Additionally, some regions are more severely impacted by climate change's effects due to their geographical location [53] [8].

In collaboration with this dissertation's co-supervisor and climate change subject matter expert, Dr. Silvia Caldararu, the following countries were identified as regions that the learners would represent:

Regions With Large Emissions

- China [54]
- India [55]
- The United States of America [56]
- The European Union [57]

Regions Disproportionately Effected from Climate Change

- South American Amazonian Countries [8]
- The Alliance of Small Island States [53]

Each region was assigned an initial number of carbon points, a relative weighting based on the amount of pollution produced by the region. These carbon points are hidden from the user and are impacted by how the user answers the questions. The goal of each user is to reduce the impact of their region.

3.2.2 Questions

Dr. Caldararu also developed the policy questions and their answers which are presented to the learners. Similar to the questions from the Climate Game discussed in §2.4.2, these questions targeted two essential environmental policy sectors: land usage and energy production. Each question has a weighting for each region, representing the relative importance of the policy question to the region. Each question has three to four potential answers, which have relative weightings depending on the answer's impact. The phrasing of the questions was checked by educators from B2C so that they would be comprehensible for the target age group.

Working with Dr. Caldararu, an algorithm was devised to take all of the decisions made by all the regions and map them to one of the SSPs.

3.3 Scope

Given the complexity and breadth of climate science and the IPCC Sixth Report, it was necessary for the author to place limitations on the project's scope. The following are the limitations and rationale for the decisions that the author took:

- For the learner to be able to contextualize and understand the data effectively, the visualizations will focus solely on maximum temperature, near-surface air temperature, and ocean sea level rise. Data from the CMIP6 covers 51 different data points [13], many of which are too complex for TY learners. The three selected are variables that the learners will be able to relate to.

- To simplify the data further, the tool will only visualize one model, CNRM-ESM2-1 (France) [58]. While there were many different models to select from, CNRM-ESM2-1 modeled all of the variables the author needed to visualize and all of the SSPs and their subvariants. This simplifies the learning experience by not teaching learners about the variation between different types of models, which is not the goal of the tool.

- All regions will be presented with the same set of policy questions to address but the answers will be uniquely weighted for each region. While the world does not face homogeneous issues, it would be too time-consuming to create enough individualized questions considering the timeline for the creation of this tool.

- A part of the project's goal is to create interactive visualizations, adequate space is needed for the different visualizations identified in §2.3.1. Therefore, accessibility and support for larger screen sizes would be prioritized over that of small mobile devices.

3.4 Functional Requirements

The author and both supervisors determined the functional requirements for the project. They were broken into the major sections of the user interface (UI): the lobby, the questions, the visualization, and any other meaningful functional requirements.

3.4.1 Lobby

- The user should be able to create a new lobby.

- The lobby should be uniquely identifiable with a code.

- The user should be able to join an existing lobby if the lobby is not full.
- The user should be automatically assigned a region once they join a lobby.
- The lobby must only allow users to start the learning experience when there are users for each region.
- Any user should be able to start a lobby.

3.4.2 Questions

- The user should be presented with questions one after another.
- The user should have a series of answers they can pick before moving on to the next question.
- Each answer should have an associated cost which should be visible to the user.
- The user should see their reserve of points to spend on questions.
- The user should not be able to select an answer if they cannot afford it.
- The user should not be able to go back to previous questions.
- The user should receive more points halfway through answering all of the questions.
- The user should be able to see their process through the questions and the number of questions left.

3.4.3 Visualization

- The user should get a textual description of the calculated scenario.
- The user should be able to interact with the data in a series of visualizations.
- The user should be able to switch variables displayed in the visualizations.
- The user should be able to switch the actively visualized scenario.

3.4.4 Other

- The user should be able to select and change languages.
- When a user is in a lobby, they should always see their assigned region and the code for the lobby.

3.5 Non-functional Requirements

The following were the non-functional requirements decided for this tool.

- The user should be able to access the tool from a web browser.
- The tool should support the four most popular browsers (Chrome, Firefox, Safari, Edge [59]).
- The tool should scale and support multiple groups of users concurrently.
- The tool should be self-explanatory or have adequate accompanying information for users to use it.

3.6 Technology Choices

In order to build the tool, the different technologies and libraries had to be examined such that the best ones could be chosen.

3.6.1 Data Preprocessing

All of the data modeling produced for the IPCC Sixth Report is publicly accessible through Copernicus [13], the European Union's earth science distribution platform. Data can be downloaded through a queue system where a user requests a specific set of variables and receives the data sometime later. This can take several minutes. This means there is no way to access any of the data in real time to visualize an outcome for the user. In addition, when downloaded, a single file containing only one model, variable, and SSP could be up to 200kb. This means that all of the data for the different combinations of variables, SSPs, and models is of a magnitude of 10s of gigabytes. Because of all these limitations, it was necessary to preselect variables, download them, process them, and store them on a server for real-time access.

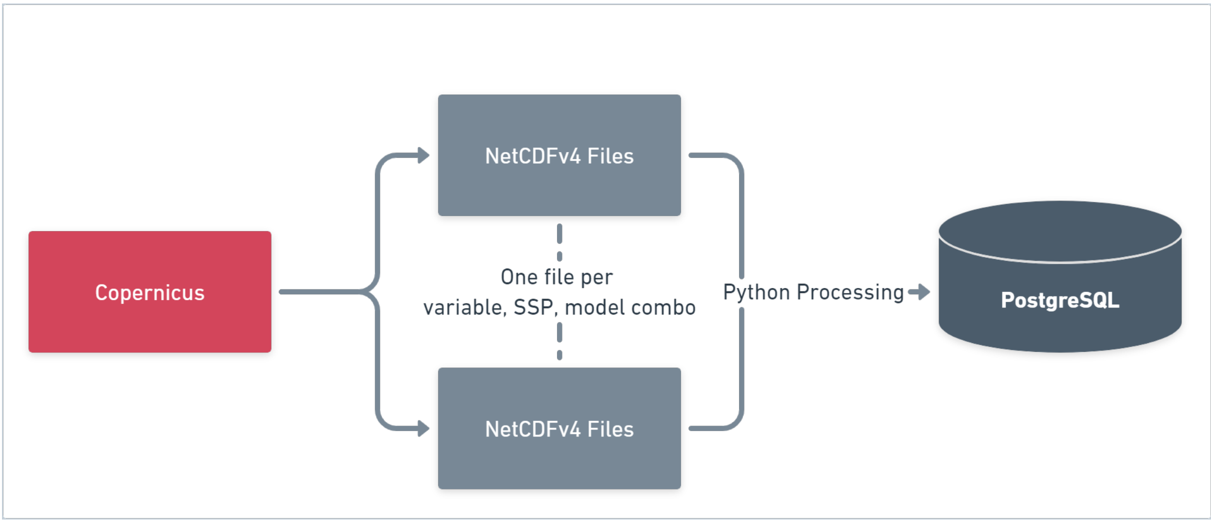

Figure 3.2: Data Preprocessing Overview

The downloaded CMIP6 datasets are stored in a format called NetCDFv4. NetCDF files are the standard used by the Open Geospatial Consortium. The format allows for the easy manipulation and storage of multidimensional arrays of scientific data, especially geospatial and time-series data.

Copernicus recommends three languages for manipulating the data: Python, R, and MATLAB [60]. Given the author's familiarity with extensive data processing in Python, it was selected as the language of choice.

To read in NetCDF files, the author used XArray [61] and its extension rioxarray [62] to load the dataset for processing. XArray is a library specializing in loading and manipulating multidimensional arrays and provides many valuable functions for NetCDF files that do not exist in other libraries. rioxarray builds on top of XArray by providing functions and manipulations specifically for geospatial data.

In order to process the regions relevant to the project, a world GeoJSON file [63] was processed using Mapshaper [64] to create a Shapefile to be loaded in with Python using two libraries; Geopandas [65] and shapely. GeoJSON and Shapefiles are file formats that store vector information, typically regarding country shapes or borders. Geopandas and shapely are libraries in Python that help load and manipulate those boundaries and provide helpful functions for utilizing the boundaries with other datasets. The Shapefile was also simplified in Mapshaper to reduce filesize. Using all of the above libraries, the author transformed the monthly global data to yearly regional data as it was determined that the monthly precision was unnecessary.

The processed data was uploaded to a PostgreSQL server using the Python Prisma client [66], as Prisma was chosen for the front end. Prisma is an ORM that allows for the easy configuration and safe manipulation and access of PostgreSQL, MySQL, SQLite, SQL Server, MongoDB, and CockroachDB databases [67]. PostgreSQL was selected as it is the most performant of the database options while using Prisma.

3.6.2 User Interface

There are several different application types that would fulfill the majority of the functional and non-functional requirements; however, in order to fulfill the requirement regarding web browser support, a web application is required. A web application can be made easily accessible and quickly deployable to many different machines while maintaining a consistent user experience. In addition, web applications are highly accessible due to their lightweight nature and do not require complex deployments or configuration for the machines of the learners.

There are many frameworks to choose from for web applications, all with their strengths and weaknesses. Table 3.1 details the options the author considered.

Framework	Description
HTML + CSS + JS [68]	HTML (Hypertext Markup Language) and CSS (Cascading Style Sheets) are the underpinnings of the web. HTML is used for the content and structure of web pages, and CSS is used for styling. In addition, JavaScript (JS) is often used alongside both HTML and CSS for responsive designs and any programming or functions needed for the web page.
React [69]	More complex web apps typically do not use HTML, CSS, or JavaScript directly but will use a framework that compiles into HTML, CSS, and JavaScript to facilitate development. React is one of the most popular frameworks in this space. Created by Meta, it is a free and open-source framework for creating applications for the web with JavaScript. Using React, developers can create components, use classes, and help fluidly update websites to enhance the user experience.
Next.js [70]	Next.js is a framework built on React that implements features such as file-based routing, server-side or client-side rendering, search engine optimization, and an integrated backend with API routes. It is used professionally by large companies such as Apple, Netflix, Uber, and more [71] due to the additional features.
Vue.js [72]	Vue.js is another JavaScript framework similar to React in its feature offerings. It allows routing, components, state management, and more. However, unlike React, it extends HTML by allowing the development of directives making coding Vue applications similar in feeling to writing HTML-based applications.

Table 3.1: Frontend Frameworks

While an application of this scale could be created with any of these options, Next.js is the most feature-rich and provides many developer comforts that the author is familiar with. Next.js allows for the creation of a web application that manages a very easy backend and that handles the routing of different pages automatically. Additionally to Next.js, the author used Typescript instead of JavaScript as it adds static typing to JavaScript before it is compiled into JavaScript. Typescript ensures better development practices and more robust software.

Multiplayer Architecture

As previously described, the tool consists of multiple learners interacting in a shared environment. These learners make a series of climate related policy decision which results in a SSP which can then be visualized. This connected environment must be handled through some mechanism, and Table 3.2 details the options the author considered.

All of the factors detailed in Table 3.2 contributed to selecting Socket.IO for its flexibility and support features that best fit the tool. All of the other libraries were either too complex, had additional dependencies that could hurt the experience of users, or were not built for the intended purpose of the tool. The socket server can be hosted on a Next.JS API endpoint. NodeCron was also used to schedule tasks on the server.

Library	Communication Protocol(s)	Description
Socket.IO [73]	WebSocket with a fallback to HTTP Long Polling	WebSocket is a type of bidirectional communication protocol handled over TCP. Socket.IO is a library that builds on this, providing additional assurances for data transmission. It also provides easy and intuitive functions to use. However, Socket.IO uses a client-to-server structure; therefore, the backend must continuously run, or else any state information is lost.
boardgame.io [74]	REST API Server	boardgame.io is an open-source library and engine for turn-based games. It allows for game state management, phases, AI, and more. However, due to the requirements, there are better libraries for the project as the tool intends to support on simultaneous interactions.
PeerJS [75]	WebRTC	PeerJS is a library meant to simplify and wrap around WebRTC, a peer-to-peer communication protocol. As the intention is to allow six regions to be in the same lobby together together, peer-to-peer communication could be complex as there are two main options to organize the system. First, the tool could assign one user as a host but would have to handle the error scenario if that user disconnects. The tool could manage communication across all the users to ensure everyone has the correct, up-to-date information. Both of these options make peer-to-peer communication with more than two users complex.
Liveblocks [76]	Communication with Liveblocks server	A proprietary service that allows for communication between different users. Requires an account with Liveblocks to be used and relies on the availability of Liveblock servers.

Table 3.2: Lobby Communication Protocols

Interface Design

In order to develop an accessible and visually aesthetic system, several libraries exist that follow existing design standards or provide out-of-the-box functionality. They allow for much faster development without having to create components or a design language from scratch. Table 3.3 details the libraries considered by the author for this project.

Library	Details
Material UI (MUI) [77]	A component library built using Google's Material Design standard. It includes a comprehensive suit of UI elements that can be used and customized for any project. It is easily theme-able.
tailwind [78]	A CSS library that allows the development of modern-looking websites without ever needing JavaScript. It is very lightweight but uses a system of utility CSS classes which can be daunting for new users.
Ant Design [78]	Similar to Material UI, Ant Design is a lighter component library that is less prescriptive. As a result, it can be more easily customized.
React Bootstrap [79]	Bootstrap is a toolkit for responsive web applications for HTML, CSS, and JavaScript. React Bootstrap is built from the ground up to enable Bootstrap with React without unnecessary dependencies.

Table 3.3: Component Libraries

All of the different libraries that the author looked at would be well suited for building any tool of this nature. MUI was chosen as the library for this tool due to the author's familiarity with the library and the ease it offers when creating UIs.

All the libraries in Table 3.3 are missing components for creating interactive visualizations of large amounts of data. As a core feature of the tool is to visualize different scenarios through a series of different charts and graphs, each of the following libraries was examined by their ability to provide the visualization techniques presented in section 2.3.

Library	Details
D3.js [80]	D3.js is a JavaScript library that visualizes data using HTML, CSS, and SVG. D3 allows for the dynamic creation of SVGs. D3 provides powerful data manipulation and transformation functions, scales for mapping data to visual properties such as size and color, and an extensive range of algorithms for position elements. It also has built-in functions for zooming, panning, and selecting elements. Because the visualizations are rendered as SVGs, it creates very performant visualizations. Visualizations built with D3 are naturally very flexible, and it is easy to change the underlying data. There also exists a very active community surrounding D3 with many examples, tutorials, and libraries.
p5.js [81]	p5.js is a JavaScript library built to replicate the popular Java library, Processing, but built for the web, with the goal of making coding accessible for artists, designers, educators, and beginners. The JavaScript library provides functions to create essential shape elements and customize them. "Sketches" consist of a setup function that runs on the first load and then a rendering loop. While highly customizable, every element and helper function must be built from the ground up.
Recharts [82]	Recharts is a composable charting library built specifically for React built on top of D3 and D3 submodules. It allows for the creation of charts such as Line Charts, Area Charts, Bar Charts, Scatter Charts, Pie Charts, Radar Charts, TreeMaps, and Radial Bar Charts. In addition, all of the charts are fully customizable, allowing for the addition of tooltips, legends, chart stacking, and more.
react-simple-maps [83]	React Simple Maps is also built on top of D3, whereas this library is specifically for geographical maps and data. It allows for the creation of interactive maps that support some of the visualization techniques discussed in section 2.3.
nivo.rocks [84]	Like Recharts and React Simple Maps, Nivo is another library providing a series of complex prebuilt charts built on top of D3. While Nivo is highly customizable, it is much more prescriptive in the type of data structures needed for the visualizations and the types of visualization that can be built. From practice, Nivo tends to have performance issues on large datasets.

Table 3.4: Visualization Libraries

Both Recharts and React Simple Maps were selected for this tool because they provide great out-of-the-box solutions for creating customizable and interactive charts like the choropleth maps and line charts laid out in section 2.3. There were additional features that were not covered by the libraries and therefore D3.js was chosen to build performant additions to the other libraries. These libraries were selected as they provided the most performant visualizations when handling large data sets which is the intention of this tool.

Language barriers often lead to tools such as this one to not be accessible outside of the English-speaking world. While the author of this paper can speak two languages (English and French), providing a structure for others to translate the tool easily would allow for more opportunities for the expansion of the tool's usage in the future. The tool is intended to be open-sourced so that others can contribute and improve it, for instance by providing a translation file. In anticipation and to facilitate the use of the tool in other languages, selecting a library to manage these translations was necessary.

Library	Details
Lingui [85]	Lingui is a comprehensive internationalization framework that includes tools for creating and managing translation strings in a web application. It allows for easy integration with existing developments and helps manage issues such as pluralization and context-based translations which helps the development of large applications.
formatjs/react-intl [86]	Format.js (formerly react-intl) is a localization library specifically designed for React applications. It provides components and utilities for formatting dates, numbers, and strings in a localized format. Format.js also includes features such as message extraction and translation management, which simplify the process of managing translations in a React application.
react-i18next [87]	React-i18next is a popular internationalization library that provides a range of features for managing translations in a React application. It includes a simple API for translating strings and provides components for displaying localized content in a React application. React-i18next also supports pluralization and interpolation features, making it suitable for applications with complex translation requirements.

Table 3.5: Translation Libraries

All of the libraries listed in Table 3.5 would be a good fit for this project. Lingui was chosen as the library for the tool because there are more online examples of integrating Lingui with Next.js.

Testing

Testing is an integral part of the development process of any piece of software as it ensures the quality and reliability of the tool being built. In addition, it allows developers to identify bugs or problems with the intended functionality. When tests are well written, any changes that break the system can be quickly and easily identified.

Library	Details
Cypress [88]	Cypress is an end-to-end and component testing library for JavaScript that mimics natural user behavior. It allows developers to test web applications in a real-world context. It also includes a visual test runner allowing developers to see their application getting tested in real-time. It is the recommended tool for testing Next.js applications.
React Testing Library [89]	React Testing Library is a lightweight testing library specifically designed to test React Components. It focuses on component testing, specifically making tests more resilient to code changes and allowing for easier debugging of issues if they do occur.
Jest [90]	Jest is a more generic JavaScript testing library. It does not require React or other frameworks and allows for front and back end testing. In addition, it allows for mocking, code coverage analysis, and snapshot testing. It is highly customizable but highly complex.

Table 3.6: Testing Libraries

Next.js recommends using Cypress when developing tests for web applications built using the Next.js framework. Consequently, it was selected to allow every aspect of the codebase to be easily tested.

Chapter 4

Implementation

This chapter goes into detail about to the implementation of the tool. The entire process can be divided into two major components: the data preprocessing and the application and user interface.

4.1 Data-preprocessing

4.1.1 Reading and processing files

As previously mentioned, the datasets provided by the IPCC are very large, not instantly available, and very complex. This meant that the data would need to be preprocessed for the visualizations. Given that the data would be transformed, it was necessary to determine the types of charts and graphs that would be visualized. In section 2.3, line charts and choropleth maps were identified as helpful visualization methods for this type of climate change data and therefore were selected for the visualizations of this tool.

When generating the data for the line charts, the following steps were taken for each different variable:

1. The world shape file is loaded in.
2. For each SSP:
   (a) The dataset is loaded in.
   (b) The data is transformed from monthly data to yearly data.
   (c) The data is clipped to be only for each specific region.
   (d) The data is uploaded to the database.

When generating the data for the geographical maps, the steps were similar but slightly different:

1. The world shape file is loaded in.
2. For each SSP:
   (a) The dataset is loaded in.
   (b) The data is clipped to be for each country in the world.
   (c) A function is applied across the data to transform it from monthly data to a single number. For example, when dealing with the monthly maximum temperature dataset, the data was transformed to the max temperature for each country in the next 100 years.
   (d) The data is uploaded to the database.

Challenges

The author ran into numerous challenges while loading the datasets. First, as mentioned previously, the data is unavailable online in a way that could be accessed in real-time, making it necessary to preprocess the data. The data itself was not uniform in the standard that it was stored. Sea ocean level data was initially planned to be included as part of the visualized data but ended up not being included. This was due to a difference in the structure of the sea ocean level data compared to other datasets, making it incompatible with the preprocessing script created by the author.

4.1.2 Uploading to database

The database schema was defined using the Prisma schema language. This schema defines the structure of the data, and then Prisma converts it into scripts that manage the database. Once the schema is defined, we can use the Prisma Client API to upload the data to the database. The client API ensures a type-safe way to interact with the database. For example, here is a subsection of the Prisma Schema detailing a part of the processed dataset:

```
model Data {
  ssp           SSP
  model         Model
  region        Region
  temp_max_rows TempMaxRow[]
  temp_rows     TempRow[]

  @@unique([ssp, model, region])
```

```
}

model TempRow {
  id         Int      @id @default(autoincrement())
  year       DateTime
  tas        Float
  dataSsp    SSP
  dataModel  Model
  dataRegion Region
  Data       Data?    @relation(fields: [dataSsp, dataModel, dataRegion], references: [ssp, model, region], onDelete: Cascade)
}
```

Enclosed within the braces of the model declaration, the left-hand side designates the column name. The right-hand side specifies the corresponding data type, often utilizing enumerated data structures to maintain data type safety. Additionally, relevant parameters related to the data may be included on the right-hand side.

4.2 System Architecture

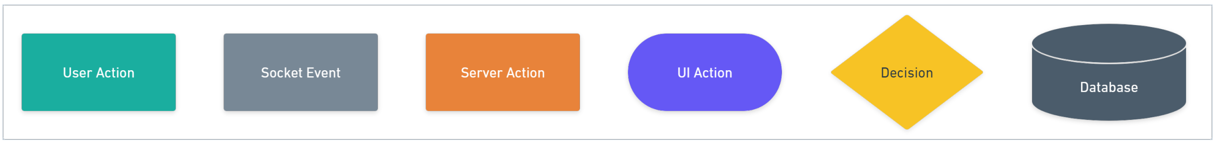

Figure 4.1: Key for the System Architecture Diagrams.

The user can trigger one of three events at the start of any interaction with the tool: they can create a lobby, join it, or start it if they are already in it. Each stage includes error checking to ensure there are not too many or too few users in a lobby. If all the users leave a lobby, the lobby gets removed from the system. If there are no changes in a lobby after 30 minutes, the lobby gets removed as well. If a user tries to join a lobby that is nonexistent or full, they receive an error message.

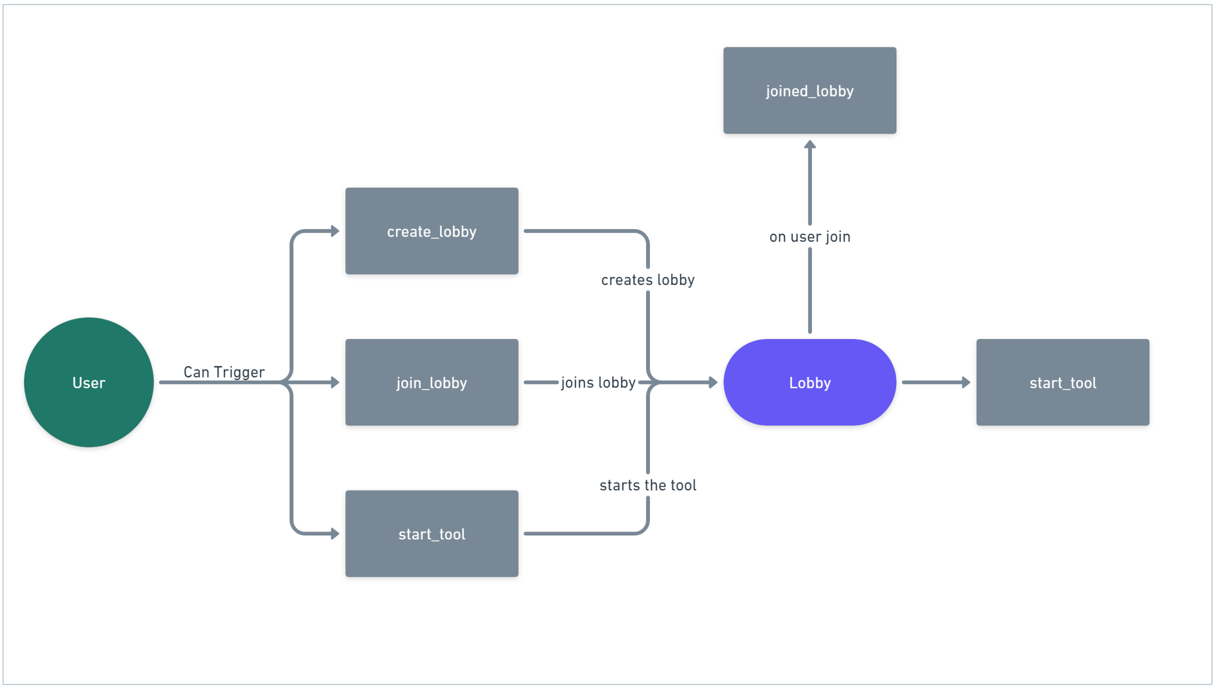

Figure 4.2: System Architecture: Start Flow

Once there are six users in the lobby, one of the users can start the lobby. Each user asynchronously goes through the questions answering to the best of their ability. The user's answers are stored locally until the user finishes every question. Once they finish all the questions, the total emissions, based on the answers selected, for that user is calculated and sent to the server managing the system. Once all users complete the question, the server moves all the users to the visualization state.

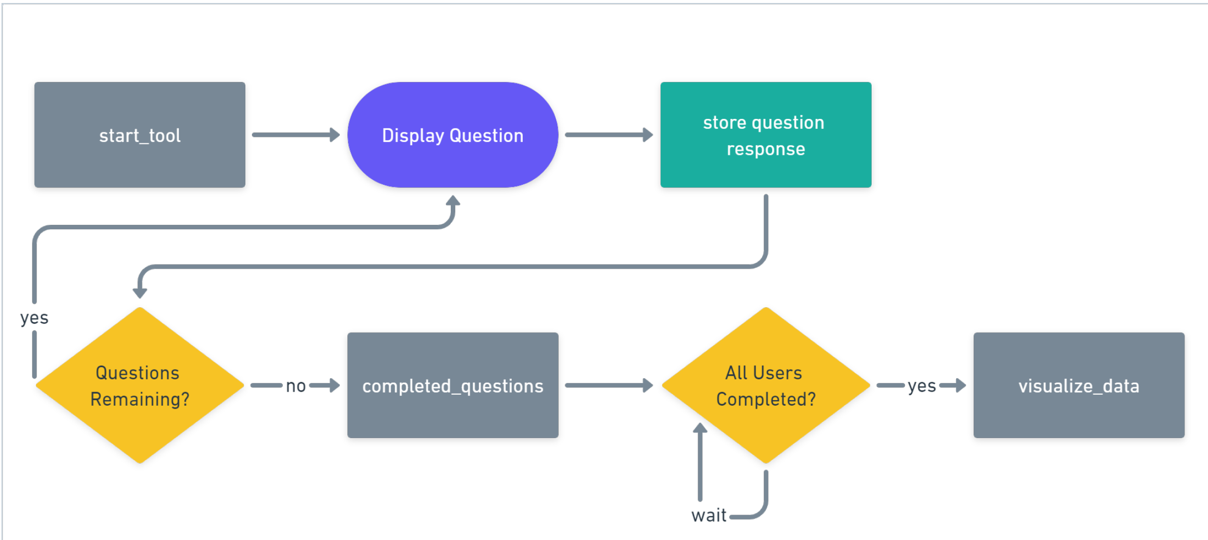

Figure 4.3: System Architecture: Question Flow

In the visualization state, the server calculates the appropriate SSP from the weights that were sent from the different users. Then, based on the calculated SSP, a request is sent to the database to receive the data in real time to send to the users. Once the data is sent to the user, it gets visualized in a series of components.

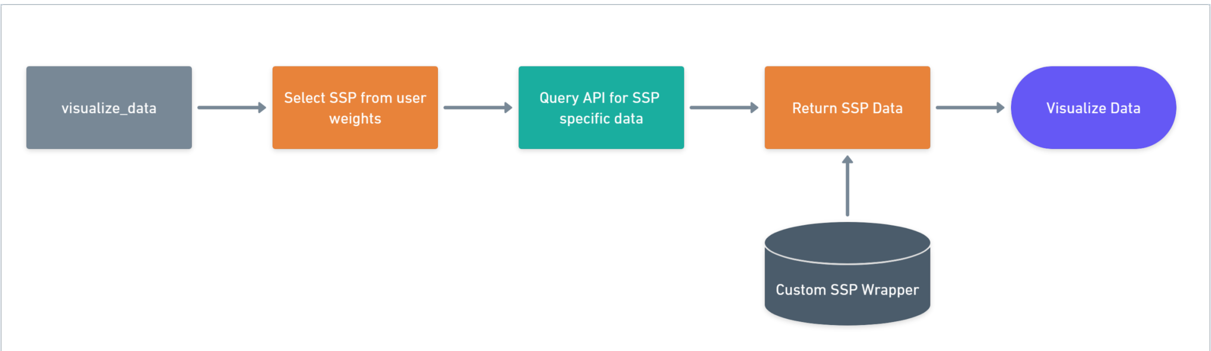

Figure 4.4: System Architecture: Visualize Flow

4.3 Frontend

Text Tooltips

Complex climate change terms can sometimes be unavoidable when teaching about climate change. Depending on a learner's exposure to the topic of climate change, they might already be familiar with these terms. In case they are not, a dictionary of words and abbreviations and their definitions are maintained on the front end. Every text in the front end is wrapped using a function that identifies these terms, underlines them with a dotted underline, and then provides a hover tooltip with the additional information. It takes advantage of the react-highlight-words library.

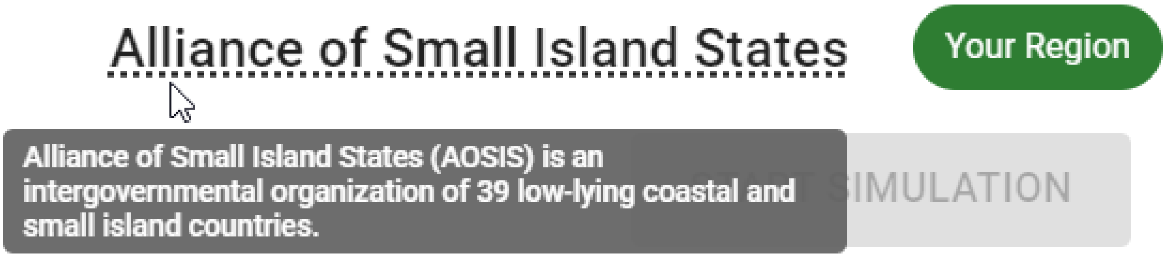

Figure 4.5: Text Tooltip of the Alliance of Small Island States on the Lobby Page

Translations

Every string in the application was wrapped using either the Trans Macro or t function from Lingui. While both operate in a slightly different technical manner, both allow for the creation of a localized string with an associated ID.

```
t({
  id: "title",
  message: "Climate Collab Tool",
})
```

For each language, this ID is then stored with the translation for that string so that when a user selects a language, it loads the correct set of strings from the correct language file.

```
# en/messages.po, English translation file
#: pages/index.tsx:89
msgid "title"
msgstr "Climate Collab Tool"

# fr/messages.po, French translation file
#: pages/index.tsx:89
msgid "title"
msgstr "Outil pour Climat Collaboration"
```

A translator can then go through a specific language file and then translate all of the strings from the website without manipulating any code.

The following sections are the front end implementations for section 4.2 and the general UI flow.

4.3.1 Home Page

The home page allows users to create a new lobby or to join an existing lobby.

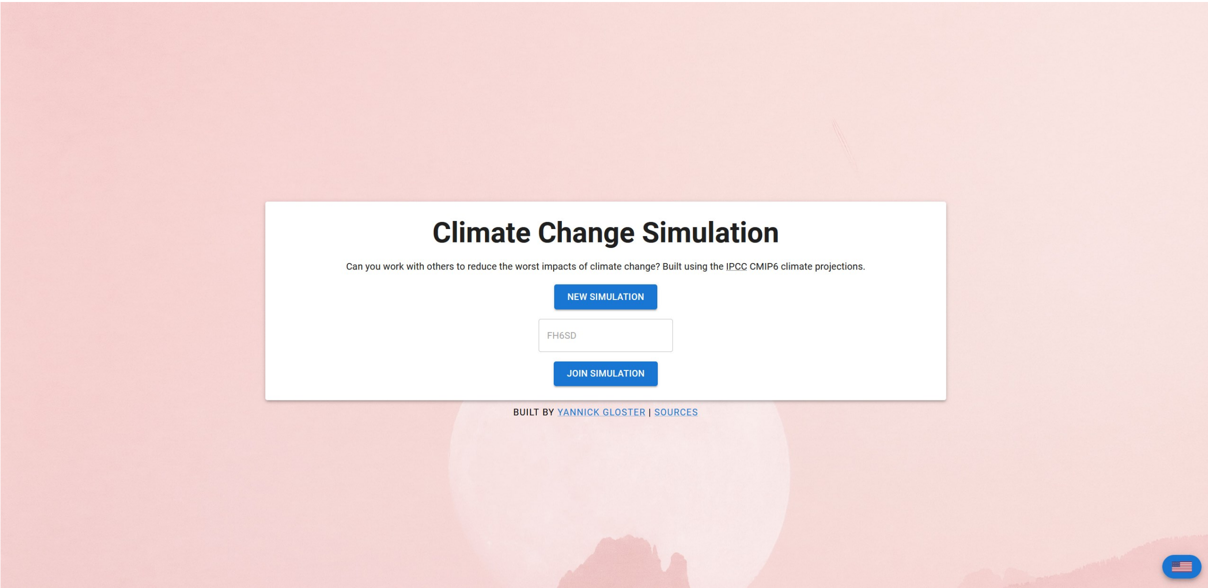

Figure 4.6: Home Page

4.3.2 Lobby Page

Once the user has joined or created a lobby, they are automatically assigned a region from the back end. This is visually represented by the green tile and text stating “Your Region” next to the region the user has been assigned. Unassigned regions remain blue, and once assigned, they transition to grey. Once all the regions have been assigned, the start button becomes available.

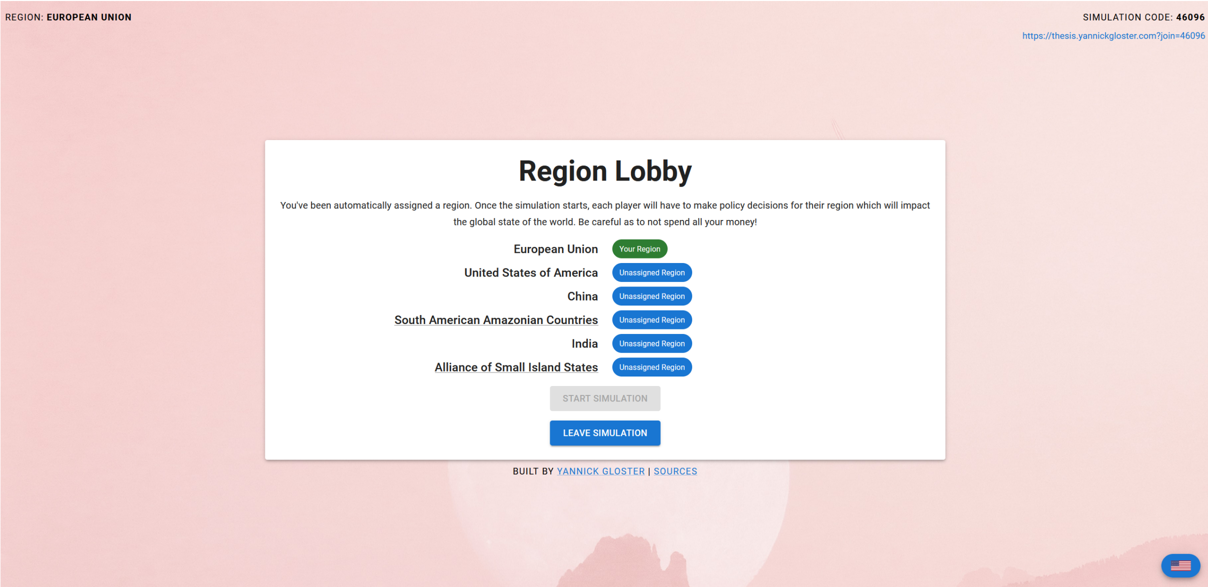

Figure 4.7: Lobby Page

4.3.3 Questions Page

Once started, the questions are loaded and presented linearly. There is no way to go back once a question has been answered, and the back button on the browser becomes locked. The user's progress is visualized with a progress bar at the top of the question. Background images are preloaded for each question, and each background image relates to the type of question being asked. As you can see, in the question in Figure 4.8 where the question's topic is about forests, the background image is a forest. All of the images were licensed from Unsplash. Unsplash is a platform containing user-generated images that are freely available for creative purposes, including educational usages.

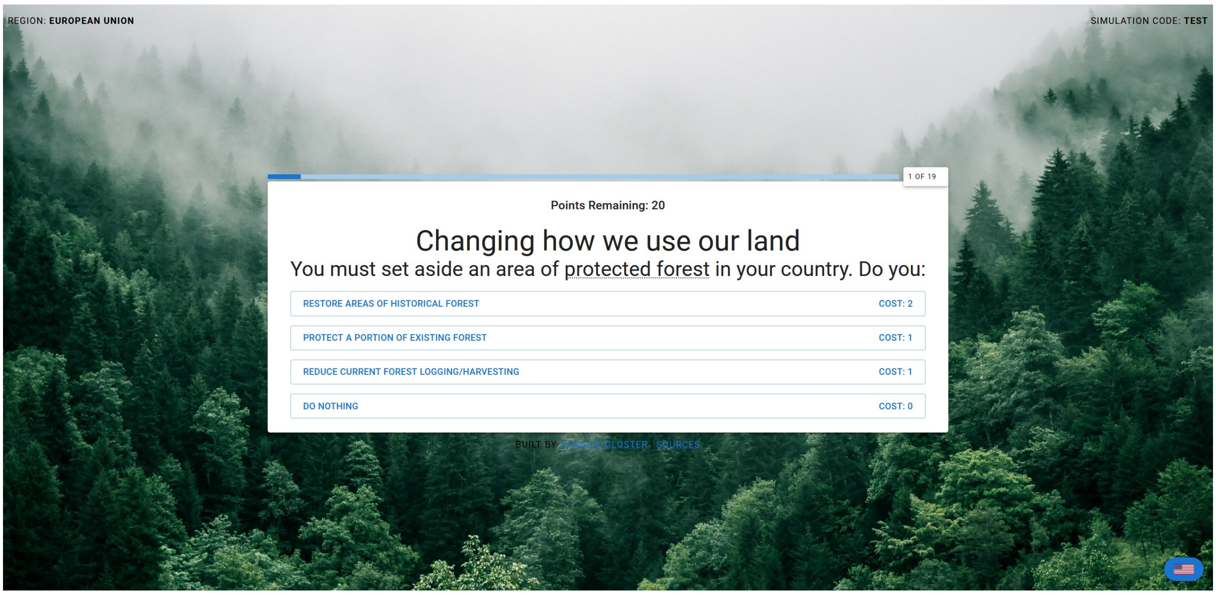

Figure 4.8: Questions Page

At this stage, the front end keeps track of the emission points locally as the user goes through the questions. The following equation is used when determining the total number of emission points. This equation ensured that achieving all of the SSP is possible while maintaining a sense of realism by making both extremities of SSPs difficult to achieve. This equation came from thorough testing by selecting all the worst negatively impacting choices in one lobby and by selecting all the best positively impacting choices in a different lobby ensuring that achieving all of the SSPs were possible.

$$\text{user.emission} = \text{user.emission} - 0.2 * \text{question.regionWeights[0].weight} * \text{answer.weight}, \tag{4.1}$$

Figure 4.9: Emission Equation Balancing

The front end also ensures that the user does not spend more points than they have in their balance. Users begin with 20 points, and as they answer questions, they spend points. They also receive a bonus set of points halfway through.

4.3.4 Visualization Page

Once all of the users have completed their questions, the back end calculates the SSP by summing all the emissions from the regions and finding the closest matching SSP from the predetermined SSP emission values. This SSP is then sent to the front end. The front end makes a request to the database for all the data needed for visualization. At this stage, the learner can freely move between the different stages of visualizations, creating an environment where they can compare and contrast the information presented to them.

The first section gives a textual overview of the scenario. The first short paragraph is a textual description written for the comprehension of a TY student, while the longer paragraph is a scientific definition.

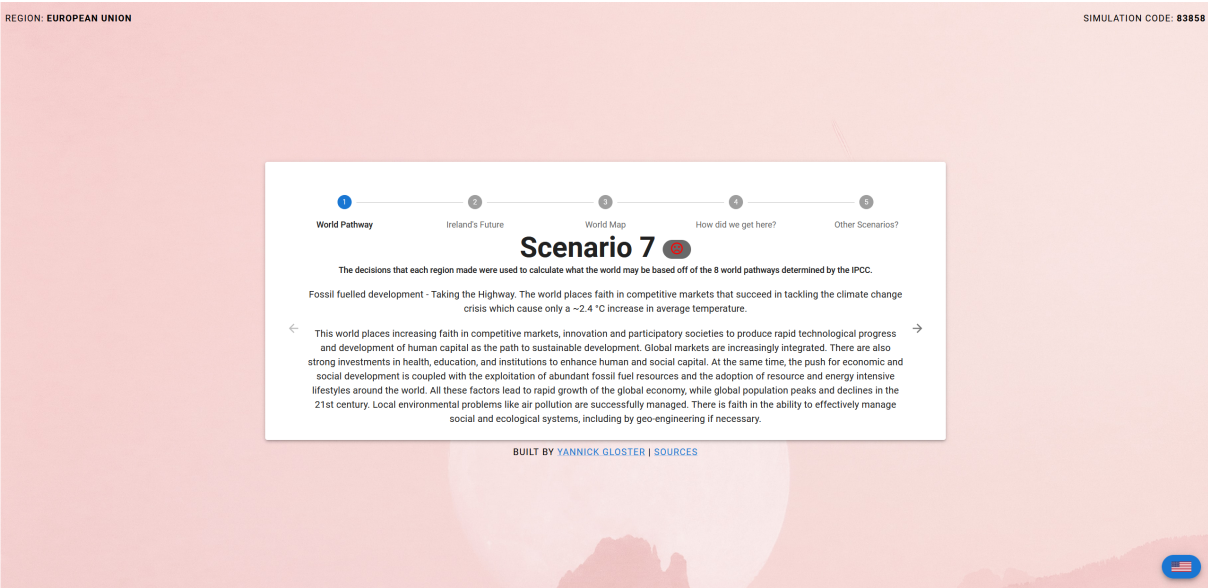

Figure 4.10: Visualization Description

Given that the students testing the tool were from Irish secondary schools, the following section contextualized the information to Ireland, presenting them with the mean temperature for Ireland over the next 100 years.

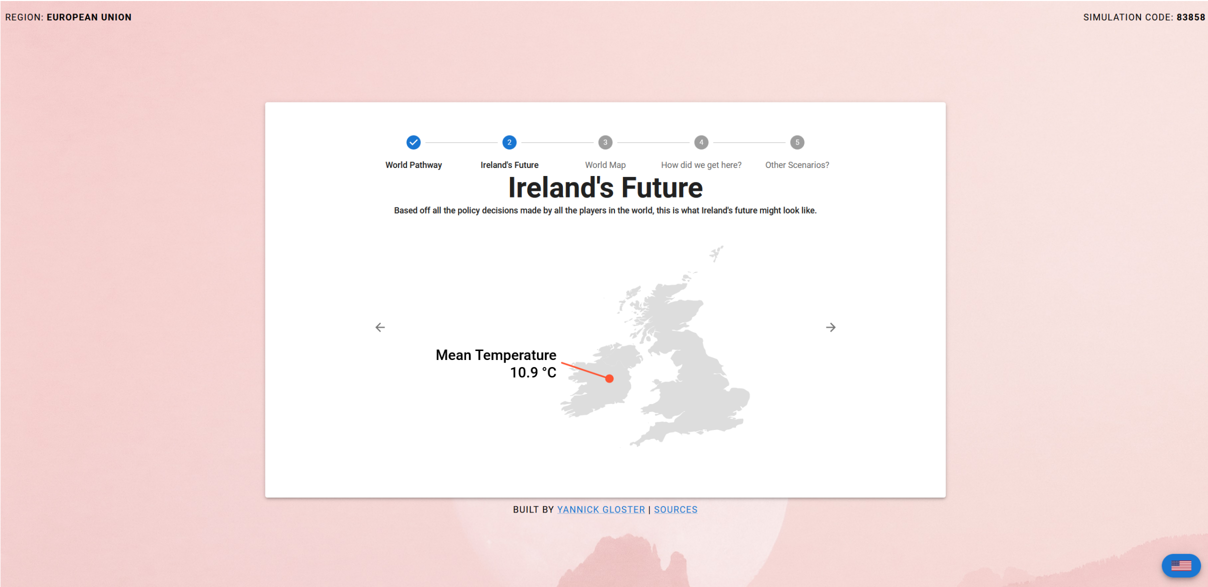

Figure 4.11: Visualization Context

Choropleth Map

In §2.3, choropleth maps, geographical maps where colors represent a specific aggregate of information for a specific region, were identified as a good visualization method for this dataset. The user can use a drop-down to select one of the two variables, mean temperature and max temperature over the next 100 years. They can hover over each country, get the specific data information, and click and drag around the map to zoom in and move around. The scale was built using D3.js, and the map utilized react-simple-maps.

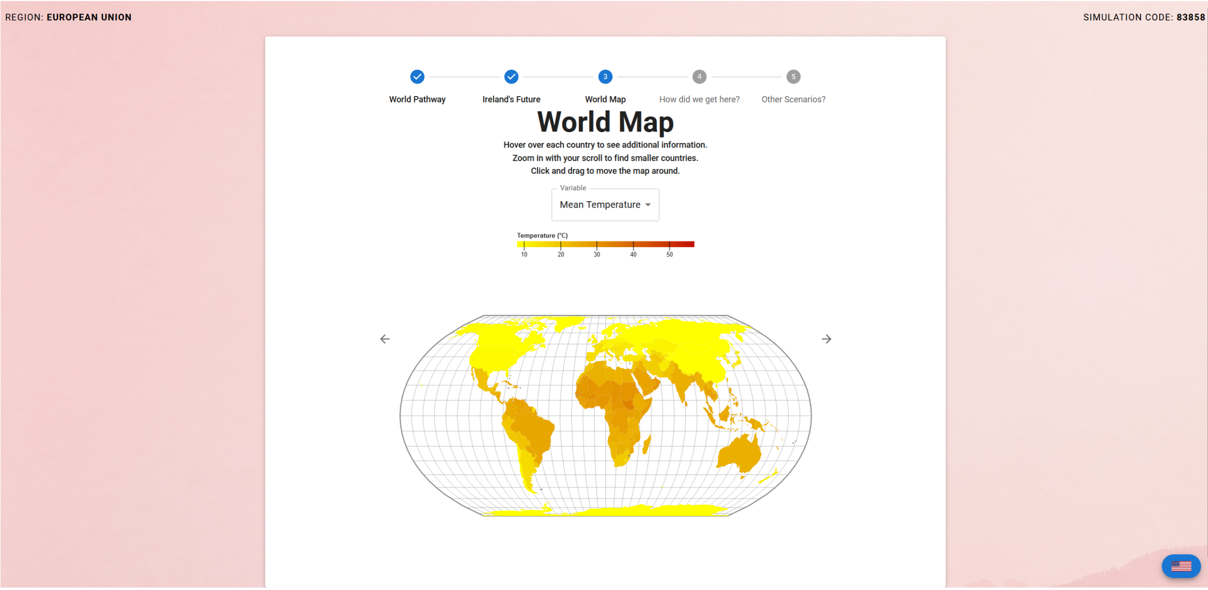

Figure 4.12: Visualization Map

Line Chart

The data is also plotted yearly in a line chart that was built using Recharts. The user can hover over each individual data point for additional information and zoom in or move around using the slider at the bottom. A simple linear regression was performed on the data to generate a trend line so that users could understand the overall direction of the data. Similar to the map, the user can dynamically switch between variable types.

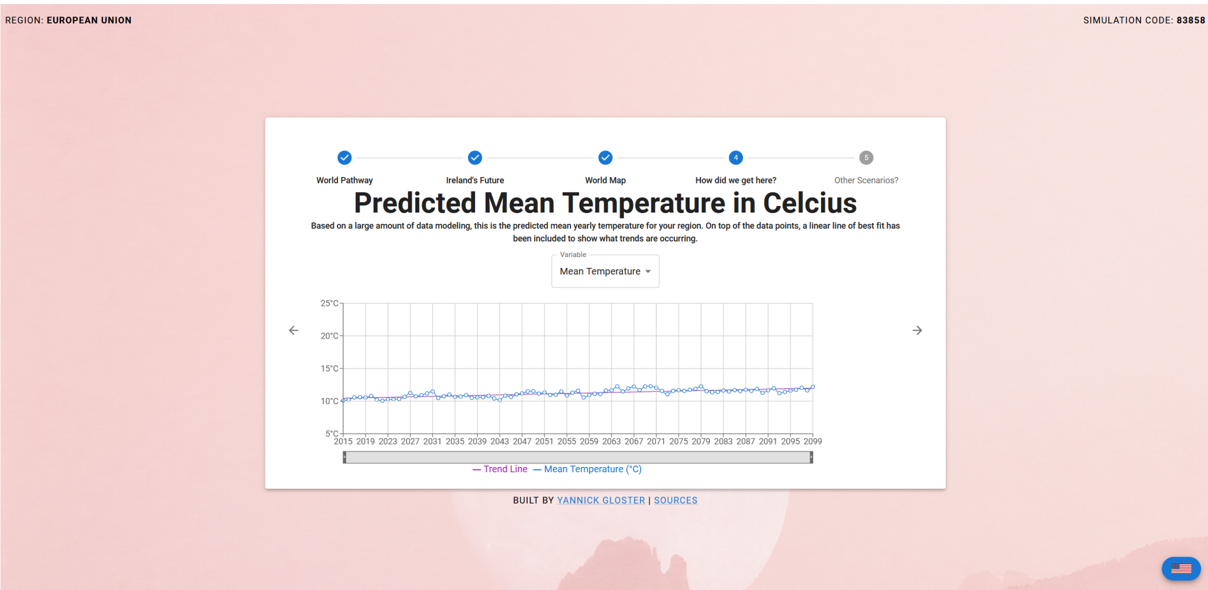

Figure 4.13: Visualization Line

All the datasets

The final section allows for the visualization of all of the other possible scenarios and regions. Users would not be able to understand the full picture of the dataset without being able to compare their region to others and their scenario to others. They can select any combination of scenarios and regions and view the data in both the line chart and the world map.

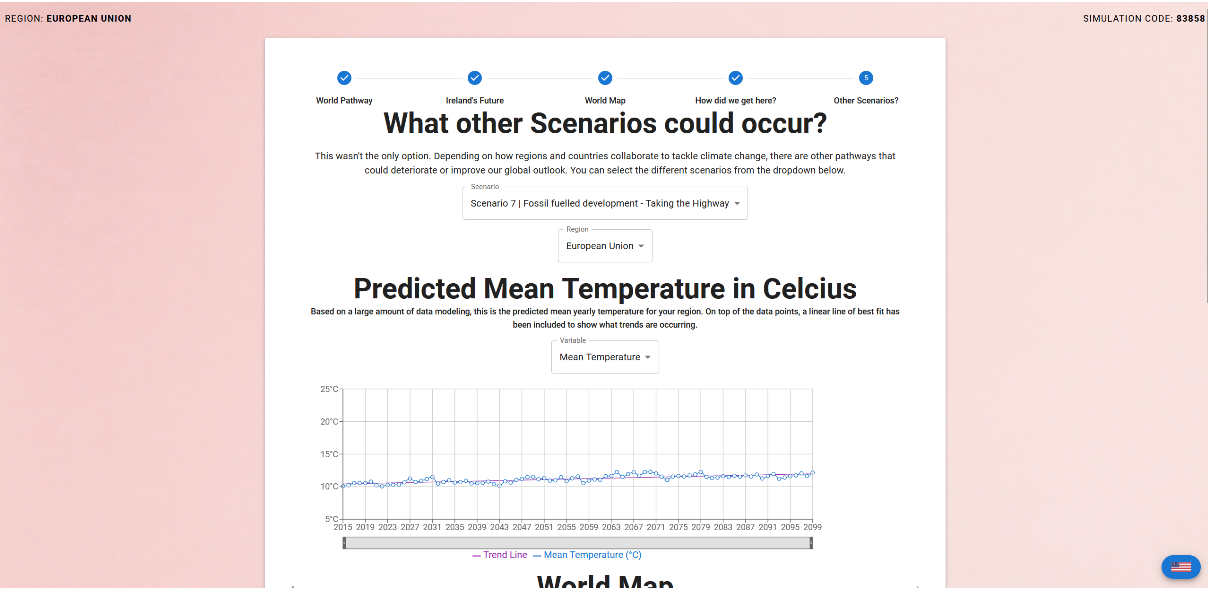

Figure 4.14: Visualization Other

4.4 Back End

4.4.1 Algorithm Configuration

The author worked closely with the co-supervisor, Dr. Caldararu, to create the algorithm and environment to map the decisions of all the regions to an SSP. Each region of the world has a set of starting emission units from 1 to 47, where the sum of all the emission units across the regions is 100. The more emission units a region has, the more pollution that region creates in the real world. The goal is to reduce the number of emission units in the simulated environment. At no stage does the user see these emission units directly. Each SSP was given a set of emission units between 10 to 100. When the user goes through the questions, the front end calculates the reduction that the selected answer has on the region's starting emission units. The values for each question were play-tested thoroughly to ensure that all possible scenarios were achievable.

Each question also had an associated cost. Users were assigned 20 points at the beginning of the simulation. Halfway through the questions, they receive 10 more points. The questions were given a cost between 0 and 3. The cost was not meant to be one-to-one to real life but rather an approximate mapping that would make it difficult for users to always select the correct answer.

4.4.2 Lobby

When a user connects to the web app, a request is made to the socket handler API endpoint, which starts the back end Socket.IO server if it has not already been started.

When a user creates a new lobby, a new custom lobby object is created, storing the list of connected users, the lobby code, and the lobby's current status. This object is stored in a hashmap, with the key being the lobby code. This allows for very performant retrieval of the lobby's information; however, scaling to hundreds of users would not be realistic as the hashmap is stored directly in memory. The server will randomly assign a region to the user who created a new lobby and then will return the updated state to the user. The user is then put into a Socket.IO lobby, a sub-channel for communicating with specific users. This allows the server to send messages and updates to all the connected users in a lobby easily.

When a user attempts to join a lobby, the tool first checks if it exists. If it does not exist, an error is sent to the user. If the lobby does exist, it checks if there are available regions. If there are no available regions, an error is also sent to the user. If there are available region(s), the user is randomly assigned one of them. They also join the socket lobby, the lobby object is retrieved, updated, and stored, and then all the users in the lobby get the updated lobby object.

Users can leave the lobby following the reverse process of joining. They are removed from the socket lobby, removed from the lobby object, and then the updated lobby object is sent to the users that remain in the lobby. If the lobby has no more users left, it is deleted from the hashmap, and the socket lobby deletes itself.

When one of the users triggers the start lobby event, the server checks that the lobby is full and if it is, it then sends a trigger to all the users to transition to the question section of the tool.

Once a user has completed their set of questions, the user sends the emission units calculated by the user to the server. Then, it updates the current total number of emissions for the group of users. Once all of the users have submitted their emissions, it goes through the list of scenarios and finds the closest matched scenario by the emission units pre-selected for the scenario.

```
const finalSSP = SSPs.reduce((SSP_a: SSP, SSB_b: SSP) => {
      return Math.abs(SSB_b.emission - game.emission) <
        Math.abs(SSP_a.emission - game.emission)
        ? SSP_b : SSP_a;
    });
```

The lobby object is then updated to have the calculated SSP. The updated final lobby object is sent to the users with the scenario, and then the users request the data to be visualized.

4.5 Deployment

There are many different platforms used to deploy web applications and they come at varying costs. The specific requirement laid out in section 4.4 stipulates that the back end server must be continually deployed on a persistent instance and cannot be hosted on something like an AWS Lambda function which spins up when needed and then stops running when not being used. The author also wanted to do it as cheaply as possible.

DigitalOcean offers $200 free credit for students and an easy configuration process. DigitalOcean connects directly to the Github Repository, where the source code is hosted. When the main branch is updated, it triggers a redeployment on DigitalOcean where DigitalOcean builds the entire project and serves it to users.

4.6 Climate Change Mitigation Questions

The choice was made to keep the parameters used to generate an SSP secret from the user. Specifically, all the weightings used to calculate the scenario are hidden from the user. This forces the user to think critically about their decisions and to create a mental model of the environment within the tool [91]. This is similar behavior to the Climate Game [6].

In order to make users engage more deeply in the questions and their answers, the author introduced the concept of “cost” associated with the answers to the questions. The cost of answers was designed to ensure that users think carefully about the decisions being made [92]. Selecting every “perfect”, i.e., highest impact answer, was designed to be impossible. The learners were given a small number of points at the start, and the questions first presented to the learners were, on average, more expensive than those presented later. Halfway through, the learner would find themselves entirely out of points, or running low, and be given 10 more points to spend. This ensured that diligent learners would be careful with their point spending and would think carefully about each question and their relative worth to the learner [93] [94].

The tool uses a combination of teaching methods to engage the learner in thinking about how to tackle climate change. Intertwining the decisions made between learners by using all of the responses to generate the SSP reinforces a sense of collaboration between different users, which enforces “gestaltungskompetenz” environmental competency [33].

4.7 Summary

Leveraging the background research and design, a tool was successfully created that allows learners to participate in a session where they represent different regions of the world, answer climate-related policy questions, and then get a glimpse into a potential future based on their collective decisions.

Chapter 5

Testing and Evaluation

This chapter outlines the testing methodologies used and how the tool was assessed in terms of the goals that were set out for it in the previous chapters. It discusses the success and drawbacks of the tool after being used in a real-world environment.

5.1 Pilot Testing

The tool was first tested with the workshop facilitators (N=7). This test was to demonstrate the software's functionality and to help the educators understand the tool's functionality so that the workshop with the TY students could be planned. During this test, an issue arose where one of the educators attempted to use the browser's back navigation button to return to a previous question. This disconnected the user from the lobby and blocked the others from proceeding. Based on this, the tool was adjusted so that the back button would not allow the user to reset and break the lobby. Instead, the user stays on the same page even when clicking the back button.

The second set of users to test the application were 2nd-year environmental science and engineering students (N=6) already studying the IPCC and these datasets. They already had familiarity with the subject and used the tool. Their feedback was positive, and they were very critically engaged with the questions being asked of the regions. One student said they learned a "clearer view of strategies and possible implementations the governments can make". Another one of the students said that the tool was "really interactive, visual and understand[able]! It's incredible". There were no technical issues that occurred.

5.2 Workshop and evaluation session

Bridge2College (B2C) is an outreach program run by the Trinity Access Progamme in Trinity College Dublin. The program aims to explore the use of technology in education and to inspire students from diverse backgrounds to apply and attend university [9]. Working with the facilitators of B2C, a two-day session on environmental science and sustainability was created. The author, alongside three other final year and master's students, would teach the students about climate change through the different tools they had created for their dissertations. Given that the tool from this dissertation engaged learners across the widest variety of topics relating to climate change, the facilitators from B2C decided that the tool would be the final one used by the students.

For each tool, the subject area would be introduced through a presentation. A discussion with the students would happen before the tool was used to gauge the student's existing knowledge and interest in the subject. The students would then have a series of tasks or challenges to achieve and would go and interact with each tool as a group.

In the case of the tool presented in this dissertation, students would interact with the tool, attempt to achieve the best scenario, and keep track of the following questions. These questions were designed to engage them with the tool so that they would not randomly select answers to questions.

- What are important factors for you to consider for your region?
- What is one of the most expensive things that you purchased?
- What are some approaches to climate change that are new to your group?
- Did you run out of points to spend?

After using the tool once, all the students returned and discussed their outcome. The students then repeated the process again to see if they could achieve a better scenario.

This testing was designed to allow the author to get an initial understanding of the usability as well as the effectiveness of the tool.

5.2.1 Usability Evaluation

Testing a system's usability is an extremely important way of determining whether a tool is effective. Surveys or questionnaires are popular for testing a user's experience. The System Usability Scale (SUS) and the Post-Study System Usability Questionnaire (PSSUQ) are two of many prevalent methods [95] of assessing a user's usability and satisfaction within software applications. They provide a standardized method of assessment that can be compared across different applications.

	Strongly Disagree				Strongly Agree
1. I think that I would like to use this system frequently	1	2	3	4	5
2. I found the system unnecessarily complex	1	2	3	4	5
3. I thought the system was easy to use	1	2	3	4	5
4. I think that I would need the support of a technical person to be able to use this system	1	2	3	4	5
5. I found the various functions in this system were well integrated	1	2	3	4	5
6. I thought there was too much inconsistency in this system	1	2	3	4	5
7. I would imagine that most people would learn to use this system very quickly	1	2	3	4	5
8. I found the system very cumbersome to use	1	2	3	4	5
9. I felt very confident using the system	1	2	3	4	5
10. I needed to learn a lot of things before I could get going with this system	1	2	3	4	5

Figure 5.1: System Usability Scale [96] [97]

System Usability Scale (SUS)

The System Usability Scale is a short set of ten questions that attempts to understand the learnability and usability of a system. Each question uses the 5-point Linkert scale, which ranges from 1 (Strongly Disagree) to 5 (Strongly Agree). A total score between 0 to 100 is calculated by adding the score of all the responses.

Post-Study System Usability Questionnaire (PSSUQ)

The Post-Study System Usability Questionnaire is a more in-depth survey comprising 16 questions, each using a 7-point Linkert scale which ranges from 1 (Strongly Disagree) to 7 (Strongly Agree). PSSUQ returns an overall satisfaction score (1 to 7) based on the averages across three sub-scores.

	Strongly Disagree						Strongly Agree
1. Overall, I am satisfied with how easy it is to use this system.	1	2	3	4	5	6	7
2. It was simple to use this system.	1	2	3	4	5	6	7
3. I was able to complete the tasks and scenarios quickly using this system.	1	2	3	4	5	6	7
4. I felt comfortable using this system.	1	2	3	4	5	6	7
5. . It was easy to learn to use this system.	1	2	3	4	5	6	7
6. I believe I could become productive quickly using this system.	1	2	3	4	5	6	7
7. The system gave error messages that clearly told me how to fix problems.	1	2	3	4	5	6	7
8. Whenever I made a mistake using the system, I could recover easily and quickly.	1	2	3	4	5	6	7
9. The information (such as online help, on-screen messages, and other documentation) provided with this system was clear.	1	2	3	4	5	6	7
10. It was easy to find the information I needed.	1	2	3	4	5	6	7
11. The information was effective in helping me complete the tasks and scenarios.	1	2	3	4	5	6	7
12. The organization of information on the system screens was clear.	1	2	3	4	5	6	7
13. The interface of this system was pleasant.	1	2	3	4	5	6	7
14. I liked using the interface of this system.	1	2	3	4	5	6	7
15. This system has all the functions and capabilities I expect it to have.	1	2	3	4	5	6	7
16. Overall, I am satisfied with this system.	1	2	3	4	5	6	7

Figure 5.2: Post-Study System Usability Questionnaire [98]

While PSSUQ, SUS, and others are valuable tools for measuring usability and are industry standards, after speaking with the B2C facilitators, a strong emphasis was put on minimizing the number of questions as the students would be filling out four similar surveys across two days. Because of this, the author chose to modify the SUS to reduce the number of questions but to use a 7-point Linkert scale and make the questions more specific about the effects of the tool.

After the session using the tool, 23 students filled out the usability questionnaire. As the questionnaire did not directly match any existing standard, we cannot compare it to any usability norms, unlike that of the SUS or PSSUQ [98]. Still, we can infer its effectiveness based on the quantitative and qualitative feedback received.

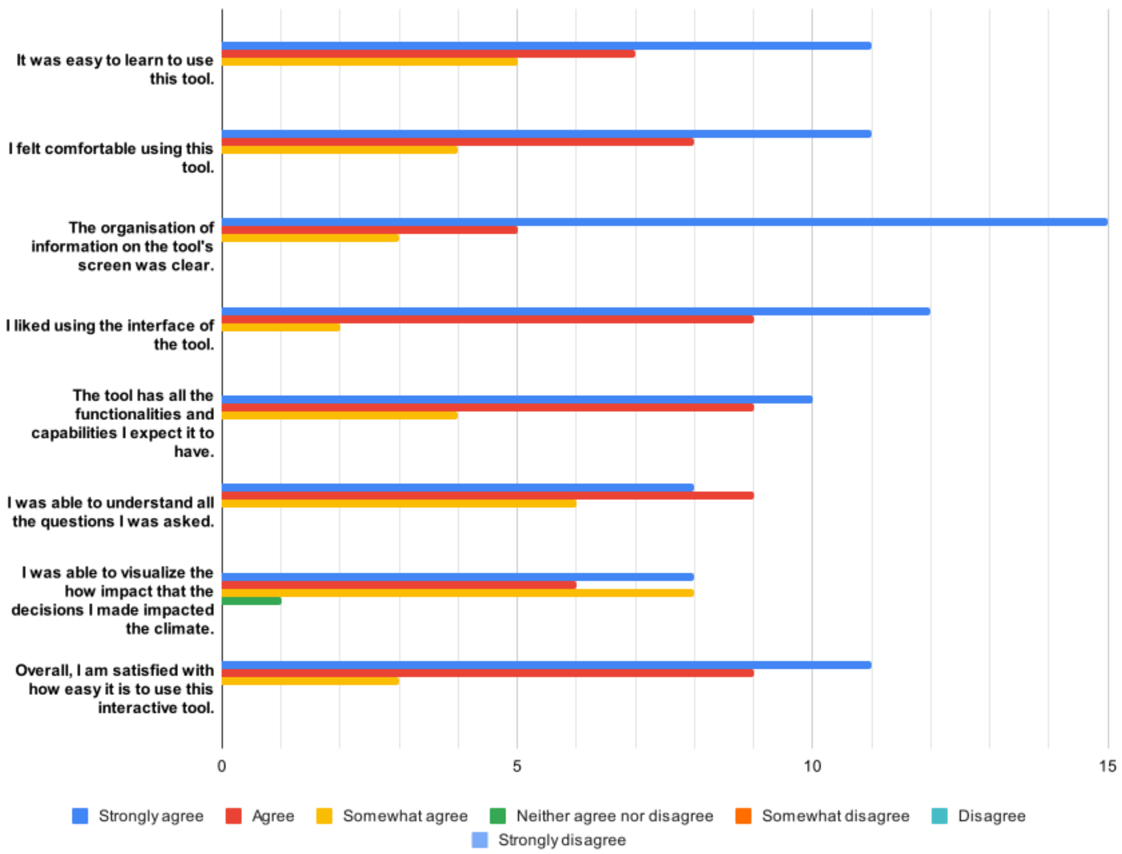

Figure 5.3: Modified Usability Questionnaire

Across the board, the feedback was incredibly positive. All usability questions, except for one (question 7), exclusively received feedback that the learners understood and felt comfortable using the tool. The students overwhelmingly believed that the organization of the information was clear, which could be attributed to the layouts the author developed using standards for data visualization described in §2.3.

The tool's biggest weakness was the connection between the student's decisions and how that impacted the final scenario. This feedback was also received in the qualitative feedback given by some students:

> "It would be helpful if the options included more information because it was harder to understand the impact it had on other countries and the world in general."

This feedback could be explained by the fact that the students were representing regions of the world they were not familiar with and, therefore, could not easily draw inferences about the impact of a region without additional research. This was a cause of confusion for some learners.

Despite this, the results suggest that the application satisfies the goals laid out at the start of this dissertation in being accessible and usable. One student said the tool was "nicely simplified by having a straightforward interface". Overall, students engaged positively with the tool, but there is room for future improvements.

5.2.2 Education Evaluation

As mentioned previously, the primary purpose of this tool is to teach the learners broadly about climate change and the importance of collaboration when taking action to address climate change. After using the tool and after the usability evaluation, the learners were also asked a series of questions to understand what they had learned from using the tool. Just like in §5.2.1, 23 students responded to the questionnaire. It would have been more robust to be able to use the same survey before and after using the tool, but this was not feasible with the B2C class. Therefore questions were only asked following the workshop conducted around the tool.

After analyzing the questionnaire, a large majority of the learners, 83%, felt more interested in climate change after using the tool, as shown in Figure 5.4.

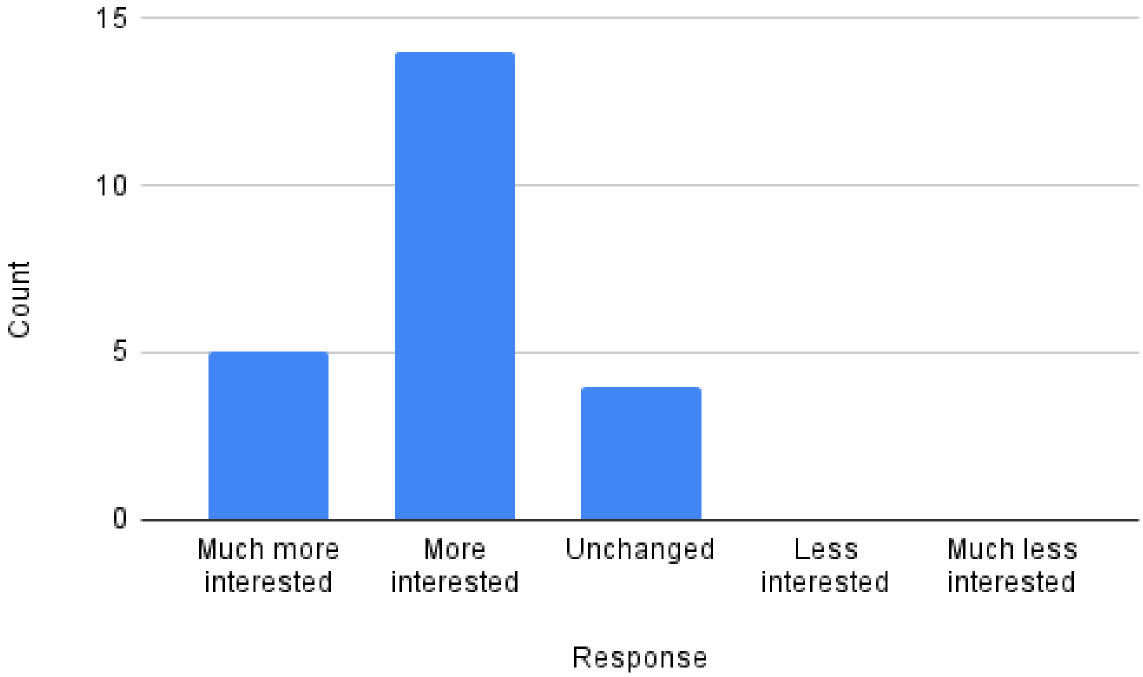

Figure 5.4: “As a result of today’s session, which of the following statements accurately reflects your interest in climate change?”

The author also wanted to identify if the learners improved their knowledge about climate change. Like the question about their interest in climate change, 87% of learners believe they are more or much more knowledgeable about climate change, as seen in Figure 5.5.

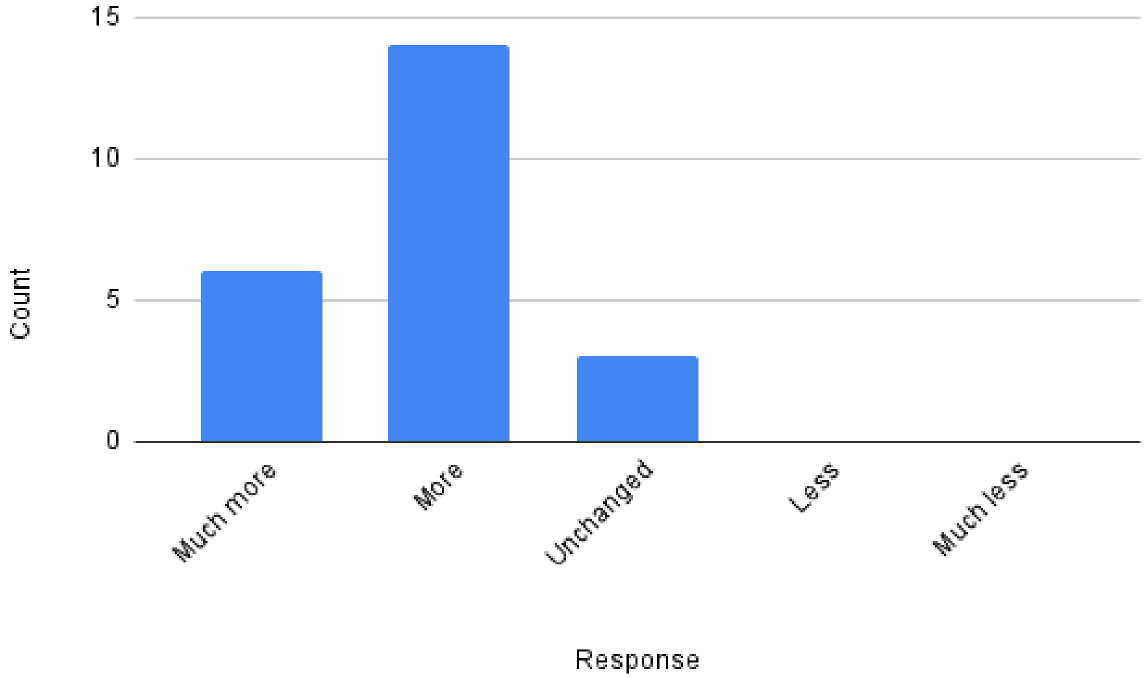

Figure 5.5: "As a result of today's session, which of the following statements accurately reflects your knowledge about climate change?"

It is a promising first step that learners are better informed and more knowledgeable, but they need to transform this new knowledge into concrete steps. Without taking action, the situation will not improve. Research consistently shows that inaction will cause continued environmental harm. 74% of the learners indicated that they would change their behavior after using this tool, as seen in Figure 5.6. This is a good indication of what the learners might do. Still, a second follow-up questionnaire in several months would be necessary to determine if they effectively modified their behavior and took any action. However, this shows that education is essential to address climate change. While one tool is not going to change the world, it has shown its effectiveness, and it can be used as an element that will further contribute to awareness and spark interest and action from the students who experienced it.

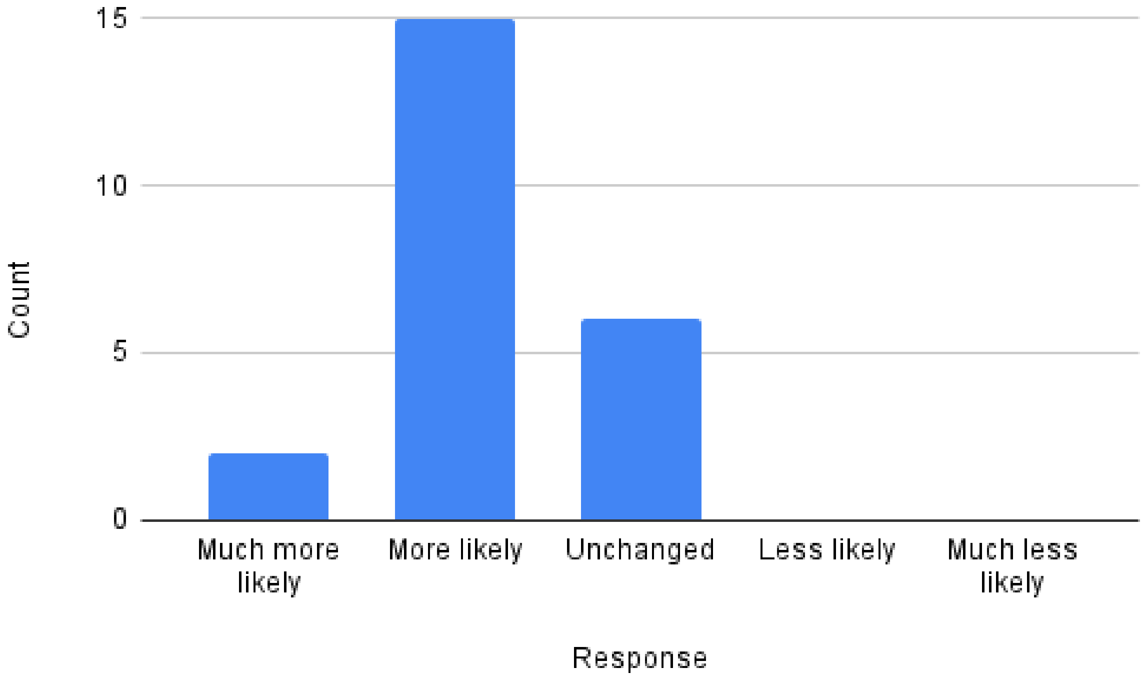

Figure 5.6: "As a result of today's session, which of the following statements accurately reflects your intention to alter your behaviour after using this tool?"

When speaking with the facilitators from B2C, one of their concerns was the depressing nature of the facts and the different scenarios. Because of this, the author wanted to identify how learners felt about the future based on their usage of the tool. As seen in Figure 5.7, there is a trend towards pessimism, with just under a majority feeling pessimistic or very pessimistic. This is troubling as pessimism could lead to inaction. The pessimism could be explained by the learner's lack of familiarity with the actions countries are already taking to address climate change. It is possible that if introduced to these ideas, it could shift the perception of the problem.

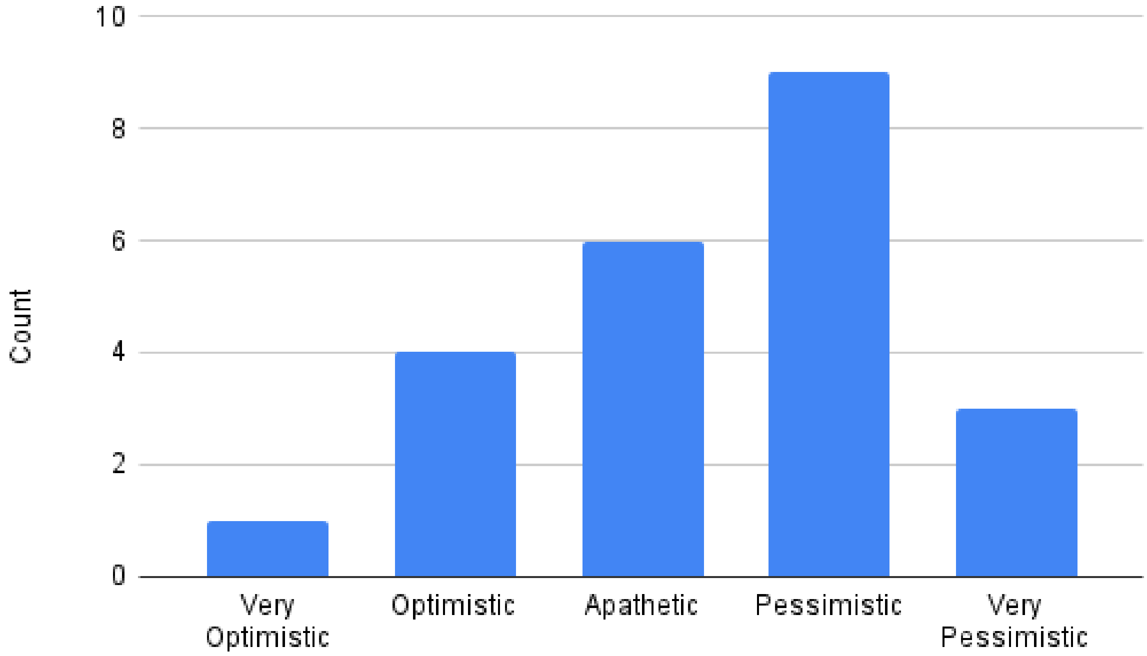

Figure 5.7: “As a result of today’s session, how are you feeling about the future?”

The final goal of the tool was to emphasize collaboration between countries. Every single respondent understood the importance of collaboration. This is a tremendous success as this was one of the primary goals of the tool.

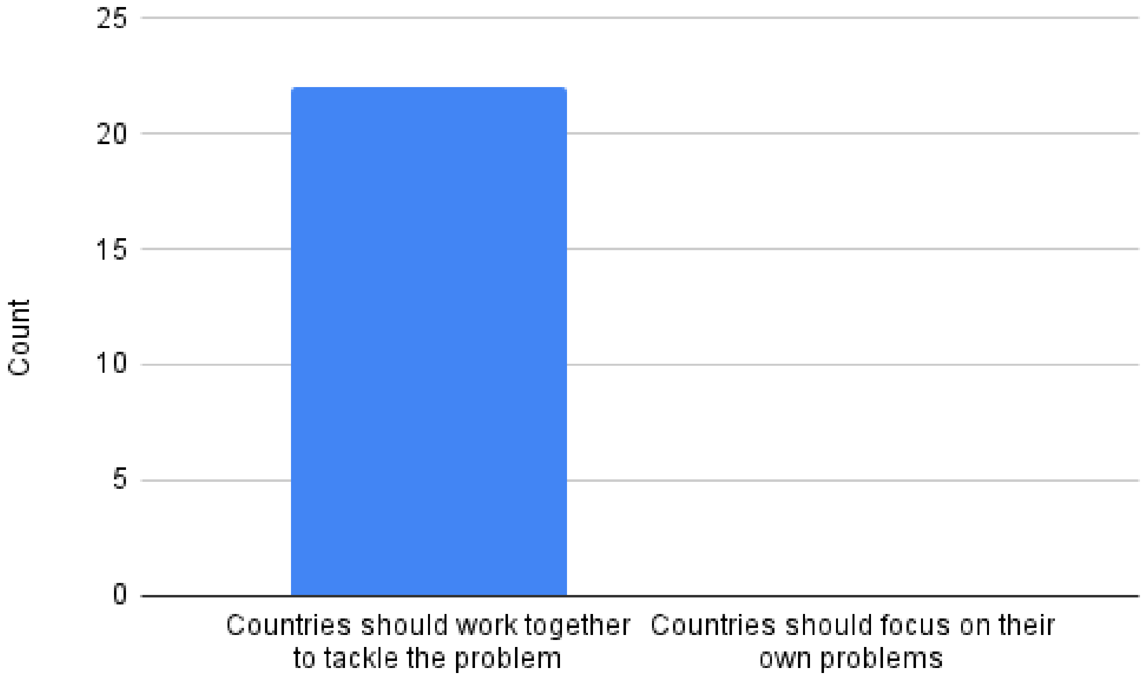

Figure 5.8: "As a result of today's session, how do you feel countries should operate to tackle climate change?"

It is important to recognize that the students had previously used three other tools regarding sustainability and climate change and therefore their responses cannot be attributed solely to this specific project. It is also important to note that the sample size of participants is quite small and is not statistically significant.

Overall, the feedback was very positive and indicates that the tool was successful in creating an environment that helped teach students about climate change, collaboration as a mechanism for success, and the enormous impact that certain regions have regarding the climate. This claim is further substantiated by the qualitative feedback from students in the survey:

> "Countries need to work together. Decisions other countries make can really affect smaller countries."
>
> "Geopolitics is important and almost goes hand in hand with climate change."
>
> "[I learned] how close we really are to serious problems from climate change."

5.3 Educators Feedback

After conducting the workshop in conjunction with B2C, the author spoke with the educators who helped facilitate the session to understand their thoughts on the tool and how the students engaged with it.

They found that "[the students] seemed to understand the concepts really well in a visual way compared to textbooks". The use of technology was effective, and the learners could easily navigate the tools. Furthermore, the educators noted that the students thoroughly engaged in the group discussion regarding the context and usage of the tool following the workshop.

They recognized that the students "didn't realize at first how much they were learning because it felt like a game". The tool was regarded as effective for initiating learners' interest in the subject matter, as evidenced by the learners' increased enthusiasm upon using it multiple times. The educators expressed that the tool could serve as an excellent launchpad for students' learning experiences and that its impact was more significant than that of a traditional textbook.

According to the educators, the tool also was found to have inspired learners to conduct additional research independently to understand better the impact that decisions could have on a region that they were not familiar with.

5.4 Summary

In summary, the testing and evaluation has provided considerable initial evidence that the tool successfully educated learners about climate change and the importance of collaboration. By creating a tool that was fun to use, many learners did not even realize the learning that they were doing. The evaluation identified areas upon which the tool could be improved and further rounds of development and testing could occur.

Chapter 6

Conclusions

6.1 Summary

This dissertation aimed to use data visualization techniques alongside pedagogical theory to tackle the teaching of climate change by building an interactive tool where multiple learners represent their respective regions of the world and make policy decisions and eventually see what the future may look like based on real climate science conducted by the IPCC and CMIP6. The primary focus was on enforcing the idea that tackling climate change requires collaboration. The goal was to leverage the large amounts of research conducted already in the climate science field and to attempt to make it more digestible for younger students. Derived from the tool's quantitative and qualitative analysis, the tool successfully emphasized collaboration in solving the climate crisis and making the learners generally more informed. The learners also broadly enjoyed using and learning through the tool.

While the evidence does point to success, some limitations should be placed on these assumptions. First, the sample size of 25 students and 7 facilitators provides only limited feedback, and their reactions may or may not represent a broader population. With more time and greater access to students and educators, it may have been possible to do a complete statistical analysis, but unfortunately, this was not the case. Additionally, the questionnaire asked the learners about their gained knowledge from the tool and their intent to alter their behavior. At the same time, there is no actual evidence of actual behavior change or knowledge retention. This could be addressed by following up with the learners and revisiting their behavior and knowledge at later date, but this was outside this project's scope.

Questionnaire data collected regarding their improved knowledge of climate change also needs to reflect the sole usage of this tool. Learners, over two days, used four different tools that focused on different aspects of climate change, finishing with this tool as their fourth and final tool. Testing in isolation would have avoided this problem, but this was also outside this project's scope.

6.2 Future Work

This section presents enhancements and extensions that could be made to the tool and its evaluation.

6.2.1 More Thorough Testing and Evaluation

By testing with more learners, it could be possible to draw statistical significance in the findings and apply them to a broader population group, which currently is impossible. It would also be better to first test the learners' knowledge of climate change before interacting with the tool, immediately afterward, and then a few months after using it. This would help see if the tool had any actionable change in their perceptions of climate change and related actions. It would also be good to use a more standardized evaluation method for usability, as this would allow comparison to other applications. It would also be valuable to investigate standard ways of measuring the comprehension of climate change.

6.2.2 Visualize Additional Variables

As part of the modeling done by organizations associated with the IPCC, there are over 50 variables that have been predicted. Some of the variables might be too complex for TY students (for example, longwave radiation from the top of the atmosphere to space per unit area is one of the available variables); however, others, such as ocean sea level, precipitation, or humidity could be useful for them to interact with. It would be beneficial to include additional visualizations for different variables. An "advanced" mode could also be developed, allowing for interaction with all of the variables, regardless of their complexity.

6.2.3 Improved Localization

While it is possible to translate the entire project and make it accessible in other languages, there were assumptions made in the tool that the user would be from an Irish background. For example, when presented with the initial scenario based on all of the decisions, the first section shows the mean temperature for Ireland for the next 100 years. It would be good to make this more flexible to represent the learner's region.

6.2.4 Additional Region Information

One of the significant points of feedback received from the learners was that they needed to learn a large amount of contextual information about the regions of the world they were representing to make properly informed decisions about regions they weren't familiar with. Two implementations could address this. The first would be an information sidebar containing some relevant information for the region. This would be quick and easy to implement. The second option could be similar to the Climate Game by the Financial Times, where there could be an advisor who helps the users, guides them in the correct direction, and gives them ideas about their region and the answers they should select.

6.3 Personal Reflection

This entire dissertation was an extremely challenging yet rewarding experience for me. I have been fortunate enough to have gotten a lot of project experience from education and industry, but this is the first time I have had to scope out, plan, build, and evaluate a tool with such a large scope. Therefore, I depended on all the knowledge that I gained from those past experiences to complete this dissertation.

Throughout the project, the development of the tool was the most rewarding part and significant part. Planning a system's design and then seeing it come to life through the development cycle and learning and understanding the limitations of the design was highly gratifying. I had the opportunity to work alongside some talented and passionate educators, from which I learned quite a lot concerning how to approach using technology to teach students.

The coding was far from the only challenge that I needed to overcome for this dissertation. I had only a small amount of academic writing experience before starting the dissertation, and everything that I had written was far from the scale of this dissertation. I needed to learn not only how to write about all of the research, planning, and execution that I had completed while developing the tool but also how to write effectively and efficiently. Managing the workload across both semesters was quite tricky, but I am proud to have completed all of it.

Fundamentally I genuinely believe that the premise of this dissertation is extremely important; climate change is a problem that needs solving, and it will not be solved by one person sitting down and trying to do something about it. It takes commitment from everyone worldwide to make tough decisions every day to improve our future environmental situation. I view this tool as a success if it can change just one person's mind. Now saying that I do hope that it has influenced all of the learners that had the opportunity to use it, and I hope that future educators can use it in their classrooms as it is open source and available for use for free.

This project was very challenging but provided numerous valuable experiences. It is only possible to know if you're capable of doing something like this once you do it, and I am confident that everything I've learned throughout this process will be taken with me for whatever challenge I will take on next.

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Appendix

The source code for this project and active deployment can be found on GitHub: `https://github.com/yannickgloster/climate-collab-tool`.