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Interactive visualization of climate change on Earth in the OpenSpace project

– with focus on the glaciers of Antarctica

Interaktiv visualisering av klimatdata på jorden i OpenSpace

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Abstract

This report describes the development and implementation of visualizing climate change on the Earth's surface in a user-friendly way for the general public. An interactive visual geographic story was created, in which a user walks through the story containing information and visualizations about Glaciers and sea level rise. The graphical user interface (GUI) is programmed in JavaScript with the framework React, and an application programming interface was created to make the GUI communicate with OpenGL, used for astronomical visualizations.

To visualize the climate, a different dataset containing georeferencing data, mainly collected from satellites, was analyzed and transformed to fit with the program to see the possibilities of using storytelling for learning more about the Earth. Results of user tests and discussions with climate experts showed that it could be done using this program. The used datasets in this project were *Ocean surface currents*, *OSCAR*, *ECCO*, *Greenland Melting Trends*, and *GRACE*. The project focuses on the ice melt of the glaciers and how it results in sea level rise.

Acknowledgments

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1 Introduction

This report contains the work of a user-friendly graphical user interface visualizing climate change on the Earth's surface in the software OpenSpace. The storytelling focuses on the ice melting in Antarctica and how the warmer currents affect the melting. The goal was to reach out to the general public with an interface that was easy to understand and a story that was interesting and informative to follow. Hopefully, the general public will be more aware of climate change after interacting with the visualization.

1.1 OpenSpace

OpenSpace is an interactive data visualization software designed to visualize the known parts of the universe. The software is bringing the latest techniques from data visualization research to the general public [5]. The project is a collaboration between *Linköping University*, *New York University's Tandon School of Engineering*, *the American Museum of Natural History (AMNH)*, *NASA Goddard's Community Coordinated Modeling Center* and *University of Utah's Scientific Computing and Imaging Institute*. OpenSpace has been developed since 2014 and is a *C++* application with a *GUI* made in *React* [44].

The idea behind OpenSpace is to develop and maintain a versatile system in that you can rapidly implement new features and functions to shorten the time between scientific discovery and dissemination. At the same time, the system should be robust enough for deployment in research and public use in museums, science centers, planetariums, and classrooms. [4]

1.2 Motivation

Climate change is an important topic where it is essential to make the general public aware of the issues. In a study by Marlon et al. [27], there were still 14 % of the population in the United States year 2021 that did not believe in climate change. The study also showed that 72 % believed in it, and 14 % did not have an opinion. There were 66 % who said that they discuss the climate changes less than once a month, and 33 % said they did it weekly. The statistics show how important it is to educate and engage the general public about climate change with help from different types of visualizations.

The major reason that has caused sea-level rise during the recent decades is the melting of the world's glaciers and ice sheets. They are both shrinking and disappearing. Since 1970 the climate reference glaciers, see Appendix A, lost a volume equivalent to almost 25 meters of liquid water. That would correspond slicing off 27.5 meters of the top of each glacier. The melting of the glaciers is an important issue and a threat to the water supplies in many places in the world [26]. By the year 2050 the sea levels are predicted to rise about 30 centimeters. The sea-level rise will for example, raise the risk of damaging flooding by ten times[33].

It can be difficult for novice users to get an overview of the climate change on Earth. Visualizations today are currently more adapted to researchers and can be too multi-faced to display to the general public directly. Therefore, there is a need to visualize the data with a more simple user interfaces to ensure that even the less experienced users can learn something new. A user-friendly interface for visualization could make it easier for the user to understand the climate changes in the world.

1.3 Aim

The project aims to create a user-friendly interface in OpenSpace [4] where a novice can explore 3D-visualized climate change on the Earth's surface. The visualization will be displayed using different datasets, meaning placing climate indicators over the Earth's surface that correspond to how it appears and changes in specific places. The user should learn about the datasets with the concept of *Exploranation* presented by Ynnerman et al. [49], meaning that a novice will use the data for exploring, and an expert will be able to explain the dataset while using the same software.

The thesis also aims to create a story for the user where he or she can learn something new by interacting with the software OpenSpace. It will be displayed locally in example cities and globally to give a larger perspective. The focus of this project is to teach about Antarctica and Thwaites Glacier, where the glacier changes rapidly [39].

1.4 Research questions

- How could the cascading consequences of climate change be illustrated using OpenSpace?
- What features should be required in an interface for novice users interacting with a climate visualization in OpenSpace to achieve a user-friendly application? How many data variables can be shown at one time while not making the visualization too complex for a novice user?
- How can we seamlessly and pleasantly change between local and global visualizations for climate change? In what ways can the local and international context be exposed in the same storyline while remaining interpretable for a novice user?

1.5 Delimitations

One delimitation of this project is that we will only use data that that is applicable on a globe were the data need simple conversions to fit into OpenSpace. Data existing will not be redone or joined together hence the project is more about telling the story from existing data then creating data to tell a story. If multiple datasets will be used at the same time they will be used as overlays and applied on top of each other in OpenSpace. A second delimitation will be the camera movement. When the user will be moving around Earth the used camera movement will be the already existing one in OpenSpace and no improvements of the camera path will be made in this project to make the path look better.

It is easy to bring up politics and economy when talking about climate change. The second delimitation is that the thesis should not be political or about economics about climate change, the focus should be on presenting facts.

2 Related Work

Several students have previously done their master's thesis related to the OpenSpace project. Web technologies were used to create a web browser *GUI*, Graphical User Interface, for a computer application. The GUI makes it possible for the user to control the software using a web browser and interact with scientific data.

2.1 Web-based graphical user interfaces

The master thesis *Creating User Interfaces Using Web-based Technologies to Support Rapid Prototyping in a Desktop Astrovisualization Software* from 2017 by Klas Eskilson provided important information for this thesis where the project focused on creating user interfaces using web-based technologies [12].

OpenSpace was, before Eskilson's project, limited to a C++ GUI and resulted in several drawbacks. One of the drawbacks of the previous application was the lack of flexibility to create a satisfying look for the GUI. Therefore Eskilson developed and implemented a new graphical user interface to replace the old one. The new GUI used web technologies and the Javascript framework React. It was built together with a web socket server to render the graphical user interface in an OpenGL environment by using the open-source framework *Chromium Embedded Framework* , *CEF*. The GUI is placed as a overlay on top of OpenSpace. A transparent layer was added at the same place as the GUI to make sure that the mouse responded to the GUI and not OpenSpace. The GUI created communicates with OpenSpace with help of different *topics* and *properties*. The topics work as requests to OpenSpace, and the properties can be information or settings for specific objects in OpenSpace [12]. Eskilson created multiple requests in the GUI to work with the properties from the GUI, which was used in the implementation for the project [12]. Eskilson describes the request in the following way in his master thesis:

- *authorize*, used to authorize a connection
- bounce, a ping-like mechanism, that simply bounces back a response,
- *Lua script*, run arbitrary Lua scripts in the OpenSpace environment,
- *set*, set the value of a given property,

- *subscription*, subscribe to the value of a given property,
- *time*, various special-case time related operations, and
- *trigger*, trigger a trigger property.

Eskilson also created a GUI in his thesis were one component was for displaying time and the possibility to pick date. This feature has been further developed since the thesis and are today a component showed in most OpenSpace profiles and also in our project.

This thesis is an extension of the master thesis that Eskilson created, where the same method when communicating from the web GUI and the OpenGL environment.

2.2 GUI for multitouch in OpenSpace

Another master's thesis developed within OpenSpace was a project named *Graphical User Interfaces for Multi-Touch Displays supporting Public Exploration and Guided Storytelling of Astronomical Visualizations* by Hanna Johansson and Sofie Khullar year 2018 and was created as an extension of the work created by Eskilson [23].

Before the project, OpenSpace was a software that was not well adapted to users with little or no experience with the software. Johansson and Khullar developed and implemented a GUI for multi-touch displays and an API for guided storytelling of astronomical visualizations were the user could fly from planet to planet and discover different moons. The graphical user interface was rendered with OpenGL and implemented. The API was implemented and provided the infrastructure needed to create different stories [23]. They created a *story file* using JSON data format that adds components with content from the story file. The web browser asks for which story to use, and when received, it reads the JSON file and adds it to Redux. The content of the set story was decided by two main things; which properties should be set in OpenSpace and the GUI components that would render. The web browser was designed to keep track of the story chosen, which was done using Lua script. They created a *story handle class* to keep track of the used properties.

Johansson and Khullar's work was an inspiration source for this project in storytelling and implementation. One example is the story API, seen in section 5.4. Another example inspired by Johansson and Khullar is the controllers they implemented, specifically their time controller, see section 5.3.2. The timing controller consisted of six components where it was possible to see the date, play/pause, and four buttons for speeding up and down the time. The last pressed button had a blue color to indicate which one was active.

2.3 Visualization in Climate Change Communication

The thesis *Exploring the Role of Visualization in Climate Change Communication – an Audience Perspective* by Anne Gammelgaard Ballantyne in 2018 aimed to explore the importance of visualizing climate change communications to the audience. The target groups in the project were non-experts and non-science audiences. The thesis contained two studies where one implied showing a visual representation of climate change in a dome theater to investigate how Swedish high school students would react and start a discussion about climate change. The movie shown is called *A Warmer World* and was a collaboration between researchers at Linköping University, Norrköping Visualization Center C, and the Swedish Meteorological and Hydrological Institute. The second study focused on a web-based tool for climate change, which is called *VisAdapt*. The tool allowed the users to zoom in and explore geographic climate scenarios and risks. For both studies, group interviews were held. During the second study test sessions, audio recordings of their conversations and think aloud sessions were held [3]. This thesis was used for the project when creating the user test.

2.4 Visualization of climate

The climate changes rapidly witch is described more deeply in section 3.2.2. It is important to be able to visualize the effects of the changes. Designing a meaningful visualization that represents the climate can be a challenge [32]. The heterogeneity of the data needs a range of standard visualizations, such as two dimensional maps, three dimensional globes, time charts and scatter plots. Another challenge is that the visualization will meet different kind of people with different skills, qualification grades and interests who will be confronted to different tasks. Visualizing scientific data is not straightforward, it needs different techniques, tools and parameters such as GUI and visualization design. These techniques are important to help the user understand the visualization [32]. Visualization is a powerful tool which can display complex data which increases the user's understanding of the data. Three research areas which are connected within climate visualization are tools for analysis, communication of climate change issues and decision making [24].

The climate science covers different areas. Some areas are atmospheric chemistry, oceanography, biology, palaeoclimatology, physics, glaciology, natural and human geography, political science, economics and sociology. A huge challenge, according to the article *Evaluating Climate Visualization: An Information Visualization Approach*, is to link these areas to each other in order to understand the consequences, how to be able to decrease the greenhouse gas emits and how to adapt to the changing climate [24]. To be able to do that, it is crucial to gather information's in all areas.

2.4.1 Global Sea Surface Currents and Temperature

One example of climate visualization is created by Greg Shirah in 2012 at NASA/Goddard Space Flight Center Scientific Visualization Studio, which shows the surface ocean streams over time. Figure 2.1 visualizes a model output from the joint MIT/JPL project entitled Estimating the Circulation and Climate of the Ocean, Phase II (ECCO2). The project shows the possibility of how ocean data can visualize the ocean currents and the sea surface temperature, and is an example of how NASA is creating visualizations of data to enlighten the world about the climate changes, read more about ECCO in section 4.2.1.3.

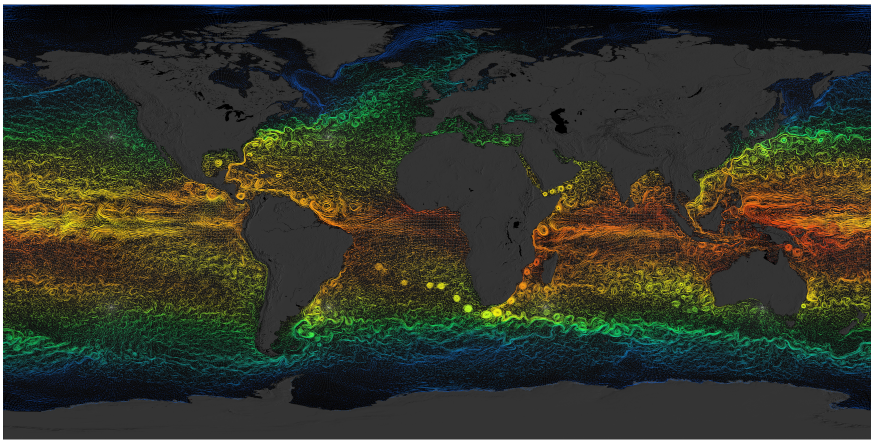


Figure 2.1: Visualization of ocean currents created by Greg Shirah [40]

3 Theory

To develop this project some research about user experience (UX), storytelling and climate change was done. Research about UX and storytelling was important to get a better insight in the fields to visualize the data in a user-friendly way. The research about climate change was necessary to know how the glaciers are melting to visualize the process of the melting with the right approach.

3.1 User Experience

When developing a Graphical User Interface, *GUI*, for the general public, it is essential to think about the user experience, *UX*. It has to be easy for the user to understand how to navigate themselves through the application. As UX designer you should ask yourself three questions, *What*, *Why* and *How*. The *why*-question involves the user's motivation to engage the product. *What* means what the user can do with the product, and what functionality and features the product has. The last question to consider is *how* which implies the design choices of the functionality in an accessible and aesthetic way. A UX designer has several different tasks, and some of them are doing user research, creating personas, and designing interactive prototypes. Another important assignment is user testing to make sure the users understand the application and easily navigate through it [22].

Six other questions that UX designers often ask themselves to solve a problem are [20]:

- Who has the problem?
- What is the problem?
- How will we solve the problem?
- What will the solution achieve?
- What features are required to accomplish the objective?
- What will the product look like and how will it function?

3.1.1 Storytelling

Storytelling is a handy tool to get the audience more interested where the technique makes it easier to remember the information [11]. A benefit of storytelling is that people often find it more entertaining to learn from a story, contrary to reading an article stating facts. Unfortunately, storytelling has a bad reputation within science. The stories often are seen as baseless or manipulated when it comes to data collection. However, storytelling is a helpful technique when communicating science to non-experts. Research advises that a story is easier to understand than just traditional information and gets the audience engaged in the topic [11].

Including storytelling in the OpenSpace project makes it easier for the general public to learn the science directly. By making the scientific information more understandable, it would be possible for the public to interact with the interface even if they do not have experience with the software or the data before. The main task of interactive storytelling within geographic storytelling is to design effective stories that motivate users to explore the area [45]. Four target requirements can be developed which support interactive visual geographic storytelling.

- Users are *attracted* by the visual representation to explore the data
- Users are *affected* by the story and can identify themselves with the topic and the scenery
- Users are able to *interact* with the visualized data to gain more insight
- Users *return* on a singular or regular basis to refresh their learning process

To construct a story two types of events are used. One kind of event is the presumed and inferred event meaning expectations and imaginations. The second type of event is the explicitly presented event. Storytelling using cartography is achieved by using story maps where the user gets more context-based information. The story maps are usually focusing on a specific issue or theme. Usually, when telling a story, the story develops over time in a tension curve where the curve is based on cause, intervention, and effect. In a story, it is also important to have a trigger because, without it, the story will be unnoticed. A story also gets more engagement if the story evolves in another way than the expected one. When creating the story, we can apply three kinds of tension; suspense, surprise, and curiosity.

The most important thing for storytelling is that the user experiences something new and exciting on the map. If the story includes topographic components, geographic 3D views support the storyline in an effective way. 3D visualizations are preferred when working with maps since they are visually more pleasing. It is a challenging, time-consuming, and expensive process to create a 3D story. Through storyboards it is possible to sketch ideas quickly and also used as a transmission between different scenes in the story. Storyboards works as a tool for interaction designers. When evaluating a scene there are four key target requirements to have in mind; attraction, affection, interaction, and potential of user return [45]. There are different kinds of storyboards. Thöny et al. [45] list six types of storyboards, where two of them are *decision-based storyboard with multiple endings* and *open world storyboard without any connectivity restrictions*. Decision based storyboard can contain one or multiple decisions. Depending on what the user decides the story will have different endings [45]. The other used storyboard is an open-world storyboard where all scenes are loosely connected. Usually, the user has some world boundaries but can move freely between the different scenes. A challenge with this storyboard is that the user might get lost when there is no guidance [45].

Every single scene in a storyboard represents a specific moment of the story. Scenes consist a combination of narrative elements and user engagement aspects. Narrative elements are similar to the plot, theme, setting, style, point of view, and character of the story.

For user engagement, there are four criteria; attraction, affection, interaction, and come-back. To raise the interest in a specific scene it is crucial to attract the users. Using interesting content and visual guides also give more attraction. To reach user engagement there has to be a certain degree of affection. When evoking emotions and personal involvements the user feels a higher affection. To achieve a good interaction there has to be interesting choices for the user that motivates him/her to continue through the entire story. Return is the last user engagement aspect. A measurement of seeing if an interactive story is a high quality or not is looking at the revisited users. A strategy is to promote new updates and features to get users to revisit [45].

The project will focus on stories of the melting glaciers since it is a problem if the water continues to rise. Therefore the public will have the possibility to learn about currents and glaciers.

3.2 Climate Change

The climate is changing and continues to do so where the sea level rise is one major problem. One cause of the sea level rise is fresh meltwater from glaciers mixed with the salty ocean water [46]. Hoesung Lee, Chair of the IPCC (The Intergovernmental Panel on Climate Change) said: "The open sea, the Arctic, the Antarctic and the high mountains may seem far away to many people, but we depend on them and are influenced by them directly and indirectly in many ways – for weather and climate, for food and water, for energy, trade, transport, recreation and tourism, for health and wellbeing, for culture and identity." [31].

3.2.1 Currents

The water heats up around the equator and cools down when it flows to the poles [41]. Deep-water currents are caused by differences in the density of the water, where the water gets denser when colder. When the water starts to freeze and transforms into sea ice, the water around it becomes saltier and denser since the salt from the frozen water remains in the sea. The denser water then sinks, making new water fill that space above, keeping the deep current in motion [41]. Strong winds are another cause why the glaciers are collapsing since they push the warm water under the ice shelves and melt the glaciers. How the warm water gets to Antarctica is still unclear, but according to *National Geographic*, it is most likely brought to Antarctica because of changes in wind patterns. The strength of the winds has increased by 15% since 1970, which results in more melting of the glaciers [42]. Unfortunately, the strength of the winds is predicted to continue to increase.

3.2.2 Changes of the ice sheet in Antarctica

The continent Antarctica is approximately the same size as Mexico and the US combined, where Antarctica is divided into three unequal parts, the Antarctic Peninsula, West Antarctica and East Antarctica, see Figure 3.1 [10, 28]. Antarctica is almost entirely covered by a layer of ice, where ice can be up to 4.8 kilometers thick [28]. If the marine ice sheet in the West Antarctica melts, there would be a 5 meters sea-level rise, whereas it would be about a 50 meter rise if the ice sheet in the East Antarctica melted. The East Antarctic ice sheet is considered more stable since it is land-based compared to the marine-based ice sheet on West Antarctica, meaning the ice is mainly floating on the seafloor under the sea. Ice that is not floating on the seafloor or on land but is still attached to the ice sheet is called ice shelves. The border where the ice goes from grounded on the seafloor to ice shelves is called the grounding line [28].

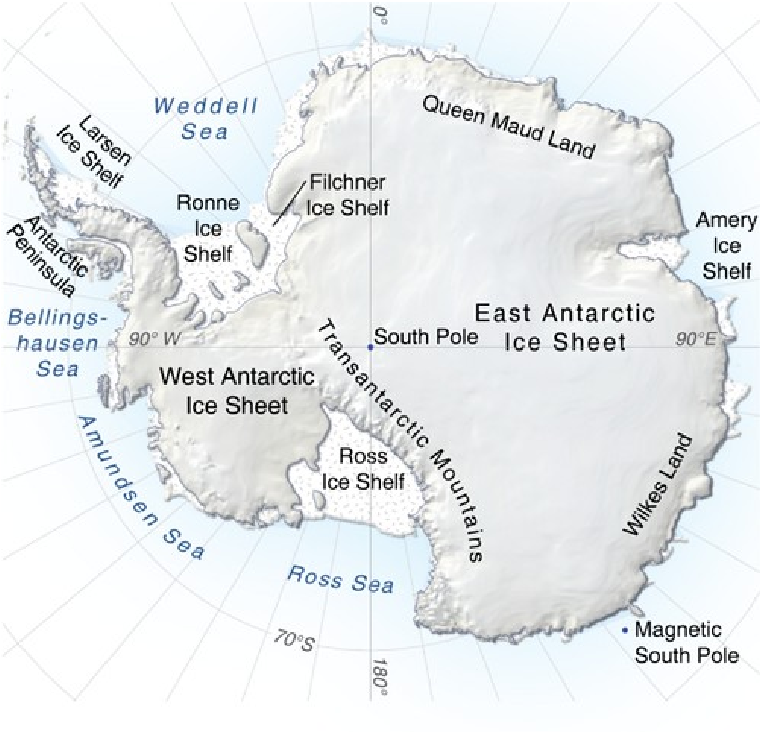


Figure 3.1: Topographic map over Antarctica showing the the three parts of the continent: East, West and the Antarctic Peninsula [1]

The ice mass of Antarctica has changed during the past decades [29]. Research, based on the *Gravity Recovery and Climate Experiment (GRACE)* satellites and *GRACE Follow-On* has measured the ice mass between the years 2000 and 2020. The ice loss in Antarctica is approximately 150 gigatons every year, resulting in 0.4 millimeters of global sea-level rise [29].

There are two reasons the ice is melting, the warmer water temperature and warmer air temperatures, according to a study by NASA [30], where the warmer sea currents are the bigger problem. In the study, the researchers concluded that 20 of the 54 ice shelves studied were melting because of the warmer currents getting underneath the not grounded sea shelves [30] and most of those sea shelves are located in West Antarctica [30]. The lead author Hamish Pritchard of the British Antarctic Survey in Cambridge, United Kingdom said "We can lose an awful lot of ice to the sea without ever having summers warm enough to make the snow on top of the glaciers melt. The oceans can do all the work from below." [30].

3.2.2.1 The Thwaites glacier

The Thwaites glacier located on the west coast, by the Amundsen Sea, has been relatively stable on the same seafloor ridge until recently, where the main grounding line has started retracting at the seafloor, see Figure 3.3 [48]. Because of warmer currents, an inflow of warm, salty water travels underneath the sea shelves, melting the ice from the glacier. The outflow from the ice shelves then contains the newly melted freshwater mixed with the saltwater, contributing to sea-level rise [46], see Figure 3.3. When the grounding line retracts, the ice becomes afloat and forms new ice- shelves and tongues [48]. Another consequence of the retracting grounding line is that the height and length of the floating ice shelf become thicker and longer when the grounding line retracts, see Figure 3.3. A possible outcome could be that the ice sheet will not be able to support the growing and thickening ice shelf, resulting in the possibility of the ice shelf cracking and falling into the sea, transforming into icebergs.

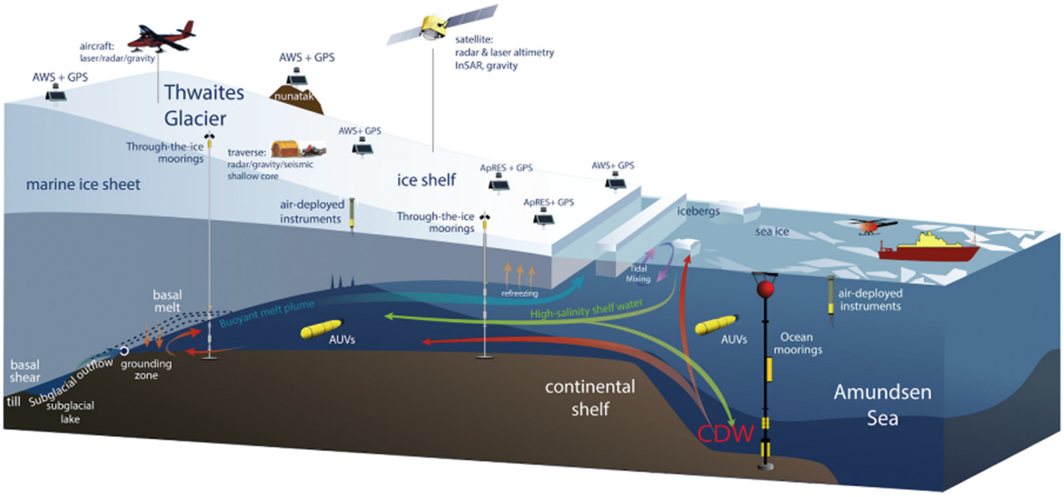


Figure 3.2: An illustration of an inland-deepening bed and connection to the ocean. The grounding line, here called the grounding zone, where ice shelves become the glacier. The currents are illustrated and how it moves under the ice shelves [39].

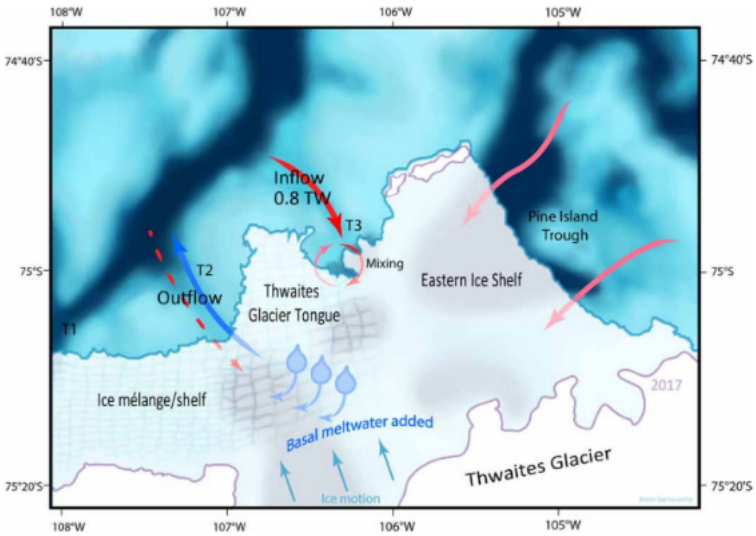


Figure 3.3: Suggested pathways and mixing areas of the water underneath the ice shelves of the Thwaites glacier. Red arrows show possible inflow of the warmer, saltier water underneath the sea shelves, and blue shows the outflow of the cold, less salty water [46].

4 Data

Multiple datasets were applied and converted for visualizing climate change on the Earth's surface in OpenSpace. OpenSpace can only handle a few specific data types, for example meshes and images, and if a dataset is temporal, one file for every time slot is needed. Climate data is often multidimensional, containing much data where scientists have used different strategies to collect the data. In this project, most data was collected by satellites where the data was converted to fit in OpenSpace.

4.1 Data Formats in OpenSpace

The data formats used in this project was *Network common data form (NetCDF)*, *Geospatial Tagged Image File Format (GeoTIFF)* and *GDAL Virtual format (VRT)*.

4.1.1 Network Common Data Form

One of the most common ways to store climate data and ocean data is in "Network common data form" (NetCDF) [36]. The data type can handle multidimensional data where the data is stored as arrays. The data format contains *dimensions*, *variables*, and *attributes* where they are used together to capture the meaning of the data, see Figure 4.1.

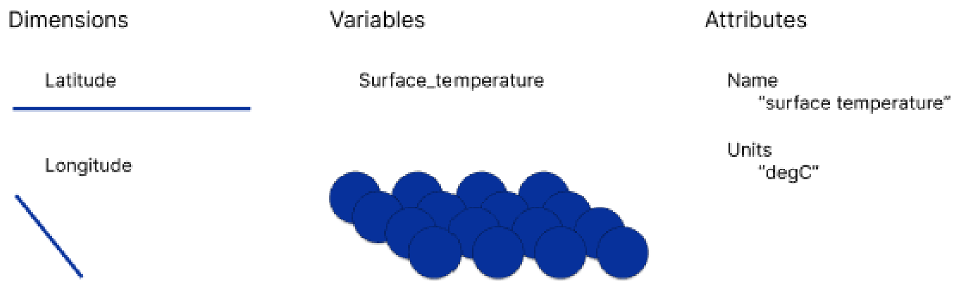


Figure 4.1: Example of NetCDF with two dimensions, one variable containing two attributes.

A dimension has a name and a size where the size needs to be a positive integer and can be as large as unlimited and grow to any length along that dimension [36]. Examples of often used dimensions for Climate data is *latitude*, *longitude*, *amplitude*, and *time*. The variables are described by names, their data type, and their shapes that are described by a list of the dimensions [36]. Examples of a variable could be a 2D array of surface temperature on a latitude/longitude grid.

A NetCDF could also contain Attributes. The Attributes could be a single variable or a vector of variables containing the metadata [36]. Examples of Attributes could be *name* and *units*.

4.1.2 Geospatial Tagged Image File Format

The tagged image file format (TIFF) is one of the most popular raster files, often used for logotypes, clip art, and similar [37]. N. Ritter and M. Ruth explains in their article that TIFF files contain tags such as ”creation date-and-time”, ”software package” and ”artist creator” but the tags have no stable structure for geospatial data. Geospatial Tagged Image File Format (GeoTIFF) is a raster format containing similar tags as for the TIFF and tags for the geospatial data. The GeoTIFF format can handle three distinct co-ordinate systems: the three-dimensional *world-space* in X, Y, Z, where typically the earth is embedded, the *raster space* referring to the pixels by row and column, and the *model space* which typically represents the surface of the earth on a 2D plane according to the article [37].

4.1.3 GDAL Virtual Format

GDAL Virtual Format (VRT) is an XML file with metadata describing properties in the raster file, example colors, dimensions and geolocation [16].

4.2 Used data

The data used in this project has been collected from multiple sources. Several datasets have been tested to see which ones that are visually attractive to look at and easy to understand.

4.2.1 Data used to visualize currents

Multiple datasets have been evaluated when looking at ocean currents. The datasets evaluated was *Ocean Surface Current Analysis Real-time* (OSCAR) [14], *Estimating the Circulation and Climate of the Ocean* (ECCO) [19] and *Simple Ocean Data Assimilation* (SODA) [2]. In addition to another dataset, *Ocean Currents*, already in OpenSpace was used to give an overview of how the currents move around the globe.

4.2.1.1 Ocean surface currents

This dataset shows arrows around Earth that visualize a model of the direction of the currents. According to Debra Tillinger (2022), it was crucial to make sure that the viewer learns that this is a simplified model created years ago and that we know more about the currents today than shown in this model.

4.2.1.2 OSCAR

The NetCDF dataset OSCAR is a model of a near-surface currents estimation derived using quasi-linear and steady flow momentum equations where the velocity is calculated from the sea surface height, wind stress, and sea surface temperature [6]. The velocity shows an average of the thickness of the top 30 meters of the ocean where the data file contains temporal data with the variables *zonal-* (west-east direction) and *meridional* (north-south) velocities collected from different satellites [7].

4.2.1.3 ECCO

The data used in the model for ECCO are from both satellites and in-water instruments to create a statistically correct model of the observations made [9]. It is further explained that when ”misfits” in the data occur, ECCO adjusts a set of ocean model initial conditions, parameters, and atmospheric boundary conditions to create a seamless model.

Ecco contains multiple NetCDF where every file included the median value for the velocity of each day between the first of January 1992 and the first of January 2018 [19]. Every NetCDF included the variables *EVEL* (zonal velocity), *NVEL* (meridional velocity), *WVEL* (vertical velocity), *latitude_bnds*, *longitude_bnds*, *time_bnds* and *z_bounds*. Evel or zonal velocity is the used variable in this project because it shows how the currents move around the Earth in the west/east direction, Meridional flow shows how the currents move from north to east, and vertical velocity shows how the currents changes depending on the depth [19]. Vertical velocity can be interesting to look at when looking at specific locations and zonal- and meridional velocity is interesting to look at when viewing the currents on a larger scale.

The EVEL file then contained *longitude*, *latitude* and a *z-values* for how deep in the water the velocity was measured as its *dimensions* [19].

4.2.2 Data used to visualize the ice sheets

Multiple datasets were explored and evaluated for visualizing the melting of ice sheets in this project. Two of the datasets was used and those datasets are *Greenland Melting Trends* [13] and *Gravity Recovery and Climate Experiment*(GRACE) [43].

4.2.2.1 Greenland Melting Trends

One dataset used for visualizing the ice melt on Greenland was Greenland Melting Trends between 1989 and 2006 from NASA Goddard Space Flight Center. The visualization shows how many melt days it was within a year in Greenland. The dataset existed in OpenSpace already and did not have to be downloaded and converted to an acceptable data type.

4.2.2.2 GRACE

GRACE is a satellite mission where two satellites are moving around Earth together in the same orbital plane, one traveling behind the other, collecting information about gravity and how it changes over time [38]. When areas have slightly higher gravity, the leading satellite will move faster, creating a bigger span between the satellites. The trailing satellite catches up to the leading satellite when passing the high gravity area. The differences in the distance are small but enough to calculate the gravity in the area. The data can then be collected monthly by the scientist who can construct monthly maps of Earth’s average gravity field. Landmass and gravity will not change and move that much over time but water and ice will, causing the gravity on Earth to shift [38]. GRACE can therefore measure the world’s land ice (ice sheets), ice caps, mountain glaciers, and icefields because the glaciers lose mass when the ice melts or when the solid land ice calves, creating new icebergs in the sea [25].

Further use for the data is to use it as a drought indicator on Earth to see locations with less ground water.

GRACE satellites were active between 2002 and 2017, and GRACE Follow-On since 2018 [43]. The dataset is in NetCDF format, where the temporal data shows the ice mass at that month compared to 2002 and each cell in the dataset is 120 km wide [43].

5 Method

This chapter presents how the graphical interface was implemented and how the story was developed. To implement the datasets in OpenSpace data conversion was needed which is explained in detail in section 5.2.

5.1 The Story

Climate visualization consists of multiple possible stories to tell, for example, pollution or extreme weather. Research about different topics, and discussions with people works on OpenSpace and Debra Tillinger, who holds a Ph.D. in ocean and climate physics from Columbia University, and working at the American Museum of Natural History, was arranged to decide on the story.

At the beginning of the project, an online course from *Coursera* called *Our Earth's Future* by Debra Tillinger was attended to get more insight into different climate topics. After the course and some research and meetings with Tillinger were arranged to have open discussions about climate change topics that could be a good idea to visualize. Tillinger told us about different stories we could read about and where to find credible information. Discussion on how sea temperature rise and how it affects Antarctica, see section 3.2.2, took place. It turned out OpenSpace did not contain the best possible data of the continent, where layers of Earth often have information missing around and on the location. It was, therefore, interesting to explore data containing more information of the continent for creating a story about Antarctica. This project will focus on certain areas of Antarctica where climate change has had the most impact.

The Thwaites glacier, also known as the Doomsday glacier, located in West Antarctica, was chosen as the starting point for the project to discover what was possible to visualize in OpenSpace by seeing how much data there was. The glacier is described in more detail in section 3.2.2.1. Articles containing research about Antarctica and the Thwaites glacier, were discussed to confirm that the articles were understandable and how to create a simplified story about the complex subject. Tillinger gave suggestions of different data that could be useful in this project where a few of the explored datasets are presented in section 4.2. The data needed to be integrated into OpenSpace or the program *QGIS* that can handle geospatial raster- and vector data, [35], to fully see what they consisted of and if they fitted with the idea for the project.

5.2 Data conversion

To reduce the number of datasets in OpenSpace an asset file for every layer on every planet is created from which OpenSpace loads the requested data. OpenSpace loads the assets from local image files (JPEG and PNG) or by using GDAL for loading dynamic datasets [34]. GDAL is a translator library for raster and vector geospatial data formats [15]. OpenSpace can also handle geo-referenced map datasets. When using datasets with other file formats, the files have to be converted resulting in the data flow used in this project shown in Figure 5.1. The data in the NetCDF, see section 4.1.1, were first converted to GeoTIFF, see 4.1.2, and then to the data format that OpenSpace accepts, VRT, see 4.1.3. The asset file created for the layer loads the VRTs and uses the GeoTIFF as a source file, and both files are therefore required together with the asset file when creating the new layer for OpenSpace.

Before translating the NetCDF, the software *QGIS* was used to get an overview of the file with its dimensions, variables, and its attributes. QGIS is an open-source software where it is possible to view, analyze and edit geographic data [21]. The software shows the data in model space (2D), where different variables in the NetCDF could be analyzed. QGIS was used in the project to give an overview of tested datasets. It is possible to try multiple color schemes for the data in QGIS, which later could be applied to the datasets in the terminal because the newly created GeoTIFF files do not contain any color information. The color schemes were saved from QGIS in a text file containing values, for example, velocity, and its connected RGB values.

Converting from NetCDF to GeoTIFF was done using Python and the GDAL library. The variables in the file were transformed one at a time. After the transformation, the variables, and its dimension, could be converted to multiple GeoTIFF files, one for each dimension. One example could be if the dimensions contain latitude, longitude, and time in the NetCDF, then the conversion would result in one GeoTIFF file for each time slot existing in the dataset over the area described with longitude and latitude.

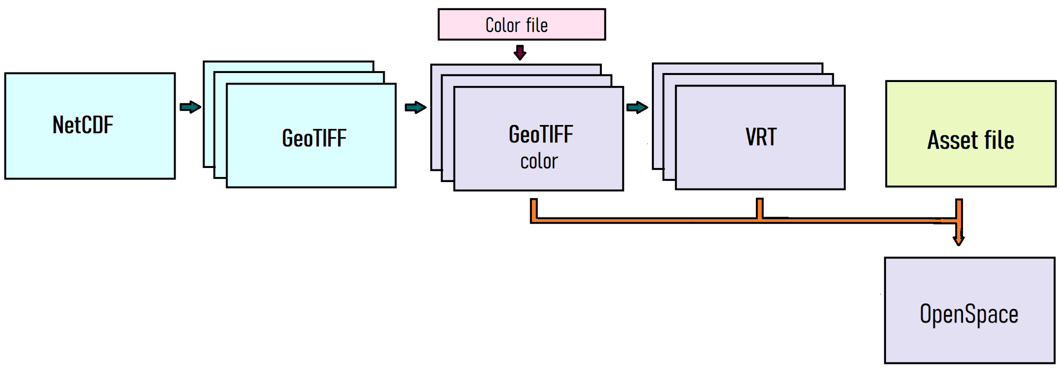


Figure 5.1: The GeoTIFF's are converted from the NetCDF with decided variables using Python. A batch file was then created to add color to the GeoTIFF and convert the GeoTIFF to VRT. OpenSpace then loads one asset file which loads the VRT where the VRT contains information about the GeoTIFF.

5.2.1 Converting NetCDF to VRT for ECCO

ECCO consists of one NetCDF for each day, and to save time, fewer years, 1992 to 1998, and only the first day of each month was converted. It was decided to focus on The EVEL variable (vertical velocity) and one band for the z-value to save time. EVEL was chosen to focus on how the sea surface currents move around Antarctica. The variable z was set to 25 meter, which was picked randomly to show the ocean surface currents because the differences in velocity when the z-values were compared were not that different. After the variable EVAL and the z-value were decided, it was possible to convert the NetCDF to GeoTIFs with the library GDAL in Python.

A batch file was created to convert the GeoTiff to VRT, required for OpenSpace to accept the data, see 5.1.

```
gdaldem color-relief "file.tif" colorfile.txt -alpha "fileWColor.tif"
gdalwarp -t_srs "+proj=longlat" "fileWColor.tif" "fileWColor.tif"

gdalbuildvrt "fileWColor.vrt" -te -180 -90 180 90 -addalpha "fileWColor.tif"
```

Listing 5.1: A batch file was created to convert GeoTIFF to VRT with the GDAL library. The file called *file.tif* is the created GeoTIFF file created in python and together with *colorfile.txt*, containg the RGBa values, *fileWColor.tif* was created

To give color to the file, the *gdaldem color-relief* was used where *-alpha* is applied if there are alpha values in the text file. In the ECCO file, all alpha values were set to 255. The function blends the colors for every value between the given ones to create a smooth result [18]. *gdawarp* and *gdalbuildvrt* are required for every GeoTIFF added in OpenSpace where gdalwarp and t_srs are used to specify the coordinate system, in this case, longitude and latitude [17]. gdalbuildvrt contains the coordinates accepted in OpenSpace, longitude: -180 to 180 and latitude: -90 to 90, and then *-alpha*, to include the values for the previously added colors.

5.2.2 Converting NetCDF to VRT for GRACE

There was only one NetCDF for GRACE with the dimensions: days since start date, longitude, and latitude. A GeoTIFF for every given date was created using Python. Since the NetCDF contained information about the number of days since the start date and not the actual date, the actual date was inferred. Further complicating the matter, the time difference between the days was not consistent in the NetCDF. After the GeoTIFFs had been converted, a similar batch file as for ECCO was created, see 5.1 where additional functions were applied. The longitude and latitude values must be between -180° to 180° and -90° to 90° for the mesh to fit in OpenSpace. The values for the longitude for the dataset for GRACE were between 0° and 360°. The GDAL library was used to convert to the correct values where the GeoTIFF files were cut in half, rearranged, and merged, see listing 5.2. The functions were added in the batch file after *gdalwarp* in 5.1

```
gdal_translate -projwin 0 90 180 -90 "fileWColor.tif" "cropped_right.tif"

gdal_translate -projwin 180 90 360 -90 -a_ullr -180 90 0 -90 "fileWColor.tif"  "
cropped_left.tif"

python "filepath/gdal_merge.py" -o  "fileWColor.tif" "cropped_right.tif" "
cropped_left.tif"
```

Listing 5.2: Placed after gdalwarp in Listing 5.1, the GeoTIFF is separated in half, depending on the longitude value, with gdal_translate and then merged together where *cropped_right.tif* is place on the left to *cropped_left.tif*, to create a new file.

where *gdal_merge.py* was a python file found in the used Conda package. The right side, *cropped_right*, of the file with the longitude 180° to 360° was placed left of *cropped_left.tif* with the new values between -180° and 0° and then merged to create a new GeoTIFF file with the longitude values between -180° and 180°.

5.3 Creating the storyline and the GUI

The first step of writing a story in visualization was to confirm that the data required for the story existed [45]. The GUI was designed and implemented after the data was converted, where the general idea of the GUI was created parallel to the research about Antarctica to create a story that seemed interesting. The user would have multiple ways to learn and see the data. One where the user can discover what is interesting to them and the possibility to go through a storyline with next and previous buttons but also have the option to take different paths in the story to keep the user interested in the next step. Therefore the project would both consist of an *Open world storyboard*, see section 3.1.1 and a *Decision-based storyboard with multiple endings*, see section 3.1.1. Different implemented components in the GUI are listed below, where the components get their information from an application programming interface (API) created for the project, see section 5.4. The components listed below were decided to be included in the GUI:

- a menu that made it possible to swap between the two different storyboards,
- a strict placement for Earth,
- a text box to write about the data,
- a color legend where the colors in the datasets are described,
- a possibility to go back and forward in the story,
- a possibility to pick new roads in the story,
- see time and date, and
- be able to move back and forth in time.

A menu, see Figure 5.2, was placed in the bottom of the window, since it is a common placement, example *Windows 10* and *macOS*. The menu contains five different components which are listed below.

Figure 5.2: Draft of the menu located in the bottom on the screen containing buttons for instructions, the decision-based storyboard, the open-world storyboard and a possibility to see and control time

5.3.1 Instructions

OpenSpace did not contain any page for instructions on how to use the software, which could be asked for when the user is not comfortable trying to move around Earth by themselves. A button for instructions was, therefore, implemented as a method to make the user more confident to use the software. Another reason for implementing instructions was to encourage the user to move around Earth.

5.3.2 Time Controllers

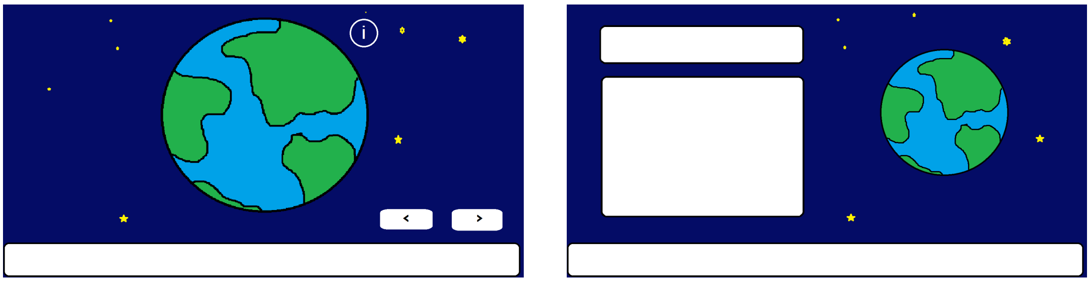
To show time and date, the time controller, first developed by Eskilson, was implemented using the request *time* to communicate with OpenSpace, see 2.1. When pressing on the controller, a menu appears where the user can write in the desired date. Left to the Time controller, a controller to go forward and backward in time was placed, which was a wish from Tillinger. She wanted to have the possibility, depending on the dataset, to easily play, pause, and move back and forth in time. The speed, frames per second, was decided to change depending on the data shown to ensure that the user did not have to wait too long for new data to appear on the screen. Johansson and Khullar implemented a similar controller where their component was further developed to fit their project, see section 2.2. Their controller was slimmed from its original six components to three containing play/pause, fast backward and forward. The last pressed button is colored blue to indicate what is active.

5.3.3 Controllers for Decision-based- and open-world storyboard

The menu contains the possibility to switch between the two storyboards with the help of two buttons.

5.3.3.1 Decision-based storyboard

Drafts of the GUI were created for the layout when telling the decision-based story, see Figure 5.3, together with a simple storyline, see Figure 5.4. The full storyline is visualized in Appendix B. The storyline was developed after discussions with Tilliner, where the drafts were created to fit- and highlight the story. Different sketches were created on paper, where the two drafts in Figure 5.3 were further tested in Figma to give the first impression of the final result.



(a) (b)

Figure 5.3: Figure 5.3a displays a text box that appears when pressing the information icon. The next and previous buttons are placed at the bottom to the right, where the menu located below, and Earth is placed in the center of the screen. Figure 5.3b displays the text boxes on left side of the screen.

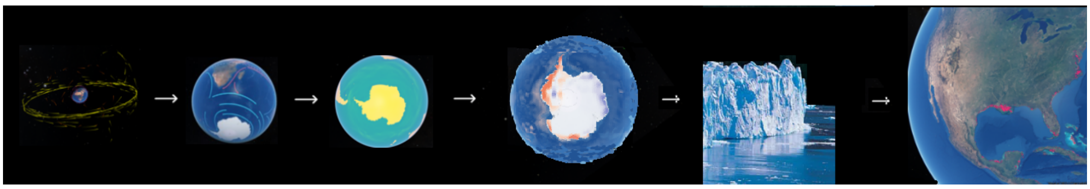


Figure 5.4: First draft over the storyline when Antarctica is picked: (1) Satellites, (2) Overview of surface currents, (3) A more detailed view of the surface currents, (4) Overview on how the ice melts over Antarctica, (5) Glaciers [8], (6) Consequences

Figure 5.3b was decided to further develop after the implementation in Figma. One reason was that it was no good placement for the information circle on the screen in the first draft, Figure 5.3a, and it needed to be placed differently in every part of the story to be visually pleasing for that dataset. Another reason was that an information box would appear and be placed on top of OpenSpace and Earth when the "info" button was clicked. There would then be a risk that the "info" box would be in the way of Earth. The information given to the user would contain information about the data and describe the colors in the displayed data with a color legend. The other draft of the layout, Figure 5.3b, was therefore planned with more structure, where the information was placed at the left and not in the way of Earth, see

Figure 5.3b. Buttons to navigate through the story were placed under the information given, containing text and color legends.

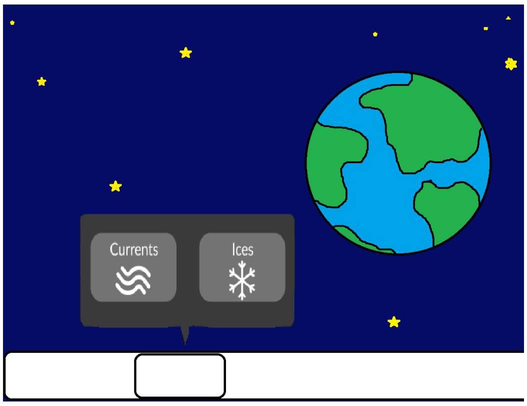
The first view, when starting the story in Figure 5.4, is of satellites explaining to the user how the data is mainly collected throughout the story. Three different options were given at the start view to let the user pick a story. The three options were chosen, depending on locations where the ice is melting most dramatically on the Earth. The three different stories are similar but with information and datasets fitted for the story.

After the user picked a story, an overview of the sea surface currents is displayed followed by two more detailed datasets of sea surface currents. The reason behind starting with an overview was to make the user comfortable with a dataset that contained information they would probably recognize. If they would not, the user will get a good start to seeing how the sea surface currents move around Earth. The simplified model in the dataset is not completely accurate and the two more detailed datasets were therefore implemented to show how data from example satellites are used to create visualizations. One reason for showing the sea surface currents is to give the user a perspective on how every part of Earth is connected and how the temperatures in the ocean change when moving around Earth. Another reason for showing the oceans is because the reason behind the glacier melting is the warmer currents that reach the glaciers.

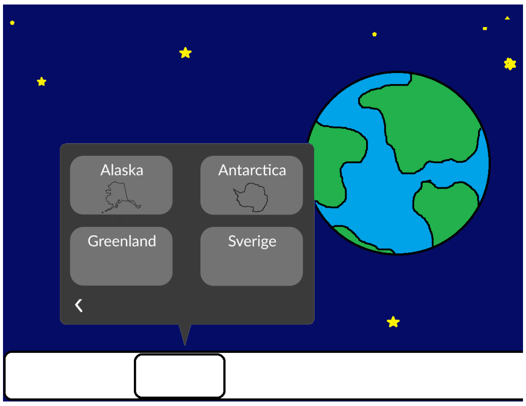
When the story about Antarctica, the Camera zooms in on the continent where GRACE is displayed when a button named *next* is pressed, explaining how the ice has been melting over the years. To show the differences in different parts of Antarctica the user can pick West- or East Antarctica and zoom in on the areas. The plan was for the user to see the height of the glaciers, and see how the ice retracts underneath the water line on the West side. When the user zooms in on the East, the user sees that the west side is land-based and therefore is not as exposed to the warming water. The last step in the story is where the user can see the consequences and what could happen if more ice would melt. This step gives the user a possibility to reflect and understand the importance of the climate and, hopefully, encourages the users to learn more.

5.3.3.2 Open-world storyboard

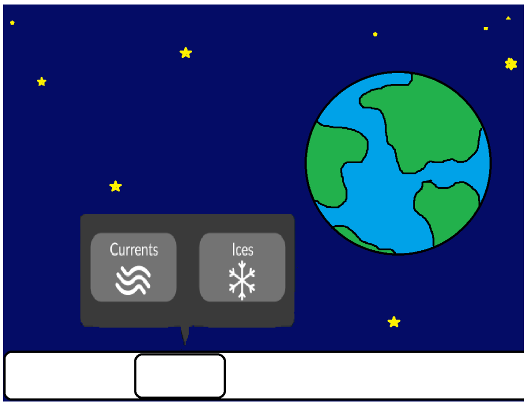
The idea behind the open-world storyboard was for the user to easily be able to switch between datasets and move around Earth by themselves discovering more about the ice sheets. If a user explores the datasets further they would also discover aspects like droughts and floods from the GRACE data set. There were mainly two prototypes created for what would be displayed when the open-world button is pressed, see Figure 5.5.



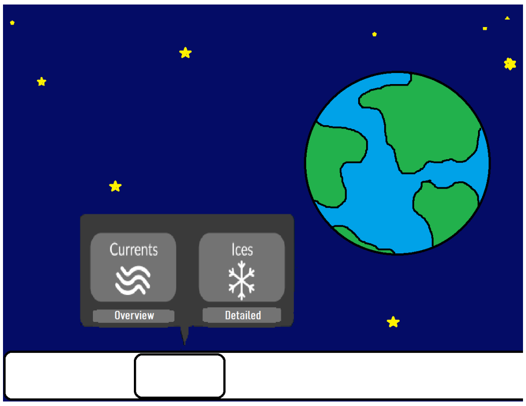
(a) Menu when "Open World" option is pressed



(b) Different locations in the world can be discovered when Ice is pressed in a sub menu



(c) Menu when "Open World" option is pressed



(d) Different types of Currents can be discovered when Currents is pressed and the sub menu appears underneath the navigation bar.

Figure 5.5: First drafts of GUI: Open world where Figures (a) and (b) is one draft and (c) and (d) is another draft

The first draft in Figure 5.5a shows a popup menu where the user can pick a subject they want to discover. New possibilities to choose from, together with an arrow to go back to the main menu, appear when a subject is picked, see Figure 5.5b. The first draft contains locations on where to go and icons matching that area where one thought was to have icons display an outline of the country or continent. But a more minimalist approach was taken for the same reason as in the decision-based storyboard where space on the screen was saved for the data visualized. Figure 5.5d shows how the options appears as a text string under the menu first displayed in Figure 5.5c. Another reason for using this approach was for the user not to need to go back and forth in the menu where they can go between the different subjects with more ease. When a place or dataset is picked, the camera moves to a fitting position, and the correct dataset is displayed where the Earth will be spinning slowly. The time will move to the start date of the dataset and the user can use the time controllers to move back and forth in time where the start date and more, is retrieved from the story API.

5.4 Story API

A story application programming interface (API), similar to Johansson's and Khullar's [23], was built to create and display the different stories for Alaska, Antarctica, and Greenland. The components and the content in the stories were added in JSON files and reached with JavaScript, containing information for the GUI components and what properties are used in

OpenSpace. Information from the story is saved into Redux when one of the three stories is picked, where Redux is a JavaScript library that keeps track of the information given. The reason for using Redux is that it makes the content accessible for the different components in the GUI for the stories. The possibility to add another story is simple where a new JSON file needs to be created, containing the same variables as the already existing files, see Appendix C. An overview of the flow when reading the file is displayed in Figure 5.6

Figure 5.6: Overview over the flow when reading in a new JSON file, from Johansson's and Khullar's thesis [23]

A web browser is responsible for handling the GUI in OpenSpace and how to communicate with OpenSpace, done with Lua. The browser uses *properties*, which can be a group of settings or information attached to an OpenSpace object to send information to OpenSpace, see section 2.1. A story handler was implemented to keep track of the steps in the story, and if the user uses the decision-based storyboard or the open-world storyboard. The process of handling a story can be divided into four parts described below, in subsections 5.4.1, 5.4.2, 5.4.3 and 5.4.4.

5.4.1 No current story in Story Mode

When the user selects a story from the start window and no story yet is picked the browser sends the commands to OpenSpace to set the right properties for the correct story.

5.4.2 New web browser instance

When a story is picked, the browser sends commands to OpenSpace with the correct properties, and when walking through the story, the browser will check if it is the recent story that was picked. If no other story is chosen, the properties are already set, and the web browser will not send any new commands to OpenSpace.

5.4.3 Selecting new story when story is picked

If a new story is picked the web browser will tell OpenSpace to reset the properties from the old story and the new file will be read.

5.4.4 Open-world mode

If there is a story set when entering open-world mode OpenSpace will reset the properties and go back to default where no story is picked.

5.5 User study methodology

After all the functions were implemented in the application, a user test was held in which seven people participated. Before the user test an email was sent to the participants. The test started with a think-aloud session where the user said all their thoughts that were coming to their minds out loud while exploring the interface. The user got a few assignments to navigate through the story. The assignments were in two parts. First, the user explored the story on the screen with a few assignments. Then the test person got new assignments to navigate through the bottom bar. After the think-aloud session, the test person got some questions about the interface, both about design choices and functions. In Appendix D the assignments for the think-aloud session and the question about the interface are listed. After all the user tests were done, a summary of what the test persons thought was written to easily make improvements according to what the test persons saw as drawbacks.

The user tests were done online through zoom, where the user accessed the remote control to be able to navigate in the graphical interface while the developers of the project shared the screen containing the project. In the email that was sent to the attendees where a description of how to enable the remote control was included, shown below.

1. Log in to zoom in on your web browser
2. Go to your profile
3. Go to settings in the left panel
4. Under ”in meeting (basic)” you can turn on ”remote control”. Turn on this feature before the meeting, but if any trouble occurs, we can fix it at the beginning of the meeting.

The idea was at first to have the user test at the *American Museum of Natural History*, then the user would have used the developers' computers to do the test instead of only getting the remote control at zoom.

The user study tested things that the developers of the project were unsure of and things that they did not agree about. The test helped the developers to get more opinions which then made it easier to make decisions. The user study also tested the important buttons and made sure the users understood how to navigate through the stories and the open-world storyboard. The study did not only result in opinions of how easy or hard it was to navigate the interface and understand the functionality but also in opinions of design choices that improved the user experience.

Depending on who did the user test the time of it varied. The people who had a background in climate change or OpenSpace had more opinions than the ones who were not engaged in the areas of the project, but most of the user studies took around 30 minutes. The seven persons who attended the user study had different backgrounds where a few worked with OpenSpace, one was a climate expert and a few of the users did not have any experience within the field of the project at all.

6 Results

The project resulted in a user-friendly graphical interface where the user can explore climate change. In section 6.1 the used interface before the user test is presented. The result that was developed after the user study is presented in section 6.2.

6.1 User study result

This section will show figures and some explanations of design choices before the user test. It will also explain the users' thoughts about the design which can be seen in Figure 6.1.

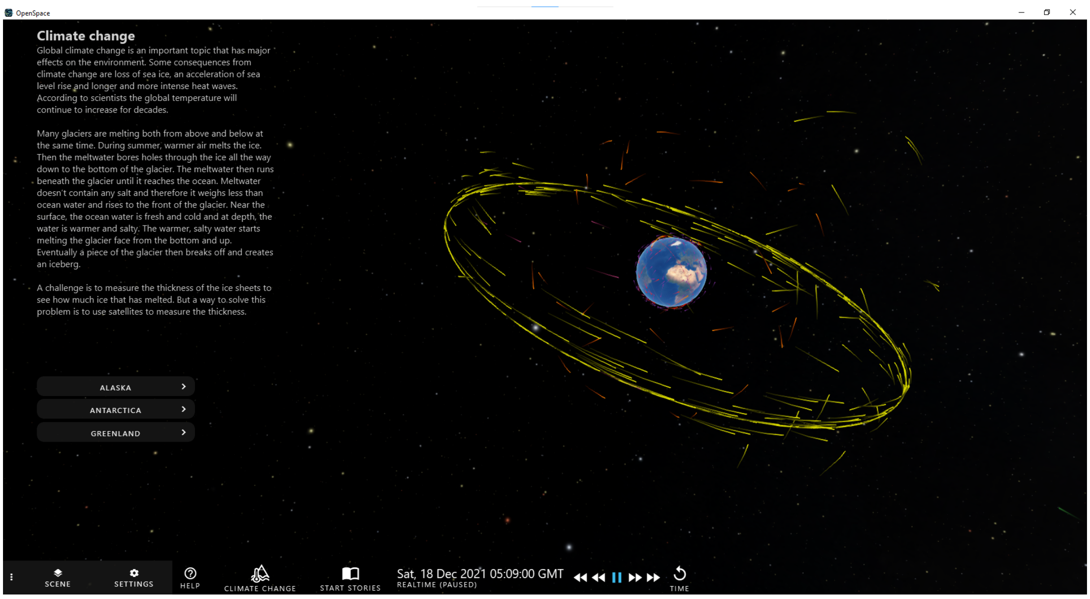
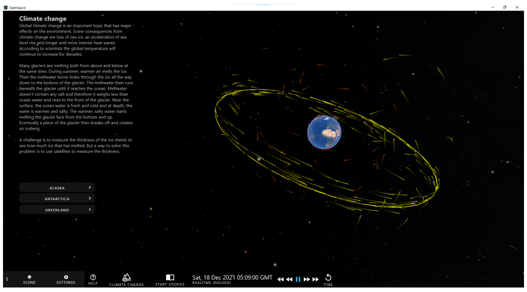


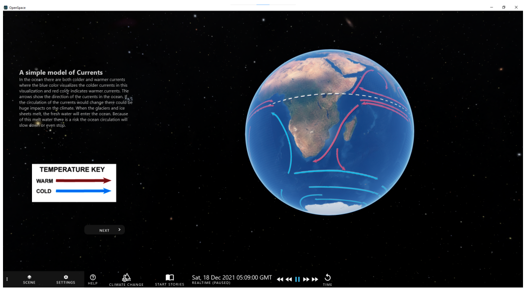
Figure 6.1: This figure shows the first screen the user sees when entering the mode for climate change in OpenSpace and where the user sees Earth far away and has the possibility to pick a from the three different stories.

6.1.1 The decision-based storyboard

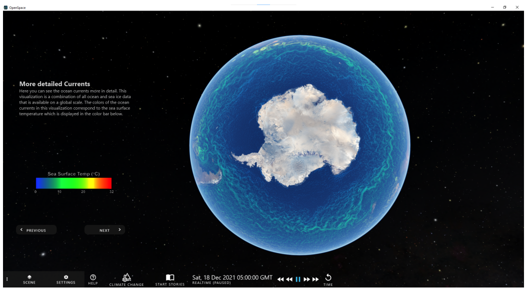
The button for the decision-based storyboard got the name *Start Stories* and a book as an icon in the menu and got a good response from the users, see the menu in Figure 6.3. The users enjoyed the layout on the screen, see example in Figure 6.2a but one user said it was too divided between the different segments. Different lengths of the texts in the different steps were used to test the length of the texts in the text boxes to see the preferred one, see Figures 6.2a to 6.2f. The user's thoughts on the length differed: a few preferred longer texts, and some preferred shorter.



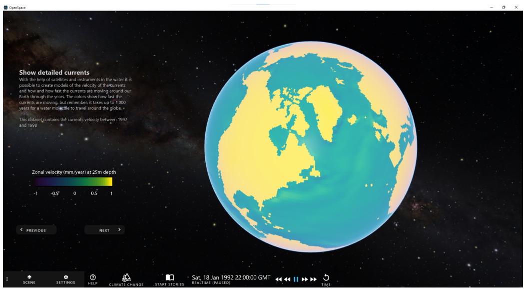
(a) Start page



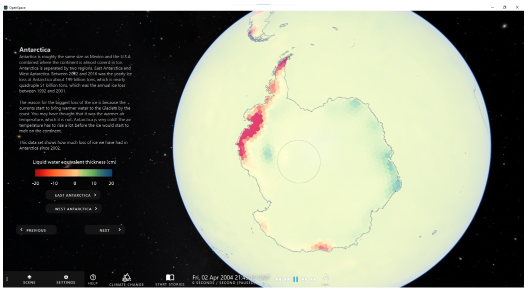
(b) Overview of sea surface currents



(c) Detailed surface currents



(d) Velocity



(e) Ice Melt on Antarctica

(f) Consequences

Figure 6.2: Story line (a) to (f) (does not contain all steps in the story) before the user test when Antarctica is picked.

When picking one of the stories, Antarctica, Greenland, or Alaska, see Figure 6.2a, the overview of the sea surface currents is displayed, see Figure 6.2b. There is a spin on the environment to give some life to the visualization. The test persons thought it was spinning too fast which made it hard to concentrate while reading the text. Since the spinning was considered fast, the specific area the person was reading about disappeared before he/she had finished reading. Therefore the speed of the spinning was reduced a lot. There was still some spinning to make the visualization more alive, but way slower than before.

In the next step of the stories, the detailed sea surface currents are displayed, see Figure 6.2c. During the user test, the users had a few comments about the color bar and the camera placement. Depending on which area the user chose at the start page, the camera will be zoomed in on that continent, meaning Antarctica, Greenland, or Alaska. While Antarctica was centered, only blue and some green surface currents were displayed if the user did not rotate the globe himself/herself. Therefore, people thought the color bar was misleading since they could not see any yellow, orange, or red surface currents in the visualization. To make the color bar more useful and also to get a more global visualization Antarctica was displayed in the most southern part of the globe. The visualization uses blue color for colder surface currents which easily get mixed up with the color of the ocean. Unfortunately, it is very hard to see the difference between the ocean and the cold currents. Therefore a color change of either the ocean or the blue currents could be necessary. This color scheme is not colorblind-friendly since it goes from blue to green to red. Removing the green part makes it more colorblind-friendly.

In the next step, displaying velocity, see Figure 6.2d, the user thought it was hard to read the color bar and understand the meaning behind velocity. The users were confused about why the continents were yellow and why that yellow appeared on the color bar. This data is temporal, meaning it contains multiple images over time. The users did not think this was clear enough.

When reaching Antarctica in the storyline, see Figure 6.2e, the user sees the data of GRACE. Most of the users wanted to place the data on top of a map of Earth instead of showing the light green color which is a zero value. They thought the locations on Earth would be more recognizable. The users had different opinions about the color bar where a few thought the data displayed temperature, with the explanation that the colors showed red and blue as the extreme values.

In the last step of the story, the consequences are shown, see Figure 6.2f. The Camera moves to America, and the user could pick different sea level rises to explore. The users wanted more possibilities to choose destinations where someone wanted the option to add exact locations in a search box to discover the consequences where he lived. Debra Tillinger, also a user, underlined the importance of not only showing what happens close to us but also places in the rest of the world. The consequences is the last part of the story, and the users wanted the possibility to start a new story with a button located in the text box, without needing to use the menu at the bottom of the screen.

A problem noticed during the user tests was the previous button located under the text. The different pages during a story is either a *global* visualization or a *local* visualization. The local visualizations are reached when a page has options to zoom in to a specific area, like West Antarctica, East Antarctica, and the six cities that were used to explore the consequences of a sea level rise. When pressing the previous button when looking at the visualization of West Antarctica for instance, you would like to return to the page the user visited before West Antarctica which unfortunately was not the case. The previous button instead took the user to the page that the user visited before the previous one. This problem was solved before the final result.

6.1.2 The Open World Storyboard

The user had the choice to explore climate change through an open world storyboard where the user could choose what to explore without any guidance and informative text. To get to the open world storyboard the user used a menu, described below.

6.1.2.1 The Menu

In the menu, see Figure 6.3 it was explained to the users that the three left buttons were not intended to exist in the final product. The buttons were only displayed in the interface during the user test if any error would occur that needed a quick fix to continue.

Several of the test persons had a hard time knowing how to start. A help button was already implemented in the bottom bar panel, but non of the test persons found it. One of the persons thought that *Help* was the wrong word for the button since she did not feel that she needed help, just some instructions. Therefore, the button changed name from *Help* to *Instructions* and a icon with a *i*. Most users wanted the button to be more eye-catching when starting the program and to make the users notice the button more, the button now flashes in blue color when entering the start page.

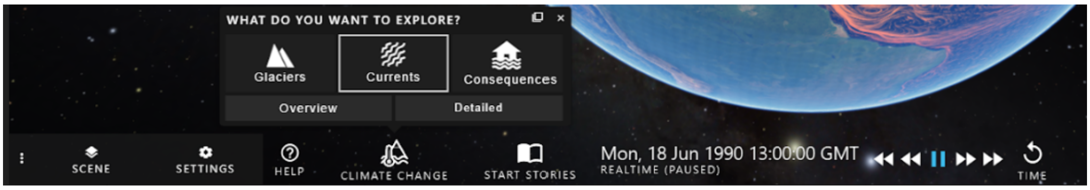


Figure 6.3: Menu placed in the bottom on the screen and what is showed when *Climate Change* and *Currents* is pressed

When the users pressed *Climate Change*, the storyline for the Open World, begins. The users wanted a more specific name because they thought the current name was too general since the whole project was about climate change. Most users were pleased with the new box that appeared when clicked, the icons, and the choices of the names. One user pointed out that "*Consequences*" should be changed to "*Sea level rise*" to make it more specific. When for example *Currents* and *Detailed* is pressed the dataset for ECCO is displayed. No informative text will be shown when discovering climate change through this menu but most users were pleased with that decision since they can read the texts when going through the storyboards, see section 6.1.1.

The button *Start Stories* is further explained in section 6.1.1. The users found it better to swap the placement of *Start Stories* and *Climate Change*. According to them, it felt more natural to start going through the data with the decision-based storyline and then discover the open world.

On the left in the menu: the user can see the date, time, the possibility to move in time, and a restart of the date. The users pointed out that it was unnecessary to have two fast-forward buttons in the menu with different speeds where one was considered to slow for some datasets and the other was considered to fast. Suggestions about a step function or a slider that allows the user to drag the bar to the wanted year or month was given. The slider or step function would then depend on the dataset, meaning if the dataset had new data every month, the next step would be next month, but if the dataset instead only had new data each year, the next step in the step function or slider would be next year. To simplify the proposals one speed button was implemented where the speed was fitted the specific data visualized. The restart button seemed unnecessary since no one used it in the user test or pointed it out. When picking a dataset, the date automatically moves to the start of the dataset, which the users were pleased with since they did not have to fast forward or rewind the date to dates the dataset covered. At the moment the time would keep on going if a time-based dataset would end and would therefore show the last data available. Unfortunately, there is nothing that tells that the time has exceeded the range of the dates of the dataset. The users would like something to happen to show the last date of the data.

6.1.3 General comments from user study

The users who participated in the user study were overall satisfied with the visualizations. They all had some comments on how the interface could be improved and most of those focused on color choices and that it was not clear enough if a dataset was temporal or not. The comments from the users during the user study came not only naturally while they got the assignments and clicked around but also after the assignments when they got questions about the GUI. Some of the assignments were a little tricky, especially this one: *"You are* *new to OpenSpace, how do you find out how to navigate in the software?"*, where we either hoped they would find the help button or try to navigate around Earth with their mouse. Most people thought the answer was in the text box to the left, and we got some suggestions to make the help button clearer. Even though all of the users struggled with at least one assignment, they all were positive about how the GUI turned out. The users thought the visualizations were cool, especially the one that visualized the detailed surface currents when rotating Earth with their mouse. They were also satisfied with the interface, meaning that they could explore climate change in two ways; through the start stories storyboard and the open world storyboard. Other comments received by all of the users were that the topic was interesting and that it would be nice to add this project to OpenSpace.

6.2 Result after user study

In this subsection the final result is presented. The first view the user meets is an interface with an informative text about climate change and how the glaciers melt. Debra Tillinger made sure the texts were correct in the texts, see the full texts used in Appendix E.

A visualization of Earth with satellites around it was displayed. The reason why the satelliets were displayed was because satellites were used to measure the data in the project. Below the text to the left, the user gets three options. It is possible to choose to explore three glaciers, either Alaska, Antarctica, or Greenland, see Figure 6.4.

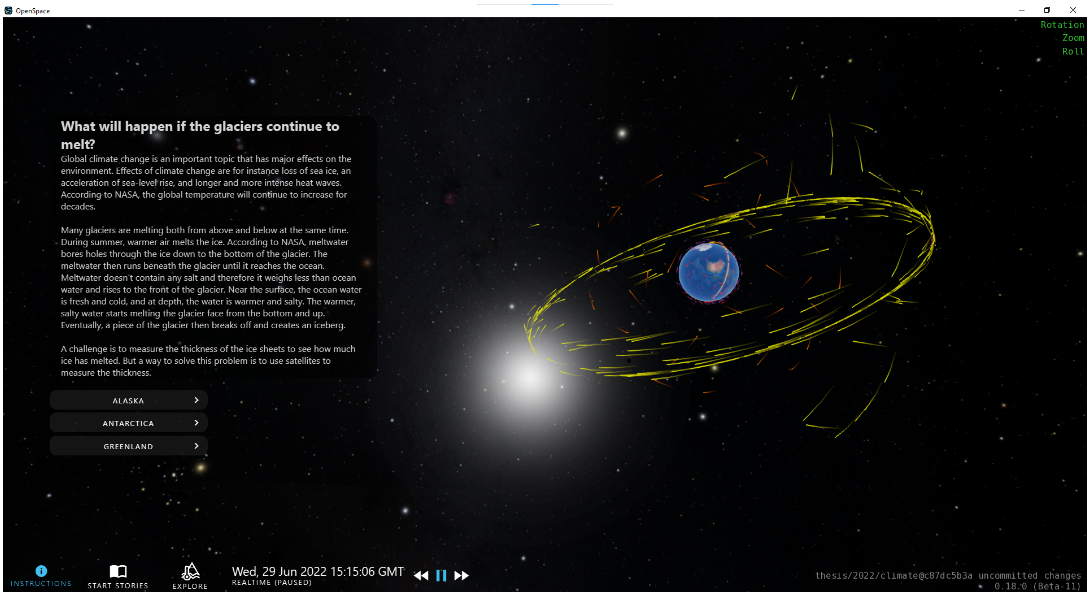


Figure 6.4: The starting page of the interface is were the user can pick a story. When the program starts the instruction button in the left corner in blinking to get the user's attention.

In the menu bar at the bottom of the page, there are three icons displayed to the left of the date, *instructions*, *start stories*, and *explore*. As seen, the information icon is blue. When entering the start page, the icon is flashing in blue to indicate that the user should press that button to get information about the interface. When pressing the button, the instructions in Figure 6.5 will appear on the screen for several seconds. The instructions explain how the user can navigate while using the mouse.

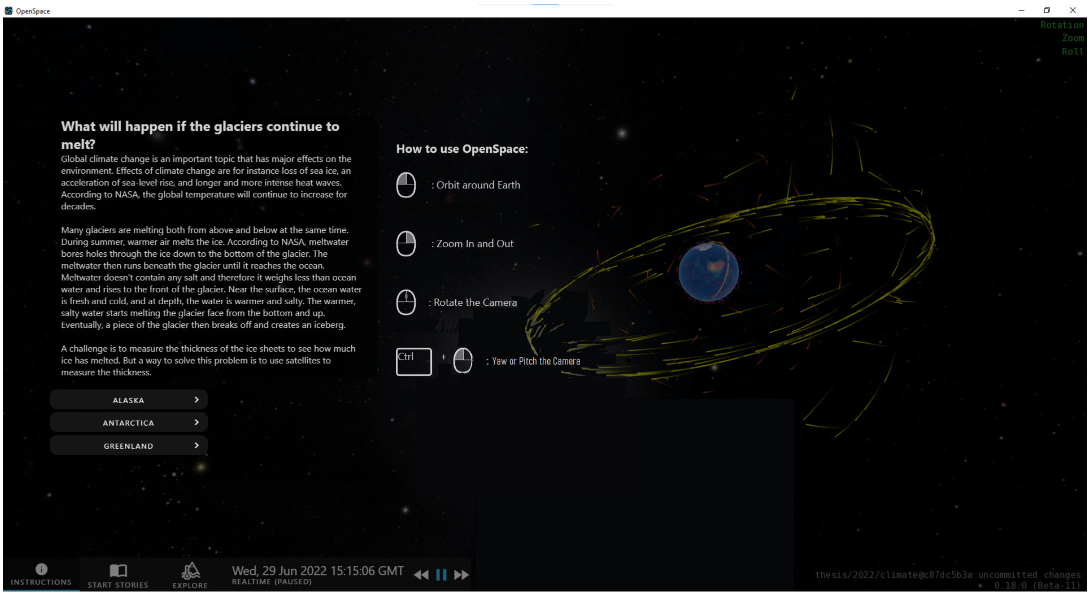
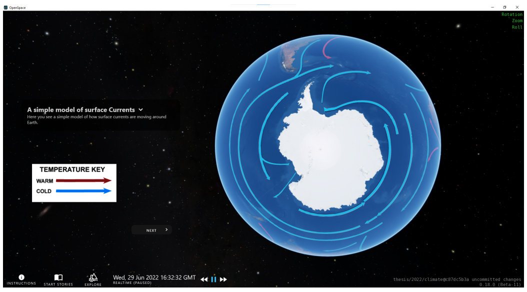


Figure 6.5: A pop-up window shows the instructions of the interface when the instruction button is pressed in the menu.

The *Start stories* button takes us back to the start screen where the icon is a book to symbolize the story. The *Explore* button is a possibility to Explore the data more freely without the information and encourages the users to move around the earth and explore the data by themselves, see 6.3. The icon is a mountain/glacier, ocean, and thermostat to symbolize the different possibilities of what can be discovered where the thermostat gives a hint about the reason behind the differences over time seen in the data. Next to the explore button, the time and date are displayed. Next to the date are a fast forward-, a play/pause- and a rewind button to adjust time and see how the data changes. The navigation bar is always visible and located at the bottom of the screen because it would not be in the way of other information.

The full storyline for Antarctica can be seen in Appendix B. The start page is displayed when pressing the *Start Stories* button where the user can choose from multiple stories. When pressing one of the stories of *Alaska*, *Antarctica* or *Greenland*, an overview of surface ocean currents will appear on the screen. Figure 6.6 is an example of an overview of the surface currents around Antarctica. The first view the user meets is Figure 6.6a where only the most important text is displayed. Then if the user presses the down-pointing arrow next to the title the arrow changes to an up-pointing arrow and more detailed information will be displayed on the screen. The arrow exists throughout the entire story, where the user can decide how much he or she wants to learn about the data. Below the informative text, a legend is displayed that indicates that the red arrows in the visualization mean warmer surface currents, and the blue color means colder surface currents.



(a) Less text - the most important information to understand the visualization

(b) More text - more detailed information for the ones who are interested to learn more about the topic

Figure 6.6: Overview of surface currents

Below the legend to the right, there is a *next*-button. When clicking on that button, the velocity around the globe will be visualized, see Figure 6.7. The data used to display this visualization is from the dataset ECCO, see section 4.2.1.3. A new feature on this page is a play button, a fast forward button and a rewind button, which are located below the text. The buttons are placed at the screen to indicate that the dataset is temporal, meaning there are different visualizations for different time frames. In this visualization another legend is presented at the screen, where zonal velocity at 25 meters depth is displayed with a color bar. The colors in the color bar goes from dark blue to yellow. Blue color means the water velocity moves towards west, and yellow color towards east. The color span was picked because it works for people with color blindness. Another reason was to have the zero value close to a more recognizable color for water where turquoise/green was used.

Figure 6.7: Velocity around the world where the darker blue shows how the water moves to the east and the yellow shows how the water moves to the west.

The next visualization presented in the story is another visualization of surface currents that is more detailed, see Figure 6.8. The data in this visualization is also from the dataset ECCO, see section 4.2.1.3. The difference between the previous visualization and this one is that here, the data was pre-implemented in OpenSpace, and in the previous one, the data had to be downloaded and converted to a format OpenSpace supports. Here, the user also had the opportunity to choose to read more like in the previous visualizations, which the user in this image chose to do. The color bar for this visualization goes from dark blue to red and indicates the temperature of the surface currents. The blue color means colder currents, and the red color means warmer currents.

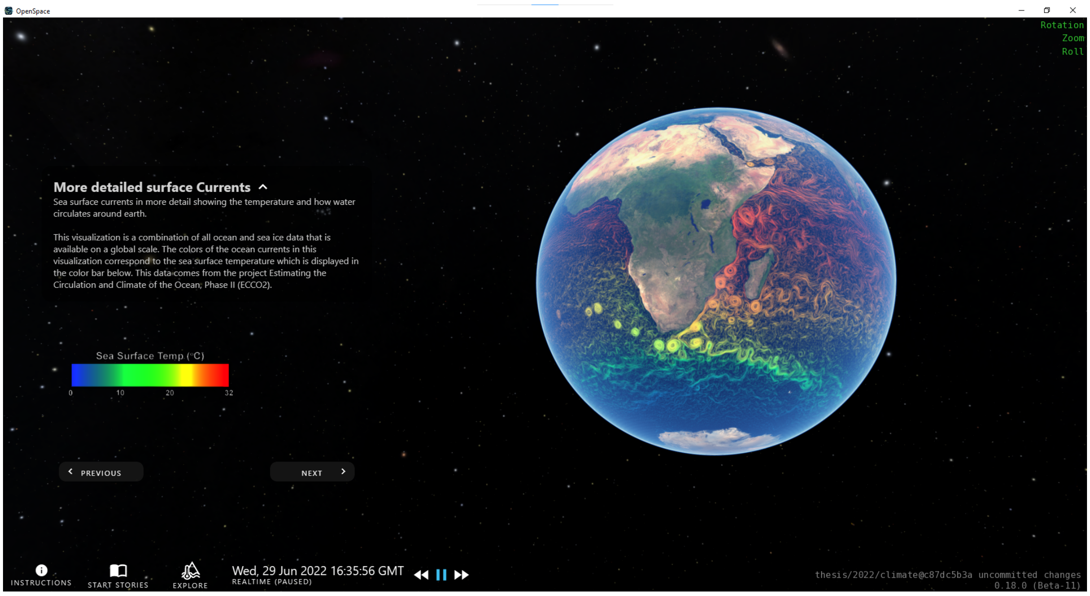


Figure 6.8: Detailed surface currents containing information about the velocity in the ocean and where the color bar shows the sea surface temperature.

The next visualization that will appear in the story about Antarctica is a zoomed-in picture of Antarctica that displays the ice melt on the continent, see Figure 6.9. The data used for this visualization is from the dataset GRACE which measures liquid water equivalent thickness. The color bar at the screen indicates that more orange color means less than zero and more purple color means more than zero compared to 2002 when the project started, see section 4.2.2.2 for more information about GRACE. When there are no changes in the equivalent water thickness the alpha value on the dataset is set to zero. The dataset is an overlay on top of a layer visualizing the globe so it easily can be seen where the changes are made.

The reason for choosing orange and purple as colors is that orange is similar to red: often something bad but that was often misunderstood as warm in the user test and orange was picked instead. Purple was picked on the opposite side because colorblind people can see the difference and it is similar to blue that could be interpreted as more water/ice but unfortunately also cold temperatures. Another reason not to have blue is to be able to see the differences in the areas with water on the planet.

This dataset is also temporal and visualizes data from the year 2002. Figure 6.9 shows what the ice melt looked like on 30 December 2003. If the user instead chose the story about Alaska, the visualization would be zoomed in on Alaska instead of Antarctica, but the same dataset would be used. Below the color bar, the user gets the option to look closer at either West Antarctica or East Antarctica if the user does not want to click next directly. If the user presses the West Antarctica button the screen will look like Figure 6.10a, which contains a closer look at the west side of Antarctica and an informative text about ice melt in the area. If the user instead chose to press the East Antarctica button the view will be zoomed in on East Antarctica with an educational text, see Figure 6.10b. When the user chose either West Antarctica or East Antarctica it is possible to go back and forth between the two areas since the West Antarctica button, and the East Antarctica button still is visible on the screen.

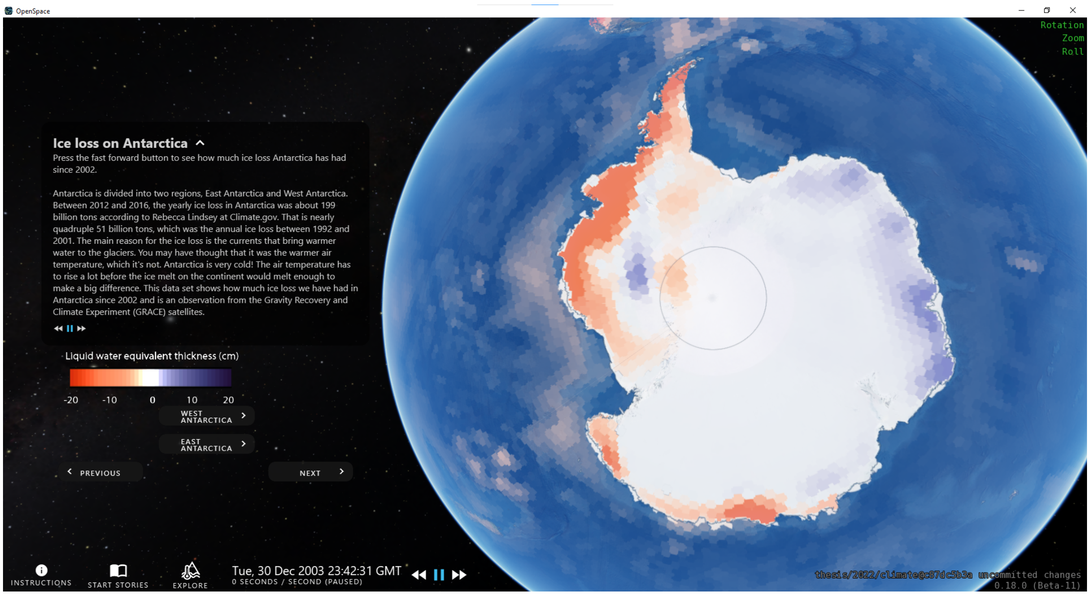
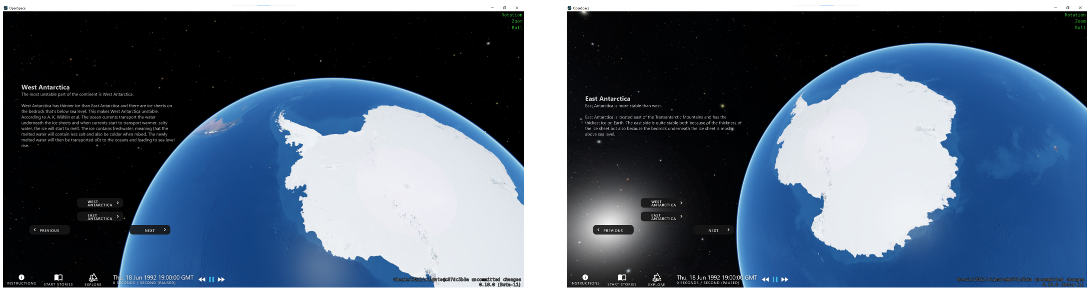


Figure 6.9: The ice melt on Antarctica using the data from GRACE. The zero value is here transparent to show the continents and the water underneath to more easily navigate around the globe and recognize where on the globe the user is looking

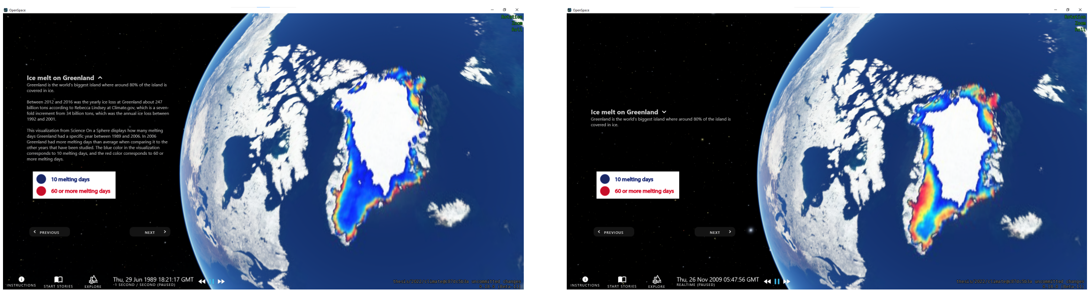


(a) West Antarctica

(b) East Antarctica

Figure 6.10: West and East Antarctica

The story about Greenland used another dataset, see section 4.2.2.1, when zooming on the area, see Figure 6.11. The legend here tells the user that blue indicates ten melting days per year and red means sixty melting days per year. When comparing Figure 6.11a that displays the ice melt year 1989 and Figure 6.11b that visualizes the ice melt year 2006, it is possible to see that the ice melted more in the year 2006 than 1989.



(a) Ice melt on Greenland 1989

(b) Ice melt on Greenland 2006

Figure 6.11: Ice melt on Greenland

After zooming in on the specific area in all the stories, the user will learn about the consequences of the sea level rise caused by the ice melt, see Figure 6.12. The interface contains a visualization of Earth and an informative text about the consequences of sea level rise. The user also gets the opportunity to choose between six cities in the world, *Shanghai*, *Kolkata*, *Miami*, *Jakarta*, *Belém* and *Amsterdam*, to look closer at. Then the user gets the possibility to compare the sea level rise of 2 meters, 4 meters, and 6 meters.

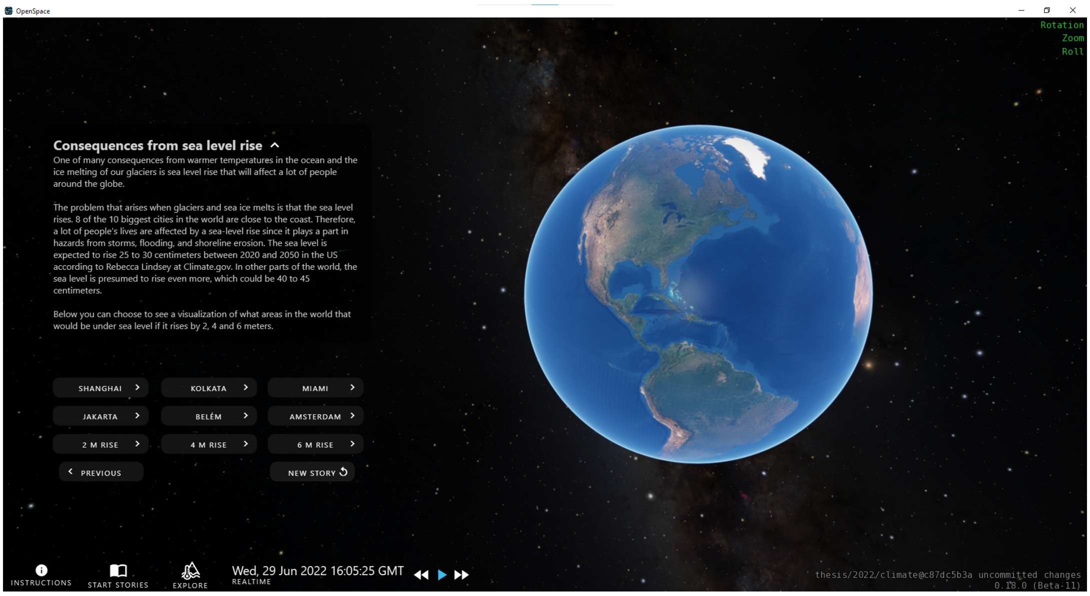
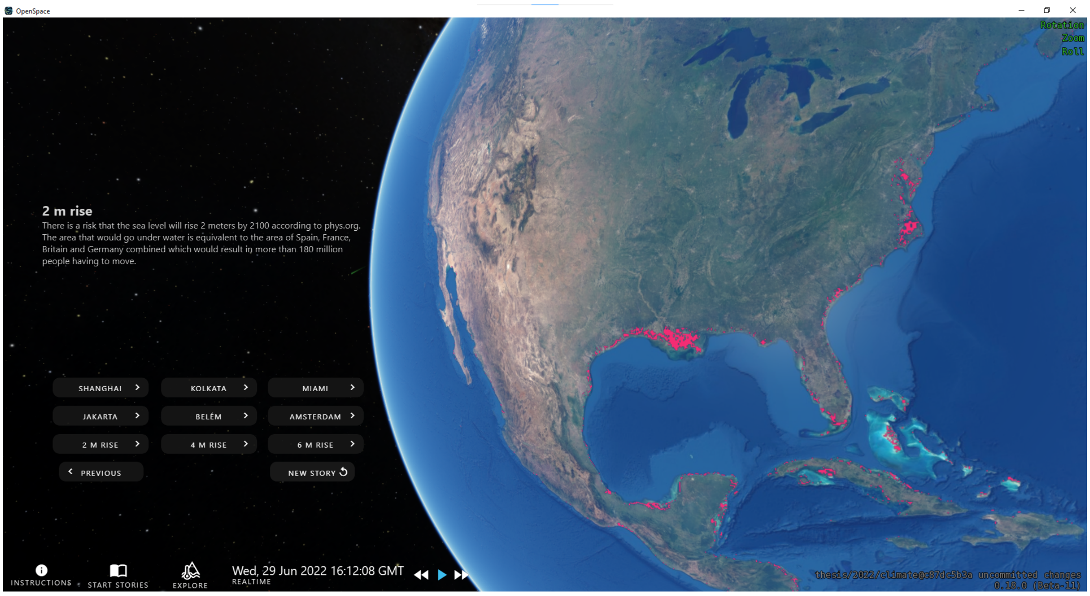
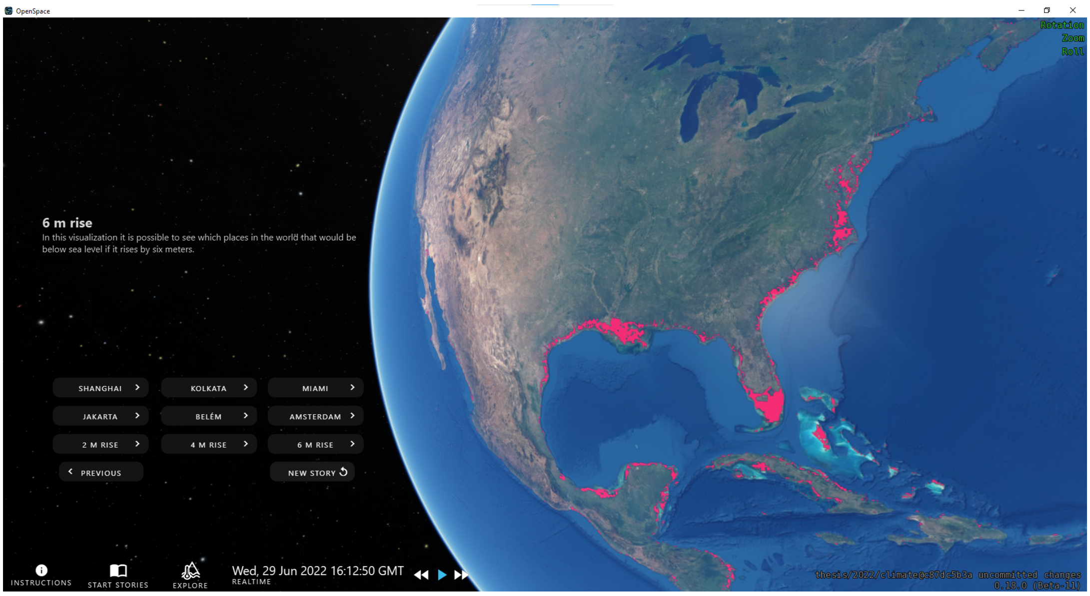


Figure 6.12: Consequences from the sea level rise

In Figure 6.13, it is possible to compare which area would be below water if the sea level rise by 2 meters, see Figure 6.13a, and the sea level rise by 6 meters, see Figure 6.13b. The red color in the visualization of Earth indicates the areas that would be below sea level.



(a) 2 meters sea level rise

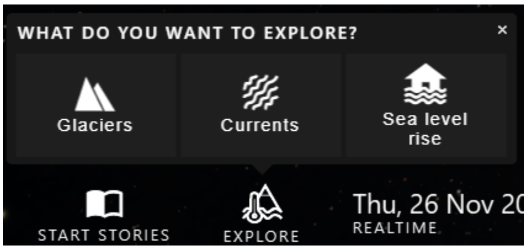


(b) 6 meters sea level rise

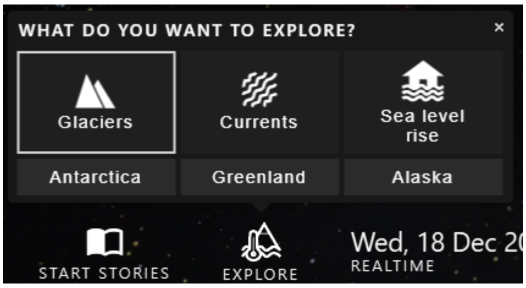
Figure 6.13: Consequences of sea level rise at Miami displaying the differences between 2 meters and 6 meters

6.3 Explore button

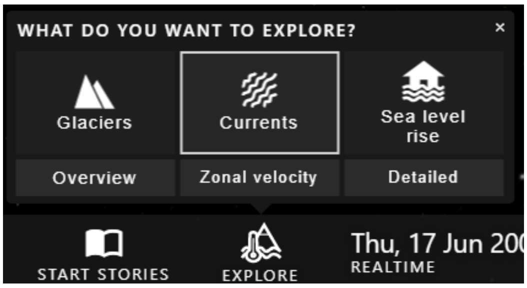
If the user more quickly wants to see a specific visualization, the user can press the button *Explore* in the bottom bar. When pressing the button the user gets three options to explore *Glaciers*, *Currents* and *Sea level rise*, see Figure 6.14a. When the user presses the glacier button three new options will appear below the previous options and the new options will be *Antarctica*, *Greenland* and *Alaska*, see Figure 6.14b. If the user instead wants to explore the currents three other options will appear instead of the three glaciers, *Overview*, *Zonal velocity* and *Detailed*, see Figure 6.14c. The last option from the original menu when the user pressed the Explore button is *Sea level rise*. When clicking on that button, the user can choose to explore the earth with 2 meters sea level rise, 4 meters sea level rise, and 6 meters sea level rise, see Figure 6.14d. The difference between exploring the sea level rise through the bottom bar compared to the stories is that here, the point is to explore the world by himself/herself instead of being zoomed in to a specific city.



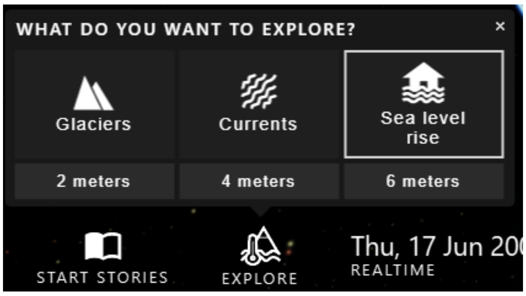
(a) Bottom bar



(b) Glaciers



(c) Currents



(d) Sea level rise

Figure 6.14: Explore in bottom for the open world story board created to navigate through the different datasets

7 Discussion and Future work

This chapter discusses the result, the method, and the work in a wider context. Further development is always possible in the project and also in this project. Possible implementations for the future are suggested and discussed throughout the chapter.

7.1 Results

The story was decided when we found out NASA had done missions collecting data over Antarctica. The soon-discovered issue was that the data collected could either contain very detailed, interesting information about certain places but maybe not be fitting to show in the story or OpenSpace. The datasets could also be complex with data that was hard to display without major operations, where implementing these datasets for OpenSpace could have been another thesis. Instead, we decided to focus on the GUI and the story instead of collecting, understanding, and creating fitted data for the project. Therefore, we have a view in the story that does not contain any data when zooming in on Antarctica, and one of the data sets that visualizes sea surface currents only displays a yellow color for the continent.

The colors of the visualization that displayed the velocity around the globe, shown in Figure 6.7, had misleading colors. Since the color of the landmass is yellow, and the yellow color is included in the color bar, a future improvement would be to fix that issue. One solution is to make the value transparent instead and use another visualization under the data. Therefore it would be possible to have the continents in colors and textures like people are used to seeing the Earth and therefore not be confused about what they are seeing. The wanted result when zooming in on West Antarctica and East Antarctica was to get a view from the side of the continent and be able to see the height difference over time. The idea was also to make it possible for the user to both see above and below the water line. Unfortunately, as seen in Figure 6.10 the wished result was not achieved.

It was decided not to change the already implemented dataset in OpenSpace even if the outcome of the project could have been more accurate and more understandable. The dataset showing the sea surface currents, together with the water temperature, see Figure 6.8, was considered alluring by the testers, but unfortunately, the color scheme was not, see section 6.1.1. Another dataset, unfortunately not considered correct information, was the dataset displaying the sea level rise, which is noticed when zooming in more on cities. There are probably more cities that should be below sea level according to our research, which is not the case in this data set. Therefore, an improvement would be to find a dataset containing a model with information that seems more correct from what we have read.

When looking closely at the result of the ice melt on Greenland in Figure 6.11b it is possible to see that the year says 2009 instead of 2006. Since the dataset only contains data until 2006, all the years after will show the same visualization as the one from 2006. This gives the user a misleading result since the data does not correspond to the date. An improvement would be to make the fast forward and play buttons disabled and stop the clock when the dataset ends.

A similar problem to the one described above is when a dataset is not temporal. Even if the fast forward, play, and rewind buttons not are located below the text, it is still possible to change the time frame in the bottom bar. Therefore, there was a discussion about if the time-button still should be displayed in the bottom bar when the data set is one image and not temporal. An improvement could be to make the ability to change date and time disabled if the dataset is not temporal or even remove the feature to make it clear the dataset is not time-based.

The text strings in the boxes were short to ensure the user kept interested and understood the text. Tillinger helped verify that the text was correct and explained enough since we are not writers.

Another discussion was held about the user's need to have the possibility to navigate through both two storyboards since they display the same visualizations. The idea for the decision-based storyboard is that the user will get a lot of information in a user-friendly way. When the user sees the interface for the first time, the thought is that the user should watch the visualizations through the stories that appear at the start screen. Then, when the user has gone through the three different stories, the user may want to see a visualization again. If wished, the user can reach the open-world storyboard from the panel in the bottom bar. Another reason for keeping the open-world storyboard is because it was a fast way to see a specific visualization instead of having to go through an entire story.

7.2 Method

This section discusses the method with possible aspects that could be further developed in the future. The section will discuss if the different parts of the method were considered a success or what could have been done to make it successful.

7.2.1 Creating the story and the GUI

The GUI was created with help from the six questions UX designers often ask themselves, mentioned in 3.1. The problem we have been solving is how to give information about climate change from complex data to novice users in a user-friendly way. The problem was solved using OpenSpace and storytelling to create a GUI to achieve and facilitate the user to learn something new without getting bored. To create the GUI, the needed components were listed, see 5.3, and sketches were created.

After the user test and some smaller fixes, the GUI was considered successful where the GUI is a good complement for the data used in the project and an implementation that could make OpenSpace more accessible for people than it is today. The GUI is today adapted to use on a computer at home where the user can learn and discover the data at their own pace or on a screen at a museum. A future implementation of the project could be to use the GUI on a touch screen or as a tool when a presenter presents in a dome or on a larger screen. The presenter could then use the interface on a separate screen where the presenter could step through the story and see the text to present while visualizing Earth on the larger screen. The camera would zoom in on the correct locations and show the decided data while stepping through the story.

7.2.2 Data conversions

Every NetCDF is created differently, consisting of different data values, meaning a new script is needed for every dataset when exploring what datasets to use in the project. Using the GDAL library and its documentation was time-consuming because it was a lot of trial-and-errors. The names of the variable were often named with a few letters like -*a_ullr* and had a short description of their functionality. When the conversions were finished, there were a few steps to see if the newly created files worked. The first step after the conversions was in QGIS to see if the data could be seen as an image and then add the file in OpenSpace to see if it worked on the sphere. If the steps worked, the file worked on a sphere, but if it did not, there was no way to tell what went wrong in the process. The dataset for GRACE was prioritized because it was the data showing the ice melt. After the user test, the data was further changed to make it easier to understand and is now considered a success. The data set less prioritized was ECCO and the time-consuming steps are the reason why the data has the color yellow for the continents. The continents are not part of the data in the NetCDF, but when we converted it, they got colors, and unfortunately, we did not find a way how to store the continents without a value.

A possible future work that was set as a delimitation in this project is to work further with the datasets and try to combine different datasets. For example, it would have been interesting to see how ECCO would have looked if we had taken the absolute value of the zonal- and the meridional velocity to see both how the currents move from west to east and how it moves from north to south. It would also have been interesting to see how the data would have looked if an absolute value had been over the bands in the data to see a conclusion of the sea surface currents and not only how it looks at z = 25 meters as it is now. A delimitation of the project was not to work this much with the data. Therefore, the suggestions above were not implemented, even though they would have given more correct data containing the actual sea surface currents around the globe.

7.2.3 The story API

The story API is a JSON file with information for the different steps in the story. The information shown is implemented in the story and could easily be changed if the knowledge given today would change in the future. It is easy to add steps to the story or create a new story as long as the added information contains the same variables existing today. The GUI and the front-end implementations would need to be changed if major changes are applied to the API, which is a drawback and limitation that is hard to avoid. Another drawback is the substories, such as when going around different places and looking at the consequences. The substories make the API more complicated and could probably be written better to make it more understandable if people in the future would like to add a story.

7.2.4 User test

If the user tests would be done again, it would be ideal to have more than seven test persons. Also, the thought was to have the user test at the *American Museum of Natural History* which did not happen because of lack of time. Therefore, if there would be another user test the plan would be to let visitors to the museum try the application. The user test was done online where the users got the remote control to be able to control our computers, described in 5.5. Unfortunately, the remote control had delays which resulted in navigation problems for the users but the user still got a good understanding of the navigation.

A final user test, which was not done because of lack of time, would also be preferred to let test persons try the final result to get proof that the improvements after the first user test were successful.

The testers had different backgrounds to get as many points of view as possible but choose to have testers that use computers daily to secure that the test was about the interface and not about using computers in general. Since the idea of the project was to create a user-friendly GUI for novice users it was important to use persons who had no experience within the area of the project. We also chose to include persons with competence within the field to make sure we got all the information about climate change correct. Persons who worked with OpenSpace also participated in the user test to give us good ideas of how to use the pre-implemented functionality in a better way.

Most of the assignments and questions were clear for the users but the first assignment we gave them, which was *You are new to OpenSpace, how do you find out how to navigate in the software?*, gave the most unclarity of all the assignments. The user did not exactly understand what to look for. That made us understand the importance of telling the assignments and asking the questions in a clear way. Concerning the mentioned assignment, it was not clear that the user should have pressed a button. Instead, most of the users just tried to navigate through the mouse without any instructions. To be more clear to the users that we wanted them to find the instructions on how to navigate, we should have told them to find the instructions instead of just finding out how to navigate in the software. This also showed that the user got interested in the interface and wanted to try and navigate by themselves in the software where they tried to navigate with the mouse and different buttons.

7.3 The work in a wider context

To state the correct facts that the scientists discovered about climate change, the first month of the project was mainly reading, watching, and discussing the changes in the Antarctic to get the information needed to create the project. It was important to only visualize the facts: what has happened and what can happen in the future. It was interesting reading the articles because they did not mention climate change or the causes behind it, only that it is happening to the ice. It showed us that it is enough to state the facts for the reader to see and realize how bad it is, and we wanted to do something similar, state the facts to start a discussion. In the section Related work, see 2.4, we mentioned that working with climate change is complex. It is a huge challenge to create a visualization containing information about the aspects of atmospheric chemistry, oceanography, biology, paleoclimatology, physics, glaciology, natural and human geography, political science, economics, and sociology. This project has mainly focused on oceanography and glaciology but also considers the consequences and therefore also mentions human geography. It is described in the delimitations that all of the aspects were not in consideration when creating this work because the time to research them all would be a master thesis by itself. It was important for us to state the facts to be able to start a discussion about the other aspects. When discussing climate change in politics, economics, and sociology aspects, the need for facts is the first step in how to solve this huge problem.

8 Conclusion

This is the final chapter of the report where the research questions presented in 1.4 will be answered. The aim of the project has been to visualize data in OpenSpace together with stories to see if a novice user can learn something new about our planet and see some consequences on what could happen if we do not care for our planet.

8.1 Research questions

In the beginning of the report, three research question were asked in section 1.4. Below the three questions are answered.

8.1.1 How could the cascading consequences of climate change be illustrated using OpenSpace?

Climate change is a big and wide subject where politics and economics often are in focus and is always in consideration when discussing climate change. The goal for this project was to not focus on these aspects and instead focus on the the changes on different glaciers over the years. The ice has mainly been melting underneath the ice shelves and to make the user more aware of that aspect, data on currents and how they are moving was added to the stories.

Different data set has been used to show how the ice is melting and what could happen if it continues. The dataset GRACE was used to show how the water has been melting over time in Antarctica and how it has been changing the world. When looking at the data set, not only Antarctica shows how the ice mass has been changing but also other aspects around the globe where the user can see locations with droughts over time in the open world storyboard.

To illustrate the sea level rise a pre-implemented dataset of a model in OpenSpace was used to end the story with an outcome for the worst scenario. The dataset showed a model on which areas would be below water if the sea level raised a different amount of meters. In this project, a visualization using the data for a rise of two-, four-, and six meters was created. In the visualization, the areas that would be under water were displayed in red color, see Figure 6.13. The visualization shows a good overview of what would have happened if the sea level raised and allows comparing the different outcomes. In the visualization, the user gets the opportunity to choose between focusing on six different cities on different continents. Unfortunately, the dataset does not cover enough information to get a more close up view, and some data are missing according to other research. Therefore, a future improvement would be to find another dataset that displays a more detailed visualization, and therefore, the user would be able to zoom in more closely to the chosen cities than in Figure 6.13. But even though the model is not 100% correct, it still gives the user a good idea of the consequences of the ice melting. Hopefully, the user gets affected by the visualization and realizes the importance of the topic and that climate change will affect the whole planet.

8.1.2 What features should be required in an interface for novice users interacting with a climate visualization in OpenSpace to achieve a user-friendly application? How many data variables can be shown at one time while not making the visualization too complex for a novice user?

Instructions on how to use OpenSpace are needed to make an interface user-friendly, which was noticed during the user tests. People who had never used OpenSpace before had a hard time navigating when not knowing how to use the mouse to achieve the wished navigation. Another way to make an interface user-friendly is to use universal icons that every user recognizes and are clear on their functions and that components are located logically, which would make it easier for the user to find what he or she is looking for.

A more important aspect was to ensure that the user was following the story and felt a connection to the story from the beginning. Therefore a simple overview of the currents was displayed where the data set is simple and hopefully recognized by most users. When walking through the story, it is both possible to see and read a longer text and a shorter one. The reason behind the decision was to ensure the user was comfortable and not forced to read if the user rather looks at the Earth. The decision behind every color used in the data sets was also crucial to ensure the data is easily readable and understandable, even if color blind which is a common genetic disorder. Therefore, the developers of the project decided to example avoid the color scale from red to green. To make sure the used colors of the visualized data were logical, the users were asked about it during the user test.

The data set containing the most information is the data set showing currents and water temperatures around the planet together. The user test showed that even if the data was pleasing to look at, it was hard to understand the actual data since the blue, cold currents were hard to see in the blue background representing water. Adding even more data on the oceans to this step in the story could be difficult since most colors already are used in the existing visualizations. Adding information about the continent at this step would be possible, although it would have been too much information displayed in one scene.

8.1.3 How can we seamlessly and pleasantly change between local and global visualizations for climate change? In what ways can the local and international context be shown at once while remaining interpretable for a novice user?

When going through the story, a camera moves around Earth and stops at a decided location. When starting the story, the camera is placed far away from Earth, and for every step in the story, the camera moves closer to specific cities and locations on Earth. The user test gave a good insight into what worked and not with the placement of the camera for different data sets.

One example when showing international context but mainly focusing on a specific location is when visualizing the currents. The glaciers are still the main focus, and while Earth is spinning, the user can see the chosen glaciers the entire time, which gives the user a hint of where the story is moving. Another example is when showing the ice loss in Antarctica with GRACE. The whole continent is in focus, yet our eye will focus on the coastlines since the color is shifting in those parts. A third example is when looking into the consequences of the sea level rise. The user gets to choose between six different cities in the world. When picking a city, the view changes from displaying the whole globe to zooming into a continent where the red color will cover the parts of the city that would be below sea level. In that way, the user can not only see the continent but also focus on the specific city because of the red color which will attract the eyes.

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9 Appendices

A Reference glaciers

List of 'reference glaciers'

MOUNTAIN RANGE	COUNTRY	GLACIER NAME
ALASKA	US	GULKANA
ALASKA	US	WOLVERINE
WESTERN CANADA & USA	US	COLUMBIA (2057)
WESTERN CANADA & USA	US	EASTON
WESTERN CANADA & USA	US	LEMON CREEK
WESTERN CANADA & USA	US	RAINBOW
WESTERN CANADA & USA	US	SOUTH CASCADE
WESTERN CANADA & USA	CA	HELM
WESTERN CANADA & USA	CA	PEYTO
WESTERN CANADA & USA	CA	PLACE
ARCTIC CANADA NORTH	CA	DEVON ICE CAP NW
ARCTIC CANADA NORTH	CA	MEIGHEN ICE CAP
ARCTIC CANADA NORTH	CA	MELVILLE SOUTH ICE CAP
ARCTIC CANADA NORTH	CA	WHITE
SVALBARD	SJ	AUSTRE BROEGGERBREEN
SVALBARD	SJ	MIDTRE LOVÉNBREEN
SCANDINAVIA	NO	AALFOTBREEN
SCANDINAVIA	NO	ENGABREEN
SCANDINAVIA	NO	GRAASUBREEN
SCANDINAVIA	NO	HELLSTUGUBREEN
SCANDINAVIA	NO	NIGARDSBREEN
SCANDINAVIA	NO	REMBESDALSKAAKA
SCANDINAVIA	NO	STORBREEN
SCANDINAVIA	SE	STORGLACIAEREN
SCANDINAVIA	SE	RABOTS GLACIÄR
CENTRAL EUROPE	AT	HINTEREISFERNER
CENTRAL EUROPE	AT	KESSELWANDFERNER
CENTRAL EUROPE	AT	VERNAGTFERNER
CENTRAL EUROPE	AT	PASTERZE
CENTRAL EUROPE	CH	ALLALIN
CENTRAL EUROPE	CH	GIÉTRO
CENTRAL EUROPE	CH	GRIES
CENTRAL EUROPE	CH	SILVRETTA
CENTRAL EUROPE	FR	ARGENTIÈRE
CENTRAL EUROPE	FR	SAINT SORLIN
CENTRAL EUROPE	FR	SARENNES
CENTRAL EUROPE	IT	CARESÈR
CAUCASUS, MIDDLE EAST	RU	DJANKUAT
CAUCASUS, MIDDLE EAST	RU	GARABASHI
CENTRAL ASIA	KZ	TS. TUYUKSUYSKIY
CENTRAL ASIA	CN	URUMQI GLACIER NO. 1
SOUTHERN ANDES	CL	ECHAURREN NORTE

List of former 'reference glaciers'

MOUNTAIN RANGE	COUNTRY	GLACIER NAME	REASON
ALPS	AT	STUBACHER SONNBLICKKEES	no recent direct glaciological measurements
ALPS	AT	WURTENKEES	influence of artificial snow management
ASIA NORTH	RU	LEVIY AKTRU	discontinued observations
ASIA NORTH	RU	MALIY AKTRU	discontinued observations
ASIA NORTH	RU	VOVOPADNIY (NO. 125)	discontinued observations

Figure 9.1: *The list of reference glaciers [47]*

B Storyline Antarctica

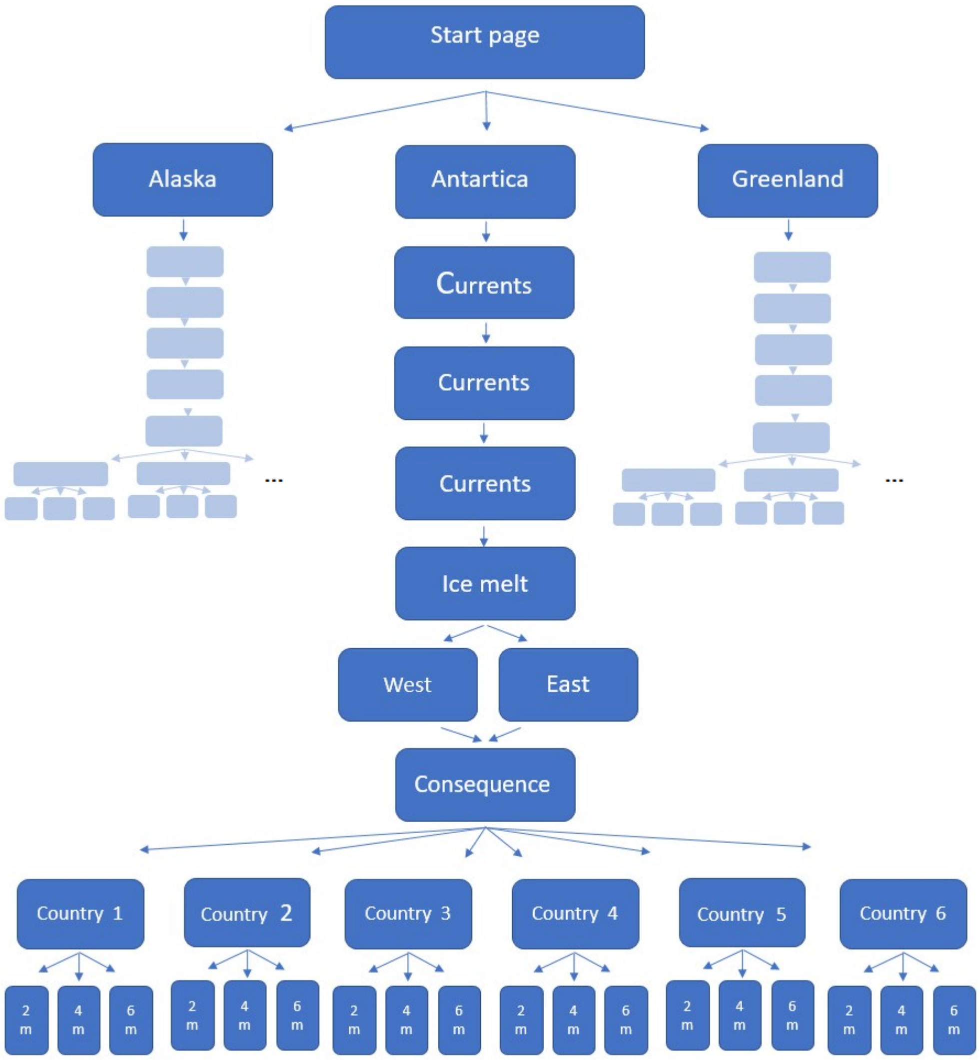


Figure 9.2: *The storyboard showing the storyline for Antarctica were the storyline for Alaska and Greenland are similar but whiteout the focus on different locations*

C JSON file

Variable name	Example or type
identifier	string (filename)
title	string
storyinfo	string
overviewlimit	double
focusbuttons	["Earth"]
timecontroller	true
actions	["climate_mode"]
journey	[]

journey contains

Variable name in journey	Example or type
identifier	”climate_antarctica”
id	int
title	string
storyinfo	string
source	source of data
timeSpeed	int
date	Y-M-D”T”H:M:S.Ms
pos	[]
toggleboolproperties	[]
local	[]

where local array is a new array containing same info as in *journey* if there is a local story, example west and east Antarctica.

pos contains the needed positions to make the camera movements

Variable name in pos	Example or type
anchor	”Earth”
pitch	double
position {x, y, z}	{double, double, double}
type	”setNavigationState”
up {x, y, z}	{double, double, double}
yaw	double

toggleboolproperties contains information on which climate data should be visible.

Variable name in togglebool-properties	Example or type
URI	string (call for layer with Lua script)
label	string
position {x, y, z}	{double, double, double}
defaultvalue	bool

D Assignments for user test

D.1 Interface on the screen

- You are new to OpenSpace, how do you find out how to navigate in the software?
- You would like to know more about how warmer currents reach Alaska, find that information.
- You discovered you are not that interested in the glaciers at Alaska, how do you change the story to another glacier?
- You want to know more in detail how the currents around Antarctica look like.
- Antarctica is very large and you find West Antarctica most interesting and want to explore it.
- You remember you saw something about Greenland, go back and choose to explore Greenland.

- The visualization shows the year 1989, see how the melting looked in 1995.
- In the last step of the story you will see the consequences. Explore which area of Jakarta that would be below water if the sea level raised 4 meters.

D.2 Bottom bar

- You are now tired of going back and forth on the screen. In the bottom bar there is another way to discover climate change, go to the right icon.
- You want to go back to Antarctica while overviewing currents.
- You are curious of what consequences there will be from the water rise level. Navigate yourself to Miami and compare the consequences between a rise of 2, 4 and 6 meters.

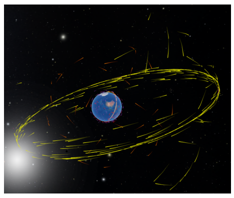
D.3 Questions

- We are at the moment using two different detailed currents. What detailed current data set did you learn most from?
- Would you like to see different places on Earth when displaying the sea level rise with 2 meter, 4 meter and 6 meter or would you rather see how much the area under water increases at the same place?
- When looking at the consequences after exploring Antarctica or Greenland, would you like to see the same cities for e.g Antarctica as for Greenland?
- Did you find it useful to be able to navigate through the story but also in the bottom bar?
- Was it something that you found useful or redundant?
- Was it some functionality you would have liked to see?
- Was it clear if the dataset was temporal or not?
- What do you think of the font size?
- Do you think the texts in the storyboard were too long or too short? Or was it a good length of the texts?
- What do you think about the size of the buttons?
- Enough info in help button?
- Any last thoughts?

E Information text in the story

Texts that are implemented in the project were the first paragraph is the text always showing and if the user decide to read more the next paragraph can be read.

START PAGE:



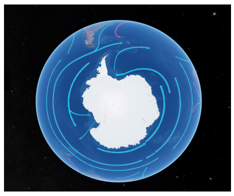
Global climate change is an important topic that has major effects on the environment. Effects of climate change are„ for instance, loss of sea ice, an acceleration of sea-level rise, and longer and more intense heat waves. According to NASA, the global temperature will continue to increase for decades even if global CO_2 emissions stabilize.

Many glaciers are melting both from above and below at the same time. During summer, warmer air melts the ice. According to NASA, meltwater bores holes through the ice down to the bottom of the glacier. The meltwater then runs beneath the glacier until it reaches the ocean. Meltwater does not contain any salt and therefore it weighs less than ocean water and rises to the front of the glacier. Near the ocean surface, the ocean water is fresh and cold, and at depth, the water is warmer and salty. The warmer, salty water starts melting the glacier face from the bottom and up. Eventually, a piece of the glacier then breaks off and creates an iceberg.

A challenge is to measure the thickness of the ice sheets to see how much ice has melted. But a way to solve this problem is to use satellites to measure the thickness.

A SIMPLE MODEL OF CURRENTS

Here you see a simple model of how sea surface currents are moving around Earth.



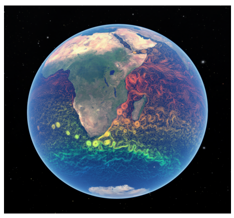
In the ocean, there are both colder and warmer currents. The blue color visualizes the colder currents in this visualization from NOAA's Science On a Sphere, and the red color indicates warmer currents. The arrows show a simplified model of the direction of the currents in the ocean. If the circulation of the currents would change there could be huge impacts on the climate. When the glaciers and ice sheets melt, freshwater will enter the ocean. Because of this meltwater, there is a risk that ocean circulation will slow down or even stop.

ONLY ON PAGE FOR GREENLAND:

According to NASA, the air temperatures in the Arctic increase faster than anywhere else on Earth every year. The balance at Greenland is therefore disturbed since the amount of ice that melts is not equal to the amount of snow that falls at the surface. Greenland is surrounded by warmer ocean water which also is a problem for the glacier to maintain its mass.

MORE DEATAILED CURRENTS:

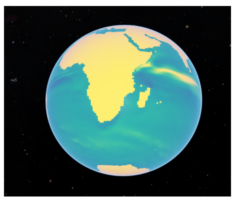
Sea surface currents in more detail showing the temperature and how water circulates around earth.



Here you can see the ocean currents more in detail. This visualization is a combination of all ocean and sea ice data that is available on a global scale. The colors of the ocean currents in this visualization correspond to the sea surface temperature which is displayed in the color bar below. This data comes from the project Estimating the Circulation and Climate of the Ocean, Phase II (ECCO2).

VELOCITY AROUND THE GLOBE:

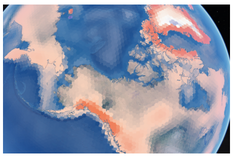
Press the fast forward button to see the speed of water at 25 m depth in the sea between 1992 and 2000.



With the help of satellites and instruments in the water it is possible to create models of the velocity of the currents and how and how fast the currents are moving around our Earth through the years. The colors show how fast the currents are moving, and according to NASA Science, it takes thousands of years for a water molecule to travel around the globe.

ICE LOSS IN ALAKSA:

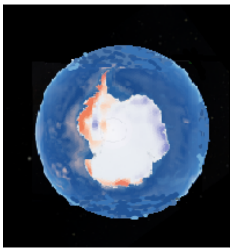
The Glaciers at Alaska are melting fast and press the fast forward button to see how much.



Alaska warms twice as fast as the rest of the US, and half the sea ice has disappeared since 1979 according to the Environmental Defense Fund. The glacier in Alaska has the fastest loss of glacier ice in the world. The warmer summers in Alaska have also increased the number of large fires in the last ten years.

ICE LOSS IN ANTARCTICA:

Press the fast forward button to see how much ice loss Antarctica has had since 2002.



Antarctica is divided into two regions, East Antarctica and West Antarctica.

Between 2012 and 2016, the yearly ice loss in Antarctica was about 199 billion tons according to Rebecca Lindsey at Climate.gov. That is nearly quadruple 51 billion tons, which was the annual ice loss between 1992 and 2001.

The main reason for the ice loss is the currents that bring warmer water to the glaciers. You may have thought that it was the warmer air temperature, which it's not. Antarctica is very cold! The air temperature has to rise a lot before the ice melt on the continent would melt enough to make a big difference.

This dataset shows how much ice loss we have had in Antarctica since 2002 and is an observation from the Gravity Recovery and Climate Experiment (GRACE) satellites.

WEST ANTARCTICA:

The most unstable part of the continent is West Antarctica.

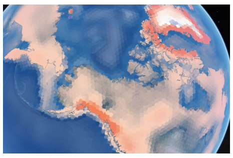
West Antarctica has thinner ice than East Antarctica and there are ice sheets on the bedrock that's below sea level. This makes West Antarctica unstable. According to research done on the Thwaites Ice Shelf by Wåhlin et. al. (2021); The ocean currents transport the water underneath the ice sheets and when currents start to transport warmer, salty water, the ice will start to melt. The ice contains freshwater, meaning that the melted water will contain less salt and also be colder when mixed. The newly melted water will then be transported out to the oceans and leading to sea level rise.

EAST ANTARCTICA:

East Antarctica is more stable than west.

East Antarctica is located east of the Transantarctic Mountains and has the thickest ice on Earth. The east side is quite stable both because of the thickness of the ice sheet but also because the bedrock underneath the ice sheet is mostly above sea level. This doesn't mean it is completely stable where a recent heat wave made an ice shelf, the size of Rome, collapse according to climate.gov.

ICE LOSS IN GREENLAND:



Greenland is the world's biggest island where around 80% of the island is covered in ice.

Between 2012 and 2016 was the yearly ice loss at Greenland about 247 billion tons, which is a seven-fold increment from 34 billion tons, which was the annual ice loss between 1992 and 2001 according to climate.gov.

This visualization from Science On a Sphere displays how many melting days Greenland had a specific year between 1989 and 2006. In 2006 Greenland had more melting days than average when comparing it to the other years that have been studied.

CONSEQUENCES:

One of many consequences from warmer temperatures in the ocean and the ice melting of our glaciers is sea level rise that will affect a lot of people around the globe.

The problem that arises when glaciers melt is that the sea level rises compared to sea ice where the sea level rise don't change if the sea ice melts. 8 of the 10 biggest cities in the world are close to the coast. Therefore, a lot of people's lives are affected by a sea-level rise since it plays a part in hazards from storms, flooding, and shoreline erosion. The sea level is expected to rise 25 to 30 centimeters between 2020 and 2050 in the US according to Climate.gov. In other parts of the world, the sea level is presumed to rise even more, which could be 40 to 45 centimeters.

ONLY FOR ANTARCTICA:

According to nsf.gov 90 percent of the world's ice is located in Antarctica, and if all the ice on Antarctica melted the sea level would rise by about 61 meters. The sea level does not have to rise much at all though to make a big impact on the world and the people.

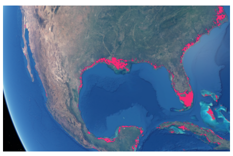
ONLY FOR GREENLAND:

If all the ice on Greenland would melt, the sea level would rise by 7 meters according to www.nsf.gov, and because Greenland is closer to the equator, the temperature is higher, and there is a bigger risk the ice will melt than at Antarctica. Even if there is a small possibility that everything melts every cm of sea level rise contributes to drastic changes for the environment with bigger risks of flooding.

Another reason for sea level rise is the thermal expansion of the water. Jpl.nasa.gov describes the process: when the temperature in the water gets warmer, the volume of water rises, leading to sea level rise.

Below you can choose to see a visualization of what areas in the world that would be under sea level if, in worst case scenario, it rises by 2, 4 and 6 meters.

2m SEA LEVEL RISE:



There is a risk that the sea level will rise 2 meters by 2100 according to phys.org. The area that would go under water is equivalent to the area of Spain, France, Britain and Germany combined which would result in more than 180 million people having to move.

2-, 4- OR 6m SEA LEVEL RISE:

In this visualization it is possible to see which places in the world that would be below sea level if it rises by X meters.