Geovisualization: A Framework and Case-study Analysis for Effective Climate Related Visualization

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B.Sc., University of Victoria, 2018

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE
in the Department of Geography

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Abstract

The impacts of climate change have resulted in the need for adaptation tools to provide stakeholders with the ability to respond to a broad range of potential impacts. Geovisualizations serve as powerful engagement tools due to their capacity in communicating complex climate data to various audiences. Studies have shown a preference towards conveying climate data through geo-visual representations, to quickly present ideas rooted in geographical challenges and solutions. However, a rapid pace of technological advancements has paved the way for an abundance of geovisualization products that have eclipsed the necessary theoretical inquiry and knowledge required to establish effective visualization principles. This study addresses this research gap by conducting a structured review of the geovisualization for climate change literature, and creating a conceptual framework that classifies existing geovisualization products into themes relating to visualization features, audiences, and the intended outcome or purpose of the visualization medium. The Climate Visualizations for Adaptation Products (CVAP) framework, is a tool for researchers and practitioners to use as a decision support system to discern an appropriate type of geovisualization product to implement within a specific use case or towards a particular audience. The process of developing a geovisualization software tool for displaying sea ice probability (SIP) in Arctic regions is detailed, in the context of suggested best practices for web development. Challenges and opportunities encountered while adhering to the best practice protocols and guidelines are examined. A usability evaluation is suggested to assess the general user attitude towards a website or service. Finally a summary with conclusions and suggestions for future research are provided.

Table of Contents

List of Figures

List of Tables

Chapter 1

A Changing Climate: The Visible Phenomenon

Climate change issues have become increasingly prevalent, and both the problems and the potential solutions to this phenomenon are geographically rooted. A discussion surrounding climate change and the inherent implications is necessary in order to understand, quantify, and adapt to these global climatic variations. Physical evidence of climate change has been observed in the globally rising atmospheric temperature trends (D'Amato & Akdis, 2020). This rise in temperatures has been linked to issues such as agricultural production yield loss (Asseng et al., 2015; Zhao et al., 2017), rising sea levels (Storlazzi et al., 2018; Vousdoukas, Mentaschi, Voukouvalas, Verlaan, & Feyen, 2017), increased hurricane frequency and intensity (Holland, 2012; Woodward & Samet, 2018), and Arctic sea ice loss (Graham et al., 2017; Screen, Simmonds, Deser, & Tomas, 2013). These far-reaching ramifications ultimately have a form of impact on all aspects of society, industry, and nature, which incites the need to have access to effective means of communication to involve multiple stakeholders and the broader public in the climate change discussion, potential solutions, and adaptation measures.

Cartography and mapping may be some of the oldest practices known to have been performed by human societies. These practices have evolved over time, and in this modern day and age, maps and the associated mapping standards and conventions have never been so complex and intricate. A map is a symbolic representation of a spatial phenomenon or a depiction of data with a spatial component, which has traditionally been represented on a flat surface. However, modern maps are more advanced, and they have morphed from rough geographical assumptions on paper, into colourful, interactive, detailed, and resourceful electronic tools that are able to communicate spatial information in an effective presentation manner.

Locational and geospatial data permeates our world, and using visualizations is advantageous when communicating the spatial data to a user due to their ability to quickly present information in an easy-to-understand format. Visualizations that illustrate geographical aspects or components can be referred to as geovisualizations, and these include conventional, static maps as well as sophisticated and interactive mapping tools that can be used to explore the dynamic geospatial data (Kraak, 2003). Even though research suggests that geovisualizations can reveal and communicate spatial data to a user, it is still unclear exactly what form of geovisualization is best suited for achieving an intended goal, serving in a specific use case, and towards which audiences a particular tool is most appropriate for. The overarching purpose of this research is to identify effective geovisualization communication strategies within the context of climate change and climate adaptation. This is achieved through the formation of a conceptual framework for geovisulization classification, an analysis on the best practices of web development when applied to geovisualizations, as well as the analysis of a novel geovisualization tool using the geovisulization classification framework.

This thesis is composed of a total of four chapters, including this introduction section. The subsequent section is comprised of a structured literature review on the state of geovisualization science and describes the Climate Visualizations for Adaptation Products (CVAP) framework developed to classify geovisualizations and facilitate the decision on an appropriate visualization product. The CVAP is intended to be implemented in cases when an organization is interested in using the best possible visualization product for a specific use case based on their individual needs. The third chapter analyses a suggested series of phases and best practices for web development, within the context of geovisualization development with reference to the CVAP framework. The development of an interactive web mapping application for viewing the maximum seasonal sea ice extent in the Northern hemisphere is described. Then a user evaluation is proposed, to assess the usability of the website and indicate the perceived user attitude towards the geovisualization or a mapping service. The final chapter summarizes the contents of this thesis, assesses potential limitations in the methodology used, and provides further direction for research in the field of geovisualization.

Chapter 2

Seeing Climate Change: A Framework for Understanding Visualizations for Climate Adaptation

1. Introduction

Climate change has resulted in the need for adaptation tools to provide stakeholders with the ability to respond to a broad range of potential impacts (Leskens et al., 2017). The field of geovisualization has demonstrated the potential for providing cutting-edge tools for communicating scientific data on climate change and climate adaptation measures in use cases such as, engaging people with future climate scenarios (Bishop, Pettit, Sheth, & Sharma, 2013), sea-level rise or flooding (Kuser Olsen et al., 2018), and urban flood risk management (Leskens et al., 2017). Geovisualizations serve as powerful engagement tools due to their capacity in communicating complex climate data to layperson audiences and other stakeholders outside of the academic sector (Grainger, Mao, & Buytaert, 2016). Studies have shown a preference towards conveying climate data through geo-visual representations, to quickly present ideas which are rooted in geographical challenges and solutions (Schroth, Pond, & Sheppard, 2015). Furthermore, employing geovisualizations to convey the multi-faceted nature of spatially-explicit data has been observed as an effective method for engaging different audiences with both complex and unfamiliar datasets or information (Neset et al., 2016).

Scientists have been developing digital data archives since the 1940s with the emergence of electronic computers (Yang, Raskin, Goodchild, & Gahegan, 2010). The rise of the digital data format has transformed research procedures by offering facilitation of rapid data transfer and sharing of information. This rapid pace of technological advancements has paved the way for an abundance of easily accessible geovisualization products that were previously only available to industry experts and professionals. Over several decades, geovisualizations have evolved into highly realistic, interactive (and in some cases immersive) digital environments that allow for greater data exploration capabilities and new knowledge discovery (Marmo, Cartwright, & Yuille, 2010; Newell & Canessa, 2015). However, the expedited rate of geovisualization production and development has eclipsed the necessary theoretical inquiry and knowledge required to establish effective visualization principles (Foo, Gallagher, Bishop, & Kim, 2015; Lewis, Casello, & Groulx, 2012).

The term 'geovisualization' can refer to a broad range of visual representations of geographical features, trends, and phenomena (Marmo et al., 2010). It is used here to describe a device or a visual medium to digitally convey geographically accurate information or data to a user (Lovett, Appleton, Warren-Kretzschmar, & Von Haaren, 2015; Newell, Canessa, & Sharma, 2017b). The topic of geovisualization pertains to the interdisciplinary field of research that is situated at the intersection of geography, visualization, computer science, communication, and cartography. This definition follows the work of Maceachren and Kraak (1997), who state that "all mapping can be considered a kind of visualization ... in the sense of making visible". The word geovisualization implies a topic involving data which contains a spatial component or geographical significance, combined with visual cues or stimuli that are implemented in order to communicate a message.

Geovisualizations have been found useful for presenting and communicating spatial ideas that are rooted in geographical challenges and solutions. These tools have been found especially useful for enabling assessment and understanding of issues or changes to a real-world environment among diverse users due to their ability to connect with people's sense of place and space (Newell, Canessa, & Sharma, 2017a). Accordingly, geovisualizations have demonstrated promise as useful tools for applications such as land-use planning (Lovett et al., 2015), property damage risk assessment (Bohman, Neset, Opach, & Rød, 2015), urban planning decision-making (Al-Kodmany, 1999), sea level rise issues (Shaw et al., 2009), flood risk management (Haynes, Hehl-Lange, & Lange, 2018), wildfire hazard exposure (Schroth et al., 2015), sea ice monitoring. Yet, although geovisualizations have shown promise for supporting climate adaptation practices, challenges still remain in applying this research in real world circumstances. There is a tremendous diversity of what is considered to be a 'geovisualization tool', as well as the intended users and/or audiences for these tools. Due to the varied nature of the geovisualizations and a lack of systematic and empirical evaluations (Lovett et al., 2015), it is often possible to encounter contradicting results regarding the most appropriate geovisualization to implement within a certain use-case, towards a target audience, or an intended purpose. For example, it is often believed that products with higher interactivity imply greater user information processing (Grainger et al., 2016); however, high interactivity can be advantageous or disadvantageous for information uptake depending on factors such as the complexity of the data and user-friendliness of the interface (Newell, Dale, & Winters, 2016; Stephens, DeLorme, & Hagen, 2015) and the specific formula and approach for creating optimal communication tools have yet been entirely determined (Marmo et al., 2010).

Research that assesses performance of spatial data infrastructure suggests that the selection of geovisualization tools needs to use indicators related to access, use, and sharing of spatial data, and these include efficiency and quality, flexibility and innovation, and transparency and reliability (Vandenbroucke, Dessers, Crompvoets, Bregt, & Van Orshoven, 2013). While such indicators may help some developers and users of these tools be more informed during the tool selection process, there remains a need for a framework that contextualizes the diversity, types, and the applications of geovisualizations in order to improve knowledge and gain a comprehensive perception on suitable approaches for using visual tools in climate adaption efforts.

This study addresses this research gap by creating a conceptual framework that classifies existing geovisualization products into themes relating to visualization features, audiences, and the intended outcome or purpose of the visualization medium. The result of this work is the Climate Visualizations for Adaptation Products (CVAP) framework, which is a tool for researchers and practitioners to be used as a decision tree or a decision support system to discern the type of geovisualization product that is most appropriate to implement within a specific use case or audiences. The following section presents the methods used in this research, namely a structured literature review used to develop, test, refine, and finalize the CVAP framework. Then, the paper presents the finalized version of CVAP, and it discusses how the framework can be applied to increase the comprehension of a geovisualization product. Finally, the paper discusses what CVAP has revealed about how geovisualizations can be used for climate adaption planning in different contexts, and it concludes with recommendations for further research.

2. Methods

This research employed a structured literature review, examining work related to the topics of visualization and geovisualization, climate adaptation strategies, and public and stakeholder engagement. The review informed the development of a framework for classifying geovisualizations, referred to here as the Climate Visualizations for Adaptation Products (CVAP) framework. This translated into a model that provides a means for organizing visualizations along axes in terms of types, application, and intended audience for the tools, similar to manner to MacEachren and Kraak (1997) and Bohman et al. (2015). Initial versions of the framework were created and subsequently tested by populating them with geovisualization products that were developed and examined in previous research. CVAP was refined after several iterations of this process, and the final decision was made regarding the included parameters of the CVAP through the validation steps. Figure 1 illustrates the workflow pipeline of the steps involved in this research, and these are described in further details in the subsequent sections.

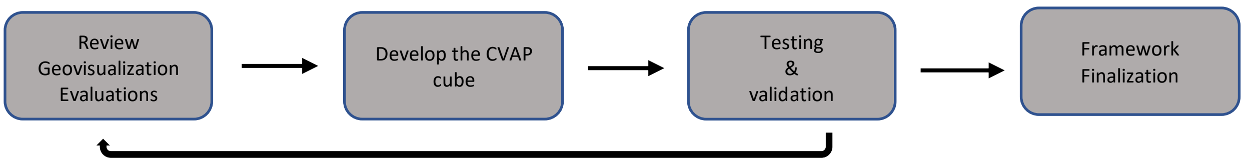


Figure 1. Methods workflow chart.

2.1 Review of Frameworks

A comprehensive review was performed of research which included geovisualization evaluations and frameworks which pertained to the topics of geovisualization, climate adaptation planning, and/or public and stakeholder engagement. These three criteria were used to structure the review, as they all relate to the necessity of developing effective planning tools for climate adaptation. The criteria together capture the benefits and the inherent trade-offs that emerge when managing solutions for mitigating climate change risks. This is a challenge as stakeholders, researchers, and members of the general public often have different perceptions of the most appropriate measures to implement in order to prepare for the potential impacts of climate change. The process entailed evaluating existing frameworks to extract relevant and meaningful aspects of the research which was subsequently used to create CVAP.

2.2 Development of CVAP

The CVAP cube is a visual framework developed for understanding different types and applications of geovisualizations for climate adaptation. It was constructed through the review of geovisualization, climate adaptation planning, and public/stakeholder engagement research initiatives. The analysed research was found by searching through peer reviewed material via the Google Scholar and the University of Victoria Library search engines using keywords such as: geovisualization, visualization, climate framework, climate change, climate adaptation, public engagement, landscape planning, and risk mitigation. The included axes were derived from recurrent and salient themes such as amount of interactivity, realism, and level of risk associated with the type of impact resulting from the decision-making process. A cube shape was chosen for the framework representation because of its capacity to represent the interaction of three axes and thusly provide interconnected considerations on how climate change visualizations are developed and used. The parameters were selected because they effectively and comprehensively describe the main differences in climatic visualization products in a clear and concise manner.

The design of the CVAP framework was informed by previous work on visualization concepts and best practices such as the amount interactivity available to a user (Grainger et al., 2016), the level of abstraction versus realism depicted (Bishop et al., 2013), communicating potential risk (Glaas, Ballantyne, Neset, & Linnér, 2017), and the general objective of geovisualizations as tools that represent geographical information (Bohman et al., 2015; Maceachren & Kraak, 1997). Populating the CVAP cube was achieved by reviewing literature that analyzed or evaluated existing geovisualizations. Each geovisualization was assigned a value of "Lower" or "Higher" amount of interactivity, risk, and realism respectively, relative to the other geovisualizations examined with CVAP. This process resulted in the formation of clusters which capture geovisualizations with similar qualities. Finally, the applicability of the cube was evaluated by examining whether the included geovisualization products fit into relevant categories based on the intended purpose they achieved and an appropriate type of audience for which the visualizations are suited. This stage indicated whether the chosen parameters for the model were indeed appropriately selected.

3. Results

3.1 The Framework

The results of the review of frameworks and research that contributed to the development of CVAP (such as the chosen shape and included axes) are summarized in Table 1, organized by the review criteria of geovisualization, climate adaptation planning, and public and stakeholder engagement. More information on how the literature contributed to the CVAP framework is detailed further below.

For the purpose of this study, a high rating of risk refers to geovisualization tools that are used to support decision-making associated with significant implications towards the well-being of communities (and human life), environmental systems, or public infrastructure. A lower risk rating implies that the tool is used for decisions which have a less significant impact on property loss or do not pose a great hazard to someone's safety. A higher amount of interactivity implies that users are able to choose options such as varying zoom levels, active data layer visibility, and panning and navigating imagery. Products with lower interactivity include visualizations like conventional maps and other static imagery. The final axis included in the CVAP cube is a rating of realism, which refers to whether the visualization presents the spatial information in an abstract, or highly realistic form.

The Map Use Cube (MUC) created by Maceachren and Kraak (1997) and further refined by Bohman et al. (2015) provided a basis for structuring a representation of a geovisualization framework and classification tool. The MUC is two decades old and thus is not entirely relevant to current technological capabilities; however, the ideas presented within the older model can still provide a foundation for building new concepts. CVAP assumes the same shape as the MUC and shares a common axis (interactivity); the remaining parameters have been adapted from the other research listed in Table 1.

Table 1. Summary of research used in formation of the CVAP framework.

Source	Theme/Contribution	Description	Audience
Grainger et al. (2016)	Interactivity	A high level of interactivity increases scientific information uptake	Academia & Laypersons

Bishop et al. (2013)	Abstraction vs Realism	Amount of realism can impact level of communication	Decision makers
Glaas et al. (2017)	Risk	Communicate magnitude of potential damage	Homeowners & Public
Bohman et al. (2015); Maceachren & Kraak (1997)	Map Use Cube	Characterizes geovisualization objectives	Academia
Robinson, L. (2002)	Community Involvement	Classification of engagement processes	General public & government agencies

Grainger et al. (2016) developed a design framework for facilitating effective communication of scientists and researchers with individuals outside of academic and scientific sectors. They found that the maximum amount of information uptake with regards to climate data occurs within a highly interactive visualization environment. Their work informed the development of the CVAP framework by providing insight on the role of interactivity in developing effective types of geovisualizations for communicating climate data across many disciplines.

Bishop et al. (2013) evaluated several climate change visualization products that were focused on a coastal region in Southwestern Australia. The geovisualizations ranged from static, low risk scenarios that imply low to non-existent risk of life loss, property damage, or serious environmental consequences, all the way to interactive, realistic, and high consequential visualizations, that represent situations and decisions with severe environmental consequences, public infrastructure damage and risk of human life loss. This work provides a consensus that geovisualizations aid in communicating information, with an integral component consisting of evaluating the degree to which a geovisualization was able to achieve effective communication of data to a user. Although they did not compare the techniques to one another in order to state one type is ‘better’ than the other, their work demonstrated the range of realism (or abstraction) present in the geovisualizations can influence how people engage with and use the tools.

Glaas et al. (2017) focused on the ability visualizations have for influencing Nordic homeowners’ perception of the risks (and extent thereof) to which their houses are susceptible to hazards brought on by climate change. This message is necessary to convey to homeowners as they are significant stakeholders within the realm of climate adaptation with regards to fortifying their homes from inclement climatic events. Most importantly, a lack of risk perception possessed by the residents can hinder their climate adaptation strategies. A salient theme within this work centered on risk, and the impacts this can have on reactions toward and level of understanding of climate change. Therefore, risk was chosen as one of the factors in CVAP.

Robinson (2002) provided a framework for understanding different approaches to community engagement in their work on waste management planning and decision-making in Western Australia. This work is relevant to CVAP as the research revolves around the importance of public participation in environmental decision-making. Robinson (2002) compared the inherent risk of a situation with the complexity of information presented to the audience, to visualize various public engagement methods. In addition, the author created themes that classified the different engagement methods within the Community Involvement Matrix: inform, consult, involve, and partner, and these are used in this research as a lens for interpreting the results of this study and CVAP application (see 4. Discussion).

3.2 The CVAP Framework

Based on the review, the properties defined for the CVAP framework were: risk (Kuser Olsen et al., 2018; Lieske, Wade, & Roness, 2014; Macchione, Costabile, Costanzo, & De Santis, 2019), realism (Bishop et al., 2013; Leskens et al., 2017; Newell et al., 2017b), and interactivity (Bohman et al., 2015; Grainger et al., 2016; Leskens et al., 2017; Lewis et al., 2012; Lovett et al., 2015). These properties have been found to have effects on the overall impression or purpose of a particular geovisualization product as based on research; however, previous studies have not yet considered all three of these characteristics together in concert. The three aforementioned parameters of interactivity, realism, and risk comprise the axes of CVAP (Figure 2).

In this research, traditional 2D maps were considered as abstract geovisualizations since they do not provide the necessary details for the user to feel immersed (i.e., as if they are actually present in the depicted place). Visualizations were classified as highly realistic, when they contained elements that accurately represented real-world objects and entities and contributed to user impressions of that they were viewing a scene or scenarios as it would like in real life.

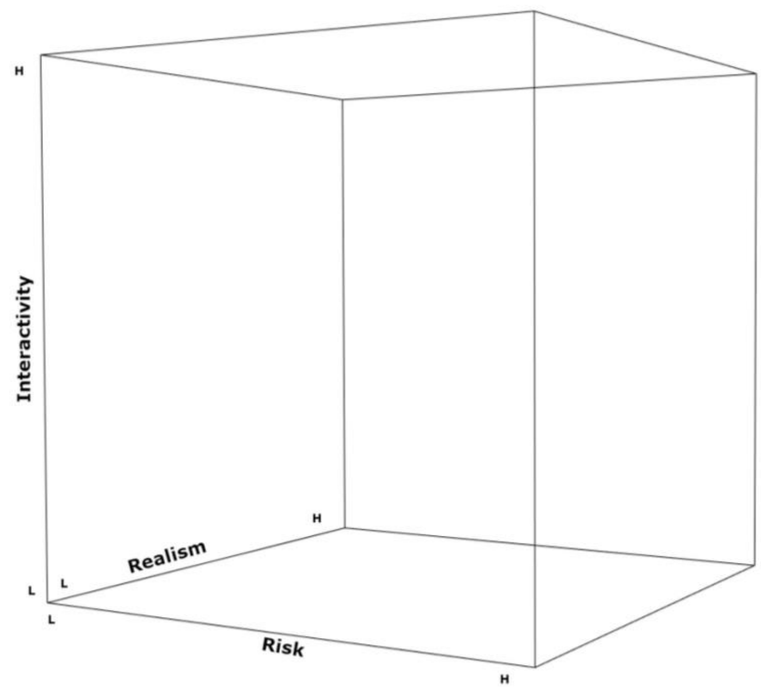


Figure 2. Climate Visualizations for Adaptation Products (CVAP)

3.3 Applying CVAP

Studies that contributed to the testing and refinement of CVAP process are listed in Table 2 and organized by the themes of the review criteria. The thematic relevance of each project identifies how the work was contributed to the formation of CVAP. The geovisualizations included in the newly developed framework all contained a user evaluation and/or usability testing component with regards to achieving a specific objective, use case, or to target a distinct audience. Some rows included in the table represent multiple geovisualization products comprised in the CVAP framework, as the specified research analyzed more than one version or type of geovisualization (e.g., Bishop et al., 2013; Schroth et al., 2015). Products were ranked relative to one another along the three axes and were assessed on binary scales consisting of either a lower or higher rating for each of the chosen parameters. This process resulted in the organization of geovisualizations into clusters or groups with similarities in terms of the features of the tools and how they are used.

Table 2. Research used to test and refine the CVAP framework.

Source	Geovisualization	Climate Adaptation	Public Engagement	Relevance to Framework
Glaas et al. (2017)	VisAdapt Product	Integration of climate scenarios & local risk maps	Adaptive capacity for homeowners	Risk, Interactivity, Realistic visuals,
Lovett et al. (2015)	3D landscape visualization	Future landscape changes	Stakeholder involvement	Level of realism in 3D visuals
Bohman et al. (2015)	VisAdapt & ViewExposed	Nordic climate change property risks	Urban planners & decision makers, homeowners & insurance brokers	Risk assessment, Public decision-making, Geovisualization
Bishop et al. (2012)	Victorian Climate Change Adaptation Program (VCCAP)	Climate change predictions	Policy and decision makers, extension staff, researchers	Visualizing expected climate change, Risk
Sheppard et al. (2011)	Local Climate Change Visioning Project (LCCVP)	Change effects at local (community) level	Public debate on climate change	Climate adaptation, Realistic visuals
Pettit et al. (2011)	Lower Murray Landscape Futures (LMLF)	Communicating landscape futures	Environmental managers, planners, & university students	Interactivity, Realism
Lieske D.J. (2015)	Community Adaptation Viewer (CAV)	Spatial decision support system to assist in adaptation planning	Community stakeholders	Risk, Interactivity
Romañach et al. (2014)	EverVIEW Data Viewer	Everglades restoration	National & International planning	Coastal environment Risk reduction, Community involvement
Tress & Tress (2003)	Photorealistic Visualization	Rural land use planning	Participatory planning	Realistic visuals
Stephens et al. (2015)	Sea Level Rise Viewer	Hurricane risk communication	Stakeholders & Resource managers	Risk

Poco et al. (2014)	SimilarityExplorer	Tool for analysis of climate data	Climate scientists	Data interaction
Li et al. (2011)	Web based GIS for sea ice archives	Sea ice monitoring	Ease of access and data dissemination	Interactivity, data exploration
Kinkeldey et al. (2015)	Land cover change analysis tool	Future land cover change scenarios	Experts	Risk & Uncertainty
Macchione et al. (2019)	3D urban flood inundation maps	Sea level rise	Engage public, stakeholders, & engineers with flood hazards	Realistic visuals, Risk, Interactivity
Schroth et al. (2015)	Kimberley Climate Adaptation Project (KCAP)	Mountain pine beetle impacts & flood susceptibility	Community awareness and participation	Interactivity, Risk
Johansson et al. (2010)	WorldView	Representation of climate change related issues	Public involvement	Realistic visuals, Interactivity, Risk

Clustering can be found in the corners of the CVAP (Figure 3), as these areas represent the higher/lower polarization of geovisualization characteristics captured through the axes. The left-most corner on the bottom plane of the cube is the only junction where all three parameters are defined as lower. The remaining three corners on the bottom of the plane of the cube all share the same lower rating of interactivity present within the geovisualization. As we move up along the interactivity axis towards the topmost plane, there are increases in the degree to which users can interact with the geovisualization tool for engaging in data exploration. An increased value on the risk axis implies an increase in the risk rating of a visualization (i.e. consequences that may result in loss of human life, severe public infrastructure damage, and/or large-scale environmental impacts), and all the products that are nearest the right most, front facing plane of the cube share the increased rating of a higher risk implication. Finally, as we move along the realism axis towards the back of the cube, the visualizations with increased realism are situated along the rear plane. This implies that the examples located in the foreground of the cube are visualizations that exhibit abstract characteristics and are therefore considered to be less realistic. The visualizations that are considered abstract may display data in formats such as tables, graphs, and two dimensional (vector and/or raster) maps. This is contrary to realistic geovisualizations, which attempt to provide the highest level of authenticity through convincing imagery such as three-dimensional rendering or visualizations containing a high level of detail (i.e. sounds and textures).

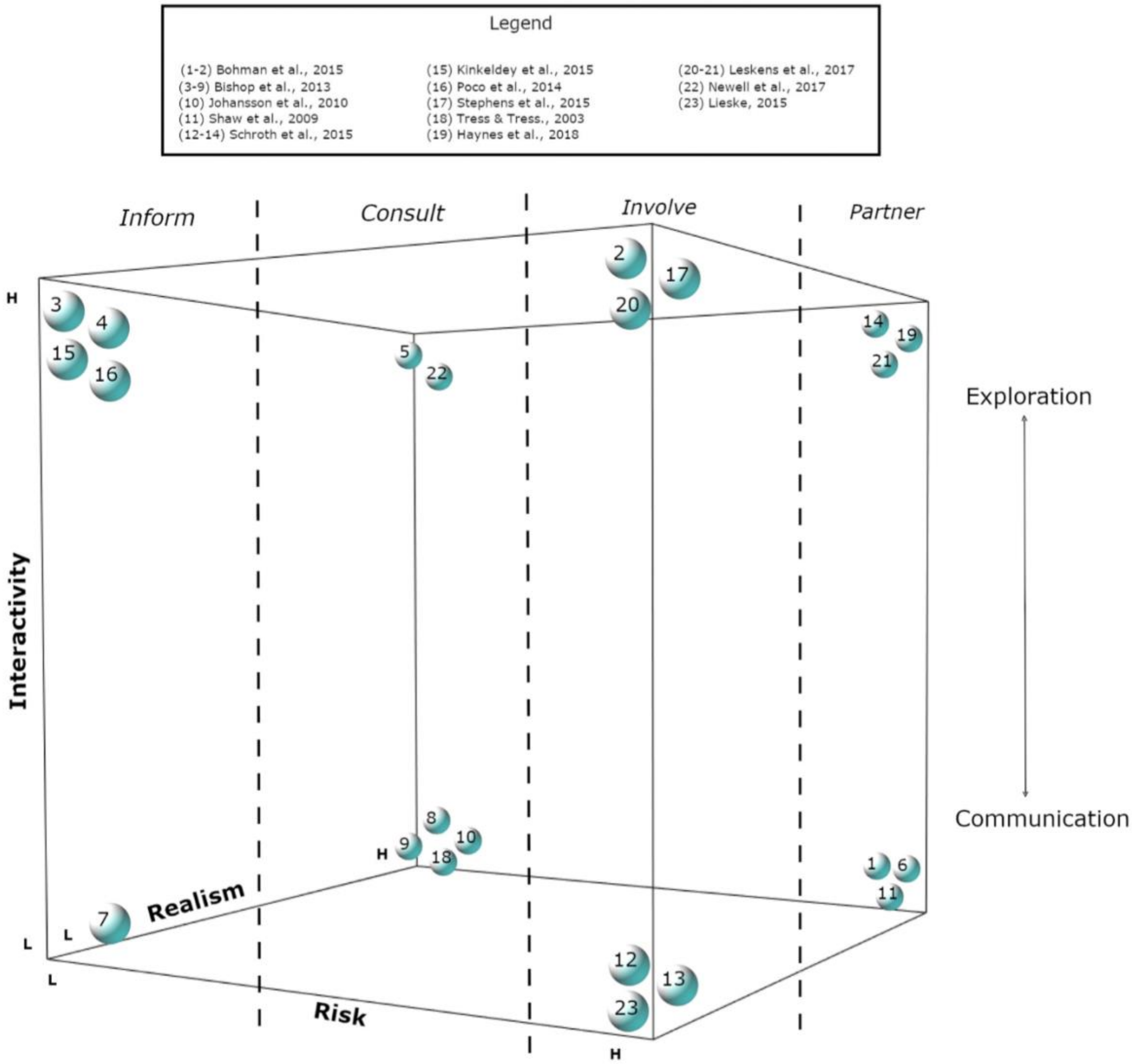


Figure 3. CVAP populated with geovisualization products.

3.4 Applying Engagement Themes

Each of the clusters of visualizations in CVAP aligned with themes of public engagement and visualization communications that have been respectively described by Robinson (2002) and Bohman et al. (2015). Robinson's community involvement matrix compared the inherent risk of a situation with the complexity of information being presented to the audience, to create a mapping of potential engagement processes that could be implemented in a specific situation. The four themes (or categories of engagement strategies) that Robinson (2002) coined were: inform, consult, involve, and partner. These themes are denoted in the framework via dotted lines separating CVAP into 4 distinct sections. The regions and clustering within CVAP align with these themes, for example, inform-type geovisualizations were found at the lower end of the risk spectrum and partner-type tools at the high end of the risk spectrum. One of the alterations that Bohman et al. (2015) applied to Maceachren and Kraak (1997) Map Use Cube was the addition of a communication to exploration spectrum that runs diagonally through the model. Bohman et al. (2015) also illustrated the lower amount of human and system interaction as primarily intended for the communication of predefined information, and the increased level of interaction with the goal of facilitating new knowledge discovery (discerning unknown patterns and relationships within the data). Hildebrandt and Döllner (2010) also associated an increased level of interactivity within a spatial visualization as a technique intended for exploration by allowing a client the capability of rotating and moving the view-point camera (point of view perspective of the user). This allowed the user to utilize the application to "show me something else", creating opportunities for discerning other information, rather than simply receiving a predefined message or piece of information from the developer of the product.

When considering the Bohman et al. (2015) spectrum and Robinson's (2002) engagement themes in the context of CVAP, eight distinct categories can be observed, and the clusters fall into ranges from Inform & Communicate all the way up to Partner & Explore. The categories are discussed further below, and are organized using Robinson (2002) themes as subsections with discussion on Bohman et al. (2015) Communicate and Explore variants in each section.

3.4.1 Inform

The Inform theme contains geovisualization tools that are used to support decisions associated with lower risk in terms of outcomes and impacts. Examples in the Communication region include 2D Projected Land Suitability maps illustrating four crop types projected for the years of 2010 and 2070 (Bishop et al., 2013). This type of visualization was used to present rather than produce research findings. Since an error in the crop suitability map does not imply direct human casualties or substantial property/infrastructure damage, this visualization is deemed as low risk.

Other low risk visualizations within the inform category contain a higher element of interactivity; therefore, they are situated in the Explore region of the cube. These visualizations included the ICchange prototype (Kinkeldey et al., 2015), the SimilarityExplorer (Poco et al., 2014), and Visual Exploration Interfaces (VEI) with an embedded Google Earth Application Programming Interface (API) (Bishop et al., 2013). The visualizations evaluated by Bishop et al. (2013) both centered on rainfall and temperature change projections (agricultural purposes); however, they provided the user with more opportunity to interact with the presented data, thus situating the products near the Exploration end of the spectrum. This is the same for both the geovisualizations evaluated by Poco et al. (2014) and Kinkeldey et al. (2015), as they provided functionality such as allowing the user to filter the level of uncertainty in the land cover change predictions (ICchange), as well as prediction models, variables, and time resolution (SimilarityExplorer).

3.4.2 Consult

An increase in Realism in the geovisualizations results in products that are more strongly related to the Consult theme. The lower portion of this theme contains visualizations with less interactivity available to the user comprised of a visualization evaluated by Bishop et al. (2013), the WorldView Project (Johansson, Schmid Neset, & Linnér, 2010), and a photorealistic tool that demonstrated potential land use changes in the Danish countryside (Tress & Tress, 2003). These visualization products all had a high aspect of realism and were used during circumstances which did not risk loss of life or vital public infrastructure. These tools were designed to communicate pre-constructed scenarios towards a greater audience to facilitate discussion and solicit thoughts and opinions on said scenarios; therefore, the geovisualizations were intended to be used by planners to consult with stakeholders regarding the future land use options such as farming, tourism, conservation efforts, or residential development. The WorldView Project presented global as well as regional effects of climate such as temperature, sea level rise, and loss of arctic sea ice cover (Johansson et al., 2010). The evaluation asked participants about the relevance of the presentation as well as ease of understanding of the presented data. Furthermore, (Newell et al., 2017a) used a realistic and highly interactive geovisualization to model a coastal environment in order to familiarize users with the region. The software allowed stakeholders and local residents to apply different park management scenarios to the simulation, such as fencing (location, length, material) and boat mooring regulations (distance from shore, restricted number of vessels). The participants were then able to virtually ’walk’ around the area from a first-person point of view using the arrow keys on a keyboard, to preview what sort of impact the different park management scenarios would entail on the area. With this capability the users were able to determine which management plan they believed to be most appropriate to enforce, as the amount of realism within the geovisualization contributed to their sense of place and understanding of the environment (Newell et al., 2017a).

3.4.3 Involve

The Involve theme of the CVAP cube encompasses visualizations that were all used for decision-making that contained a higher amount of potential risk to property, infrastructure, or human health/lives. This includes the Community Adaptation Viewer (Lieske et al., 2014), a spatial decision support system intended to implement pro-active community adaptation strategies for both home-owners and renters, in order to reduce their vulnerability to tidal forces. There was minimal interactivity present within the product; therefore, it falls within the Communicate end of the spectrum. This visualization was successful at both engaging the community and also communicating to the residents their personal level of susceptibility to the risk of local dyke failure, and the influence of climate change on the frequency and severity of storms. Another example of community involvement was exhibited within the Kimberley Climate Adaptation Project (KCAP), an initiative which focused on community adaptation to climate change impact at the local level (Schroth et al., 2015). The authors found that in certain cases, ’traditional’ methods of presentation (such as posters, and over-head slideshows) were successful at communicating a message in real-world settings such as an open house or in order to reach less technologically advanced individuals and stakeholders. Increased interactivity leads to visualization that can serve as a tool for data exploration such as ViewExposed (Opach & Rød, 2013). ViewExposed was developed as a means to involve local authorities with planning a response to natural disasters caused by climate change, by identifying the most vulnerable regions. A usability evaluation indicated that users of ViewExposed considered it to be a valuable tool for collecting and viewing complex data sets and would prefer to have even more interactivity functions available with the data, such as the capability to upload personal databases (e.g. natural hazards data).

Two more visualizations located in the Involve-Explore region are both related to sea level rise. One of these was developed by (Stephens et al., 2015), whom evaluated the effectiveness of the communicative ability of an interactive sea-level rise viewer designed to allow coastal resource managers to support their decision-making process regarding ecological changes such as marsh migration, infrastructure addition, and general communication regarding the dynamics of sea level rise. Participants responded positively to the ease of use of the application, and all were able to complete the specified tasks as well as correctly respond to the questions posed during the evaluation. Some participants found that the ability to select and view multiple data layers at the same time was difficult to understand, which implies that increased interactivity does not always correlate with improved tool performance.

Another sea level rise geovisualization was studied by Leskens et al. (2017), who compared two versions of a tool intended to demonstrate the risk of coastal flooding in urban regions, which are, a two-dimensional and a three-dimensional versions of the same visualization. Since the 3D rendering of the visualization contained an increased amount of realism with regards to the two-dimensional version, that product was placed within the Partnering theme of the framework while the 2D version is situated within the Involve theme. A user study conducted with non-domain experts indicated that participant's sentiments were split half and half between the 2D and 3D versions of the tool for the purpose of estimating whether an evacuation order is necessary for a region when presented with appropriate data. Due to the complexity of information being presented, the flood risk visualizations are placed closer towards the Exploration end of the spectrum in the CVAP cube. A case study was conducted with practitioners and flood model experts to assess the level of product accessibility amongst an expert crowd. In this case, the 3D version was considered beneficial over its 2D alternative for several reasons including better inundation estimates, which ultimately leads to improved decision-making during a time of crisis. With the 3D version, participants of this session were also able to propose various adaptation measures for different stakeholder groups to mitigate disaster impacts. This indicates that both dimensionalities of the product were successful at visually communicating coastal flood risks to the user, however the 3D was more effective with experts due to the complexity of information and the increased level of realism allowing for greater data exploration capabilities. This allowed different stakeholders (i.e. provincial and municipal governments, companies, residents) to form a partnering relationship and work together to insure community resilience in the wake of climate change.

3.4.4 Partner

Partnering tools include realistic visualizations with a high level of inherent risk present in the decision-making process. Visualizations intended for communicative purposes (less interaction available to the user) include the Local Climate Change Visioning Project (LCCVP) (Shaw et al., 2009) and VisAdapt (Bohman et al., 2015). As stated by Bohman, VisAdapt had significantly less interactivity present (when compared to its counterpart ViewExposed) and was better employed for presenting already known information. VisAdapt can also be used by private property owners to determine strategies for rendering their residence more resilient against climatic exposure, thus making them partners with other stakeholder and community leaders. This is similar to what was observed within the LCCVP, where a participatory approach with a coastal community focused on increasing community resilience with regards to rising sea levels and the risk to their property. This type of visualization was successful in creating a partner-like relationship between decision-makers and stakeholders.

Visualizations with increased interactivity are intended for partnering feature more exploratory capabilities. These can be useful in situations where the answer to a particular problem may have multiple possible solutions, and those solutions are not easily apparent and require discussion to reach an appropriate consensus. Examples of such visualizations include a Mobile Augmented Reality (MAR) tool for flood visualization (Haynes et al., 2018), a 3D coastal flooding risk tool (Leskens et al., 2017), and a virtual globe tool implemented for KCAP (Schroth et al., 2015). The MAR tool was intended as a supplementary application to existing flood risk management tools, in order to aid the comprehension of inundation maps by industry experts. The results indicated that the participants found the application mostly easy to understand and rated it as useful for emergency services. Such a tool could be passed onto local community leaders for the purposes of community resilience, thus positioning them as partners with larger governmental sectors in charge of resource distribution and planning. The 3D version of the urban flooding visualization (Leskens et al., 2017) was preferred by the majority of participants as best suited for estimating the damage to houses, and as the most suited tool for estimating life loss. Similar to the previous example, this type of visualization would be appropriate for local community adaptation planning, and to form a partnering relationship between stakeholders at both smaller and larger scales. This would facilitate rapid communication and sensible resource dispersal, ensuring that the regions and people in need of the most assistance would receive it first.

The virtual globe geovisualization presented in the KCAP (Schroth et al., 2015) was intended to effectively increase awareness and the understanding of the risks and impacts of effects brought on by climate change. It was interesting to discover that this format, which provided the highest degree of user interactivity and realism (evaluated within Schroth et al.'s study), was deemed as an ineffective and an unreliable source of information by some participants of the study. This could have been caused in part by pre-dispositioned attitudes of certain participants, lack of technological ability, or perhaps a shortcoming in the presentation format itself as technical glitches were reported during the demonstration process. However, this again draws attention to the fact that creating an effective geovisualization product does not directly imply generating the highest amount of interactivity and realism present within the product, rather this should be decided on by a case-by-case situational basis.

4. Discussion

This study sought an in-depth understanding of the current state of effective geovisualization approaches in order to advance research in this area and assist practitioners in harnessing technological opportunities. The CVAP framework that was developed during this project can catalyze further research and practices for effectively developing and using platforms for academic, stakeholder, and practitioner groups to communicate, interact, and engage with spatial data. The research is built upon the Map Use Cube (Maceachren & Kraak, 1997), among other work, in order to update the original framework for modern technologies. With this modernized framework, researchers and practitioners can understand the preferred methods of visual communication for different user groups and/or the intentions for a specific purpose or circumstance.

4.1 Challenges and Opportunities Around Classifying Geovisualizations

It is necessary to acknowledge a specific difference between interactive and immersive visualization. Certain differences in the visualizations proved to be difficult to discern since the formation of the CVAP was a qualitative process. Such issues were observed when classifying the WorldView product (Johansson et al., 2010), which is an immersive dome-shaped chamber environment with realistic qualities. This geovisualization took participants on a journey showing them local and global effects of climate change; however, in CVAP, this product was ranked as having lower interactivity. This is because even though the participants were provided with a realistic geovisualization that gave a 360˚ view of the landscape, there was little to no user interaction with the data, such as selecting custom data layers or the availability of zoom and pan functionality. This sort of difference between immersive and interactive geovisualization needs to be further researched, in order to attain a better understanding regarding the benefits of these types of geovisualizations. Another notable discrepancy between the geovisualizations included in the CVAP framework was exhibited in the product analyzed by Tress & Tress (2003). The authors created highly realistic, but static, imagery of the Danish countryside using Adobe Photoshop. This was a visualization which at the time of its release, was at the forefront of what is possible to achieve via a computer-simulated image. However, if this research had been performed in more recent years, one can assume that the visualization product would have been a more advanced and interactive tool simply due to the amelioration of and ease of access to visualization technology and software.

The CVAP framework was created with the intentions of formulating a comprehensive understanding about both the current state and the (relatively recent) history of geovisualization use for climate change adaptation. The purpose of this process was to create a framework that organizes existing geovisualizations into clusters and themes that describe the intentions that the particular visualization product was successful at achieving and the most suited audience for those specifics of the visualization. Accordingly, CVAP can be used to guide the development of new geovisualization products by determining an appropriate type of visualization to use within specific circumstances. Decisions regarding the amount of realism or interactivity presented to the user of a particular geovisualization, are able to be resolved with increased confidence after using CVAP to justify the decision.

A pattern that emerged during the formation of the CVAP relates to the level of inherent skill or previous domain knowledge present amongst the user group when evaluating a geovisualization. Visualizations with higher levels of interactivity were favoured among more expert user groups due to the geovisualization's capabilities to act as tools for knowledge discovery. This describes situations where the potential solution to a problem was not immediately apparent and required new perspectives on data analysis in order to reach a conclusion. This is contrary to the visualizations which are intended for communicating a predefined or an already known message to a user group, as those products often had a low level of interactivity associated with their use.

4.2 Potential Framework Use

A workflow which implements CVAP resembles a three-step pipeline. This process can be described with the following use case: an organization is faced with a decision that is impacted via climatic variation, such as coastal flooding from sea level rise and changing precipitation patterns (e.g., Leskens et al., 2017). Using a geovisualization to communicate the information is considered to be a conceivable option; however, there is uncertainty regarding what form of visualization would best be suited for the intended purpose (i.e., disaster mitigation) and audience (i.e., policy analysts). The organization consults the CVAP framework to affirm the most appropriate form of geovisualization. Step 1 consists of determining the intended outcome of the geovisualization with regards to the audience (i.e. to inform, consult, involve, or partner with the user group). Then, it is necessary to decide whether the tool in question is intended to communicate already known facts, or if it is to be used for new knowledge discovery (Step 2). This can be partially influenced by considering the expertise level of the intended user group, as exploratory products (highly interactive geovisualizations) were often preferred by more advanced users. Finally, Step 3 involves commissioning a team of developers and analysts to create a product based on the insights derived from applying CVAP.

The CVAP will further guide visual product development because this framework determines what qualities of a geovisualization were preferred in a specific circumstance, and towards which audience. Different versions of the same geovisualization product could be developed based on the target audience (layperson or expert) or intended purpose (communicate known message or knowledge discovery), thus ensuring that each user group is able to extract the most amount of information and ultimately attain a level of better judgement when considering the effects of climate change on their personal business, well-being, and interests. Most importantly, the CVAP serves as a tool to guide the decision-making process regarding whether a geovisualization will be an effective medium based on specific qualities of the intended task, as per research regarding effective ways of communicating data through a visual tool.

4.3 Conclusions and Future Work

Geovisualizations have demonstrated potential as tools for communicating complex scientific data on climate change to a wide audience with different levels of expertise in the subject at focus. However, albeit promising, there are still challenges that remain in applying research to real-world settings. There is a tremendous breadth in the diversity of geovisualization tools and the audiences that they are designed for; therefore, it is often possible to encounter contradicting conclusions regarding what makes for useful climate planning and engagement tools. This research addresses the gap in geovisualization knowledge and understanding by creating a conceptual framework that classifies geovisualization products into groups or themes, which best represent the aspects of the visualization medium. The CVAP framework can be used as a decision tree system for determining which form of geovisualization is most appropriate in a specific situation and for which audience.

The CVAP is also relevant within research fields which may not be directly related to climate adaptation, planning, and community engagement. For further study, it is recommended to test the use of CVAP within alternate sectors in order to determine whether it is appropriate to implement within different circumstances. These fields include areas such as nuclear disaster evacuation (Tsai et al., 2012), urban flood evacuation (Bodoque, Díez-Herrero, Amerigo, García, & Olcina, 2019), Indigenous knowledge mapping (Smith, Ibáñez, & Herrera, 2017), urban development (Lewis et al., 2012), arctic shipping sector (Hong, Bae, & Yang, 2018), resource management (Goode, 2016), and recreational tourism (Tress & Tress, 2003). Even though the CVAP framework has demonstrated its potential within the climate adaptation and community engagement fields, more usability evaluations are still required in order to attain a complete understanding of effective visual communication strategies and their intended audiences.

Chapter 3

Creating Geovisualizations: An Analysis on the Process of Geovisualization Development and Suggested Best Practices

1. Introduction

Developing and implementing web-based geovisualization software tools for presenting climate data provides the potential to effectively communicate spatial information to diverse audiences, including industry experts, various stakeholders, and policy-makers. A well-designed web service can increase usability and overall functionality (Wang & Senecal, 2008). Additionally, research suggests that visual forms of data representation are especially effective in memory uptake when compared to text-based presentations (Dwyer, Hogan, & Stewart, 2010), further underlining the importance of presenting climate data visually. Furthermore, creating geovisualization products in a web application format is convenient for disseminating research results or promoting a message to a greater audience. When compared to physical, hardcopy publications, the web application method allows for up-to-date information retrieval and refresh capabilities. This format also permits the geovisualizations to be interactive for the user, and maintainable for the developers.

There exists a plethora of unique tools, frameworks, and libraries for web application development. The various methods for web development often provide both benefits as well as challenges, the latter including operational costs, necessary technical skill, data storage limitations, performance, and functionality. Even though general website design and software development processes have both been formally analyzed in academia (Beaird, Walker, & George, 2020; Kelo, 2017; Yahaya, Ibrahim, & Deraman, 2017), there has not been enough research invested into applying these best practices, protocols, and guidelines during the development process of web-based geovisualization tools and mapping software. Al-Hawari, Al-Zu’bi, Barham, & Sararhah (2021), introduce a website development process, with a focus on the best practices to design and develop a high quality website. This six phase process is proposed based on a literature review of previously suggested website development processes, and is implemented in context of the development of a university website. This research repurposes the proposed web development process in the context of a web-based geovisualization application development.

The main purpose of this thesis chapter is to analyze the process of developing geovisualization software tools in the context of climate change according to the best practices for web development, and to identify the challenges and opportunities encountered while adhering to these protocols and guidelines. This goal is achieved through a multipart analysis which is based on the Climate Visualizations for Adaptation Products (CVAP) framework, discussed in an earlier part of this thesis. This chapter also includes a case study on the design, development, and future deployment of the Seasonal Sea Ice Coverage (SSIC), an interactive web-based mapping application designed for viewing seasonal Arctic sea ice extent. The remainder of this chapter is structured as follows: Section 2 analyzes the design and development process of the SSIC application against the six phases of website development best practices introduced by (Al-Hawari et al., 2021). In section 3, this website development process is referenced in context of different types of geovisualizations as described in the CVAP framework, in order to understand where we may encounter certain barriers and opportunities during the development of geovisualizations. Section 4 suggests a novel usability evaluation that combines aspects of a user evaluation and a conceptual framework for enhancing the user's attitude towards the website or service. Finally, a summary with conclusions and suggestions for future research are provided in section 5.

2. Geovisualization Development Case Study

2.1 Seasonal Sea Ice Cover Application

The Seasonal Sea Ice Coverage (SSIC) application is a web-based interactive mapping service (Figure 4), intended for viewing the seasonal forecast of sea ice cover extent in the Northern hemisphere. The application displays sea ice probability data for seasons ranging from 2000 to 2019, with four different ice concentration thresholds available for each season (Dirkson & Merryfield, 2020). The SIP quantifies the probability that forecast sea ice concentration (SIC) will be larger than a particular threshold. The forecasts are initialized on the 1st of May, and demonstrate the expected ice conditions for September of the respective season. Even though the 15% SIC threshold is most commonly implemented to estimate the sea ice edge when using passive microwave satellites, the remaining SIC thresholds may be relevant for other users (Dirkson, Merryfield, & Monahan, 2019).

The application is developed using the JavaScript programming language with the React library. The data is supplied as a NetCDF (network Common Data Form) file and the pre-processing is accomplished with the SNAP Graph Processing Tool (GPT), as well as the netCDF4 interface and the Pillow (PIL) imaging library for Python. Base-maps for the application are provided by OpenStreetMap, using the Leaflet JavaScript library. Package management is handled via the Node Package Manager (npm) and the source code for the application is available on GitHub.

Functions that are available to the user include the capability to select available seasonal ice probability forecasts, and choose from four ice concentration thresholds. This is useful for determining the probability of a specific marine area located in the Northern hemisphere to contain a concentration of ice above the specified threshold. The probability of sea ice is a value between 0.0 and 1.0, and is categorized into five classes represented on the map using the colours blue (0.0<b<=0.2), yellow (0.2<y<=0.4), orange (0.4<o<=0.8), red (0.8<r<1.0) and black (1.0). The absence of sea ice, indicated by a value of 0.0 is intentionally left transparent.

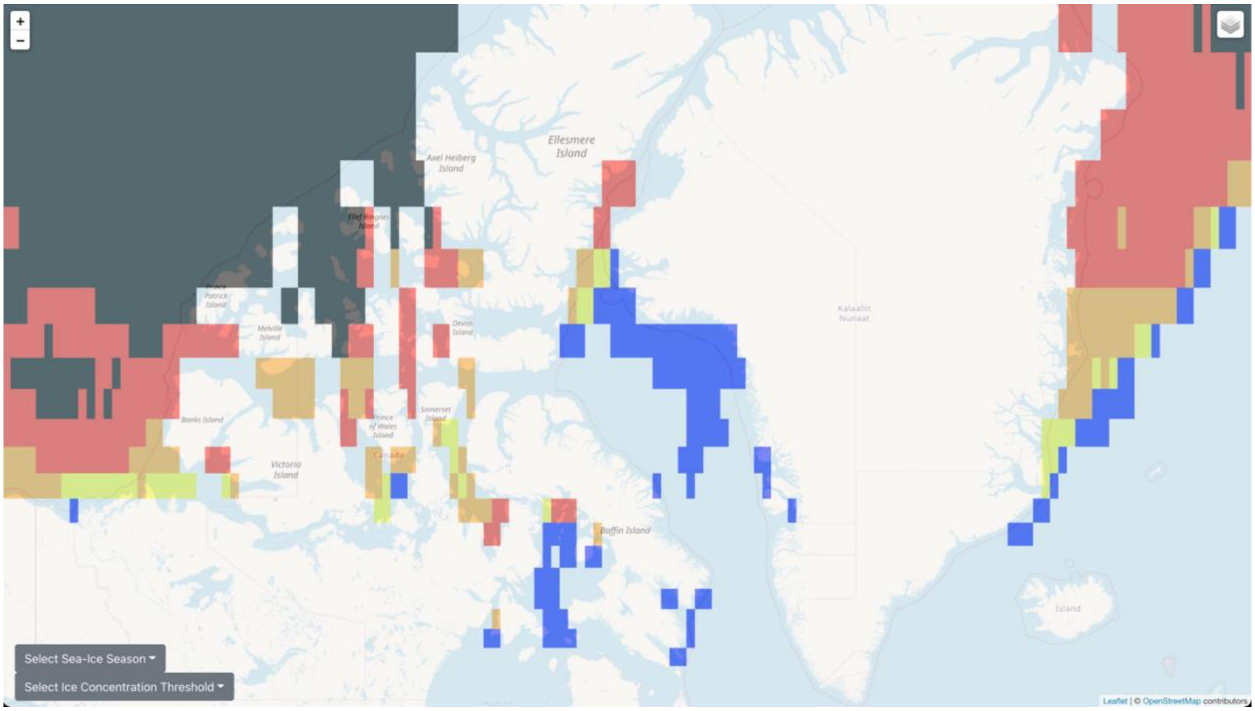


Figure 4. Seasonal Sea Ice Coverage application home page.

2.2 Website Development Best Practices

Al-Hawari et al. (2021) conducted a holistic literature review of the website development process, and have proposed a version of website development and best practices to adhere to during the development process. Their website development process comprises six phases (Figure 5): 1) Requirements phase, 2) Content phase, 3) Design phase, 4) Development phase, 5) Launch phase, and 6) the Maintenance phase. These best practices were applied in the context of development of a university website, indented to be the first point of contact for stakeholders of the German Jordanian University (GJU).

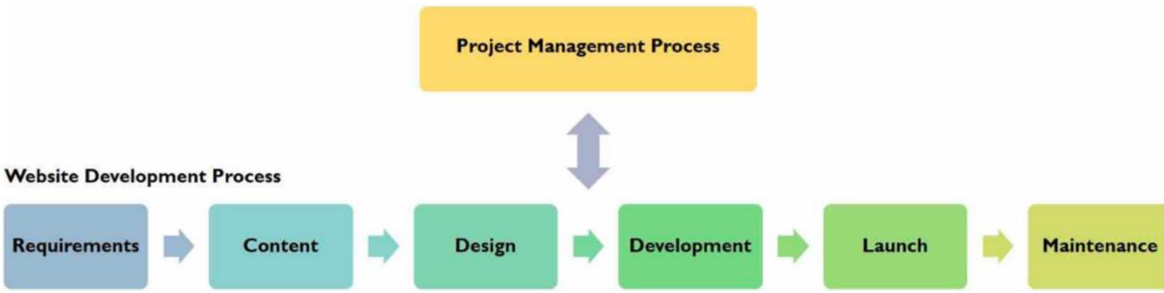


Figure 5. Six phases of web development process (after Al-Hawari et al 2021).

The suggested best practices are relevant in the topic of geovisualization software development because general websites and web-based mapping tools share several principles that render them as high quality interfaces. A website's quality, as in all information systems, is important for an organisation and for the satisfaction of the organisation's clients (Rocha, 2012). This directly applies to mapping software, especially web-based, as a high-quality interface is both in the map creator's and user's common interests. Furthermore, a website is distinguished from a web portal when the focus is on content, a user login is not required, and a visitor is not able to edit the presented content (Al-Hawari et al., 2021). Which is similar to the functionality that is expected from a web-based mapping service because the focus of the application is on the available layers (content), anyone can view the map (no user login required), and visitors cannot make changes to the hosted layers. It is also necessary to note that not all mapping services share the same principles of open access, as certain web-based mapping applications are embedded within a data portal like The Wildlife Crossing Database Platform (WCDP) (Newell, Lister, & Dale, 2020). This is an online tool that can be used to upload, access, and explore data on wildlife crossings in North America. At the time of writing, the WCDP is only accessible to registered users however, there are intentions to allow for some public access in future iterations of the product. This is an important distinction to make during the planning and development processes because websites and mapping tools can greatly vary, and therefore the goals and requirements should be assessed on a case by case basis.

2.2.1 Requirements

The first phase of the best practices for web development is requirements, which is intended for establishing the website objectives, audience, content, available services and features. In the case of the GJU website development, the gathering of this information was achieved by forming a website committee, comprised of representatives from the related institutions and led by the IT director. This committee's main responsibilities include the specification, prioritization, and the approval of the website requirements. After the final determination of requirements is completed, these requisites were consecutively passed onto a software development team that proceeded with the remaining development phases. Such a scenario, as mentioned before, is a suggested best practice and is only feasible when there is a larger research team available.

Often the requirements phase can also be the responsibility of the development team, similar to the situation during the SSIC application development. The main requirement for the application was to meaningfully present sea ice data in a web-based format that could allow for the planning of bulk carrier ship scheduling through the North-West passage in the Canadian Arctic archipelago. This allowed for technical decisions to be made based on the most suitable technologies and frameworks available for the task, since there were no specific limitations or conditions to adhere to.

A decision was made to use open-source software in as much of the software stack as possible. This is to decrease any associated costs with the licensing fees or potential API requests, and to set the project up for easier maintainability if the project is to be adopted by another organization or community. Therefore, the SSIC web application is setup using the Create React App project, and the Leaflet JavaScript library for building and interactive map using base maps provided by OpenStreetMap; all of which are open-source projects. The source code for the web application as well as the data processing scripts are freely available on GitHub.

2.2.2 Content

The content phase of website development best practices is now handled by the development team after receiving the sufficient requirement documents. The main intention of the content phase is defining the structure of the interface, and ensuring that all content can be accessed using the least clicks possible. Al-Hawari et al.(2021) stress the importance of content and describe it as the essence of the website. The paper goes on to say that based on that notion, the whole website should be structured around the content that is being presented, and not the other way around.

The SSIC application is centered on presenting the seasonal ice cover probability in the Canadian Arctic, therefore the focus of the content phase is selecting the sea ice probability season and the associated ice concentration threshold using the least number of clicks. The sea ice probability layer quantifies the likeliness that the forecasted sea ice concentration will be larger than a particular threshold (i.e. 15%, 50%, 75%, 90%). Accordingly, the map and selected layer are always visible on the web page, with layer selection achieved in two or four clicks, for choosing a season and an ice concentration threshold respectively. There are two button dropdown menus located in the bottom left corner, one for the selections of available seasons and the other for choosing the ice concentration threshold (Figure 6).

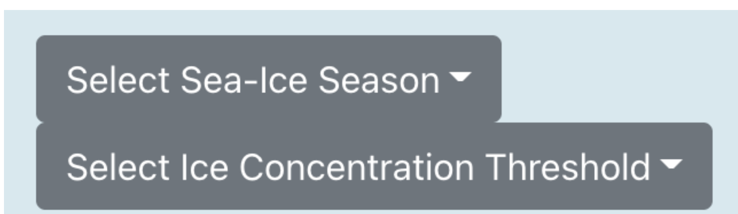


Figure 6. Button dropdown menus for season and threshold selection.

The data that has so far been incorporated into the SSIC application, consists of the Sea Ice Probability (SIP) layer that quantifies the probability that the sea ice concentration in a particular region will be larger than the selected threshold. The available threshold concentrations are 0.15, 0.5, 0.75, and 0.9 (Figure 7). The 0.15 threshold is typically viewed as the industry standard; however, including the other concentration thresholds in the original file provides more flexibility to the user, depending on the vessel classification in question.

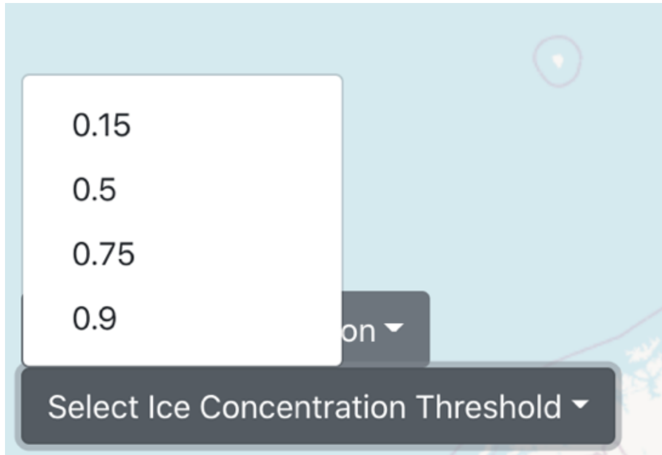


Figure 7. Available ice concentration thresholds.

The data were provided as a netCDF file (Dirkson & Merryfield, 2020), which was rasterized into PNG format in order to be displayed in the web-browser. A Python script using the NetCDF4 and PIL libraries for reading the netCDF file and creating a PNG file respectively, was written to produce the desired output files with unique names for display in the browser. In order to achieve accurate alignment between the basemap and the produced PNG files, the netCDF file was put through a mosaic step in order to remove polar coordinate values and then reprojected into a web browser friendly format using the ESA Snap GPT tool. This step was necessary because the netCDF data were provided with latitude and longitude coordinates (EPSG: 4326), and the OpenStreetMap tiles are provided in the Pseudo-Mercator (EPSG: 3857) projected coordinate system. The EPSG: 3857 projected coordinate system is not valid for coordinates above 85.06°N, therefore any values considered invalid were removed during the mosaic step (Figure 8).

```xml
<graph id="mosaic">
<version>1.0</version>
 <node id="mosaic">
 <operator>Mosaic</operator>
   <sources>⋯
   </sources>
   <parameters>
    <variables>⋯
    </variables>
    <orthorectify>false</orthorectify>
    <elevationModelName>ACE2_5Min</elevationModelName>
    <resampling>Nearest</resampling>
    <westBound>-180.0</westBound>
    <northBound>85.06</northBound>
    <eastBound>180.0</eastBound>
    <southBound>40.5</southBound>
   </parameters>
 </node>
</graph>
```

Figure 8. Mosaic step graph file.

2.2.3 Design

The design phase is necessary for ensuring proper website functionality, usability, and responsiveness. This phase is also emphasized as one that requires extra consideration, since a poor design can drive visitors away despite having a high quality of content (Al-Hawari et al., 2021). Some major design concerns are related to templates, usability, functionality, and responsiveness. Mock-ups were created using the Lucidchart wireframe maker and then transposed into ArcGIS Web AppBuilder in order to be able to quickly demonstrate basic map functionality. This phase in the web development process was important to ensuring a well-planned out user interface.

The available functionality is useful for determining the probability of a specific marine area located in the Northern hemisphere, to contain a concentration of ice above the specified threshold. Depending on the class of vessel, or its ice breaking capabilities, different users or organizations can alter routes or plan travel accordingly. This may also help users on the other end of the spectrum, which may rely on a solid ice cover for travel and/or hunting. There is also a potential for using this functionality in an ecological research setting. For example, the analysis of wildlife migration patterns in species such as the polar bear *(Ursus maritimus)*, which are affected by either the presence or absence of sea ice in Arctic regions (Cherry, Derocher, Thiemann, & Lunn, 2013).

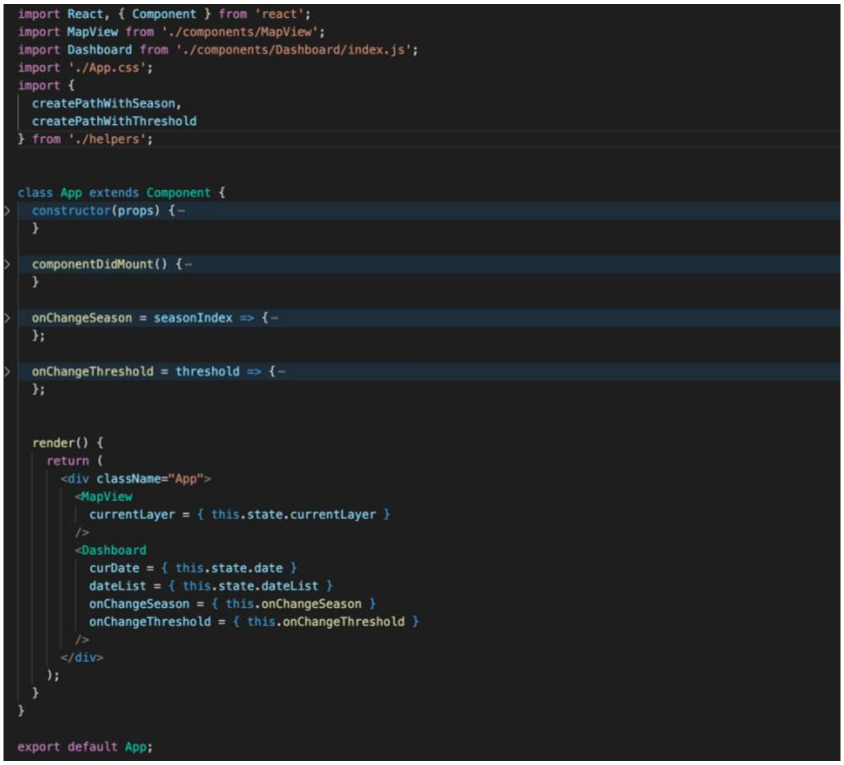
2.2.4 Development

The development phase of an online application can be referred to as the meat and potatoes of the initiative, as during this step all the previous ideas, decisions, and visions are brought to life in the form of a usable deliverable. This section encompasses aspects such as the framework used for developing the product, the implementation details (cascaded style sheets (CSS), templates, plugins, scripts), and the content available on the page. The GJU website was developed using the Drupal Content Management System (CMS), which is praised by Al-Hawari et al. (2021) for its flexibility, performance, security, and for the large developer community actively working on the project. Using the Drupal CMS program has also been found favourable for the development of a website for housing, embedding, and displaying a geovisualization (Newell et al., 2020). Therefore, using a CMS should be given further consideration for future geovisualization projects.

Driven by the objective of accessing the sea ice probability data with the fewest possible clicks, the design of the SSIC application is kept as simple as possible with the map view always visible in the background and the seasons and threshold selectors in the bottom left-hand corner. Unlike the intricate structure of a university website, the SSIC application has no need for re-directing the user or switching between pages and functions. Therefore, the application is developed as a Single Page Application (SPA), where a user interacts with the application with new data fetched from the server, rather than reloading new webpages when a new request is made.

An in-depth comparison of three popular SPA frameworks (AngularJS, React, and Angular 2) revealed many similarities, concluding that it is in fact difficult to differentiate between the frameworks (Molin, 2016). Molin suggested AngularJS as the most suitable framework due to its highest level of popularity (most watchers on GitHub, most questions tagged on StackOverflow, and most searches on Google) and its stability. However, it is also noted that this may be due to the fact that AngularJS was the oldest framework of the three SPA frameworks analyzed.

For the development of the SSIC application, React was chosen as the development framework for several reasons, including the presence of previous development experience with this particular framework. React is a framework originally developed by Jordan Walke, an engineer at Facebook Inc., and was released as open source in 2013 (Andrea Papp, 2018). This framework is actively maintained by a large corporation, therefore it is reasonable to assume that this particular framework may have a long life span and up to date security and bug fixes. Furthermore, the React framework is based on the methodology of Component Based Development (CBD), which entails several benefits such as better code maintainability, scalability, reliability, and usability (Krznar & Svogor, 2016). The focus of CBD is to use small and manageable software elements in order to simplify the software design. This is demonstrated in the SSIC application code by the breakdown of functionality into smaller components (Figure 9) which communicate information using props (properties) to set the state of the components (i.e. displayed layer).



```
import React, { Component } from 'react';
import MapView from './components/MapView';
import Dashboard from './components/Dashboard/index.js';
import './App.css';
import {
  createPathWithSeason,
  createPathWithThreshold
} from './helpers';

class App extends Component {
  constructor(props) {-
  }

  componentDidMount() {-
  }

  onChangeSeason = seasonIndex => {-
  };

  onChangeThreshold = threshold => {-
  };

  render() {
    return (
      <div className="App">
        <MapView
          currentLayer = { this.state.currentLayer }
        />
        <Dashboard
          curDate = { this.state.date }
          dateList = { this.state.dateList }
          onChangeSeason = { this.onChangeSeason }
          onChangeThreshold = { this.onChangeThreshold }
        />
      </div>
    );
  }
}

export default App;
```

Figure 9. App.js file with MapView and Dashboard component imports.

2.2.5 Launch

The launch and maintenance phases are out of the scope of this study, and thus, this project describes them in terms of how they would hypothetically proceed. The launch phase handles concerns such as website testing, security, user accounts, training, documentation, and deployment. These are important aspects to consider when launching a website to ensure the operational quality of the service once exposed to regular network traffic. Not all of the aforementioned criteria need to be accounted for during the launch phase of the SSIC application. There are no-user accounts or permissions involved in this service and no sensitive information is stored, therefore the user accounts and security aspects are not applicable. However, further quality assurance testing is required to ensure consistency and standardization across different web browsers and screen sizes.

Detailed documentation is an integral part of a successful software project, especially an open-sourced project which relies on the notion of different contributors to remain functioning and bug free. The current state of the SSIC documentation contains the necessary command line statements to perform the netCDF data processing steps, and to run the application locally using the Node Package Manager. Creating a static asset of a production build of the application, is achieved with the NPM command `run build`. This artefact can then be deployed on a server and accessible via a registered domain name. The SSIC application is intended for deployment on the SURREAL web-server part of the Arbutus Cloud hosted by Compute Canada located at the University of Victoria.

2.2.6 Maintenance

The maintenance phase contains the post-launch elements such as quality assurance, application updates, administration, and training. More quality assurance testing is required after deployment as new unexpected errors or behaviours may arise in the program, data layers may become corrupt or un-readable, as well as a myriad of other problematic behaviours that need to be accounted for with testing and validation.

A goal of the project is to remain operational for a long time; therefore, a developer community and active contributors are essential. Using open-source software increases the chances of this happening. However, since the SSIC application is expected to be deployed on Compute Canada infrastructure, the issue of administration becomes apparent. One possible solution is to have a site administrator or manager with access credentials to the SURREAL server, review pull requests and push the accepted commits from an open GitHub repository on a scheduled basis. This way the project may continue to operate while limiting public access to the server.

3. CVAP Framework & Geovisualization Development

3.1 Web Development Best Practices with CVAP

The Climate Visualizations for Adaptation Products (CVAP) framework (Figure 10) is a tool for researchers and practitioners to use as a decision tree or a decision support system in order to discern the type of geovisualization product that is most appropriate to implement within a specific use case or audiences. The following section discusses the website development process in reference to the different types of geovisualizations, as described in the CVAP framework.

In order to understand where one may encounter certain barriers and opportunities of adhering to the best practices of web development, during the development of varying geovisualizations as described by the CVAP framework, it is necessary to outline which areas of the cube may result in the largest differences from the development of the SSIC application.

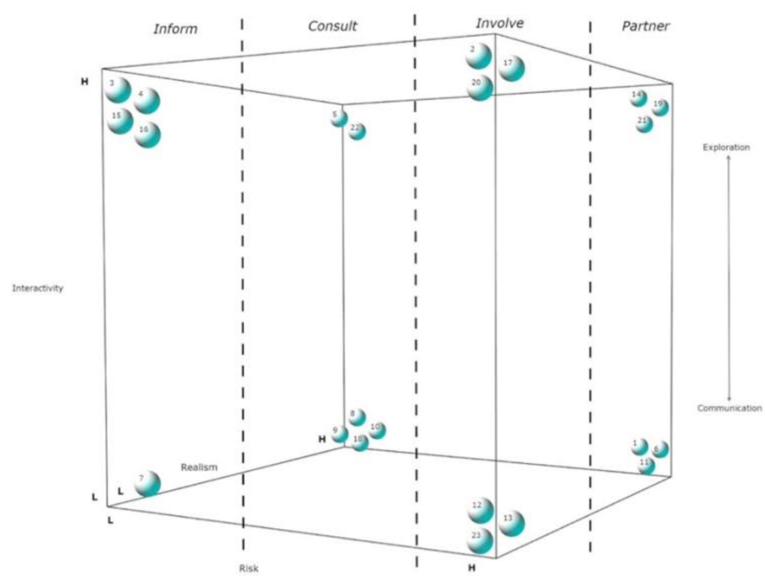


Figure 10. Climate Visualizations for Adaptation Products (CVAP) framework.

3.2 Requirements & Content

The requirements and content phases are preliminary planning phases that can be grouped into a single category, since this involves brainstorming and critical thinking. Establishing the requirements for a geovisualization enables the development team to focus on specific features and limit the scope of the application or product. This is critical because given certain project limitations (such as hardware limitations, deadlines, resources, etc.), it is important to identify the necessary functions and differentiate these from the auxiliary (nice-to-have) features. This principle of necessary planning and careful considerations may be implemented in almost all types of software development projects.

Determining the content of a geovisualization dictates the entire purpose and the message communicated by the application. The data that are rendered through a particular visualization are undoubtably the most important aspect of the product, since this is a tool designed for presenting spatial data visually. Even though there may be certain similarities observed between geovisualizations, this process is not guaranteed to remain constant across the development process of a variety of different types of geovisualizations as described in CVAP. Examples of this can be observed with the Sidney Spit Visualization (Newell et al., 2017a) and a crop land suitability projection tool (Bishop et al., 2013). Both the geovisualizations are classified as a part of the consult theme of the CVAP framework, with the Sidney Spit Visualization being assessed a higher level of interactivity available to the user. Even though these two visualizations are related with their assigned theme, the content is substantially different. The Sidney Spit Visualization focuses on realism through the use of sounds, surface textures, and other real-life details (signage, boat moorage, fencing) to imitate the study site through a first-person perspective, and allowing the user to navigate the area using arrow keys. This tool is intended for public consultation of future park management policies, and the content consists of real-life detailed visualization to re-create the regions. On the other hand, the land suitability analysis tool's content is focused around larger scale phenomena such as temperature and precipitation maps for agricultural purposes in Southern Australia. This indicates that even similarly classified geovisualizations are shaped by their content, which exhibits the main purpose or goal of the specific geovisualization tool. Divergent content will often be observed in geovisulization tools intended for different purposes as seen in CVAP, and may be further exacerbated when comparing geovisualizations that are classified in other themes.

3.3 Design & Development

The design and development phases are correlated because the development process is impacted by the decisions made in the design phase. This implies, that since the different types of geovisualizations differ so much in their appearance and functionality, they will require entirely different software stacks and development frameworks or technologies to achieve their intended goals.

This is exhibited when comparing geovisualizations in the inform and partner themes of the CVAP framework. The visualizations intended for partnering are often more interactive, realistic, and may have a more significant amount of risk associated with the decision outcome resulting from the use of the particular geovisualization. This creates extra challenges for the research and development teams, especially when there is greater amount of risk associated with a decision concluded from the use of the geovisualization software. This requires extra verification and quality assurance measures in order to ensure the validity of the results and content presented. Furthermore, highly immersive realistic visualizations (i.e., 3D visualizations, augmented reality, virtual reality) require a different set of programming and digital modelling capacities to create and illustrate the objects and environments, which may lead to higher operational costs during deployment due to increased processing and memory requirements.

Geovisualizations with lighter requirements, like static or non-realistic maps, are often associated with the inform theme. This contains products that may present an either static or interactive 2D map, similar to the SSIC application. An opportunity to progress research and data visualization is by providing a medium for researchers who typically do not work in the fields of GIS and mapping to present their findings visually. It may be possible that some projects have omitted creating a map with their data, if it required extra resources or time in order to create an effective visual. Therefore, providing easy to use templates could facilitate this process if a user can substitute their data to present in a web browser format. With easy access to geovisualization templates, developers can spend less time with set-up and backend issues, and may instead focus on new functionality, increasing content, and improving the general experience for the user of the service.

Certain organizations offer quick web mapping solutions and deployment; however, many users may be deterred by the licensing fees associated with the provided services. This opportunity to promote and contribute to cartography as a whole can be achieved through open source mapping solutions. This underlines the importance of creating projects like the SSIC application, and continuing to build and promote using open sourced mapping solutions to maximize stakeholder inclusion.

3.4 Launch & Maintenance

The launch and maintenance steps of geovisualization development can both be considerably simplified by using a proprietary software stack since testing, security, documentation, deployment, and updates are can be handled by the proprietor of the service. This scenario can be favourable in certain situations, like perhaps a local government or community which seeks to consult or involve the residents through the means of the geovisualization. Depending on the theme or outcome of the geovisualization (as described in CVAP), the organization is able to present spatial data without a development team or expert responsible for the project. This may be a barrier for geovisualization development due to the increased operational costs, but may serve as a benefit in the long run since the infrastructure is assured to operate as expected.

3.5 Seasonal Sea Ice Coverage and CVAP

Based on the current state, available content, and functionality of the Seasonal Sea Ice Coverage (SSIC) application, this geovisualization would be classified as a part of the involve theme, closer towards the exploration end of the spectrum. The SSIC application provides the user with interactive capabilities, allowing to use the tool for data exploration capabilities. However, the high amount of abstraction apparent within the tool assigns SSIC with a lower rating of realism. This classification is not set in stone, and with further development of the SSIC project it is likely that the primary engagement theme may change.

With the addition of more data sources and increasing the application's functionality, the realism rating of the tool may be increased thus positioning SSIC as a member of the partner engagement theme. This may be achieved through the addition of a "condition verification" function, that allows recent imagery (such 2D photography or 360^{o} viewing) to be uploaded to the application with a geolocation tag. This imagery would increase the realism rating of the SSIC application, and it may be analyzed by other end users of the product in order to reduce the uncertainty associated with a sea ice conditions, in turn allowing for a partner like relationship as described by CVAP.

4. Novel Geovisualization Usability Evaluation

Even when the best practices are adhered to as much as possible and the potential opportunities during development are realized to their full potential, it is difficult to judge the effectiveness or the impact that a geovisualization may have on the user. Therefore, this thesis proposes a novel user evaluation approach to assess the usability of a mapping service. The approach consists of a general questionnaire or survey, which when combined with a usability framework, can help identify the perceived attitude of a user towards the geovisualization.

4.1 User Survey

Al-Hawari et al. (2021), conducted a user survey with nine Likert-scale questions to evaluate the quality attributes of the GJU website. The responses were then averaged to identify trends in the user impressions. Three out of nine questions used in Al-Hawari et al.'s (2021) questionnaire were included here and adapted to fit the evaluation approach for geovisualizations. The Likert scale was revised in order to simply the evaluation, and the answers would be gathered in a binary, Agree or Disagree method.

4.2 Conceptual Framework

Wang and Senecal (2007) propose a conceptual framework (Figure 11) to assess the general attitude towards a website by determining website usability through using three metrics: Ease-of-navigation, Speed, and Interactivity. Their goal was to develop a short, reliable, and valid perceived website usability measurement, and based on a conducted literature review the framework was created. It is based on the premise that a user should be able to accomplish their desired task with ease, which amplifies the importance of the ability to identify which features of a website render it more useful, and which do not.

This thesis repurposes this framework for developing geovisualizations as described by CVAP by making the following changes. The factor of interactivity was replaced with content, in order to reflect the importance of the map data featured in the geovisualization. Furthermore, this fits well with the web-development best practices as outlined earlier, as the importance of content is described as one of the development phases.

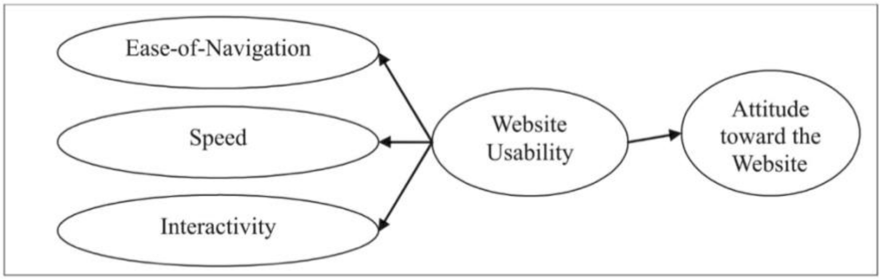


Figure 11. Conceptual framework (after Wang and Senecal 2007).

4.3 Usability Evaluation

The proposed outcome combines aspects of the user survey and the conceptual framework to create a new system that can help determine the user's attitude towards a geovisualization in an efficient manner. As seen in *Figure 12*, the geovisualization is assessed on three metrics, each determined with an Agree or Disagree answer. As per Wang and Senecal (2007), there is a positive correlation between the usability construct and the general attitude towards a geovisualization; therefore, it is reasonable to assume that a geovisualization with high usability will provide for a positive user attitude towards the product.

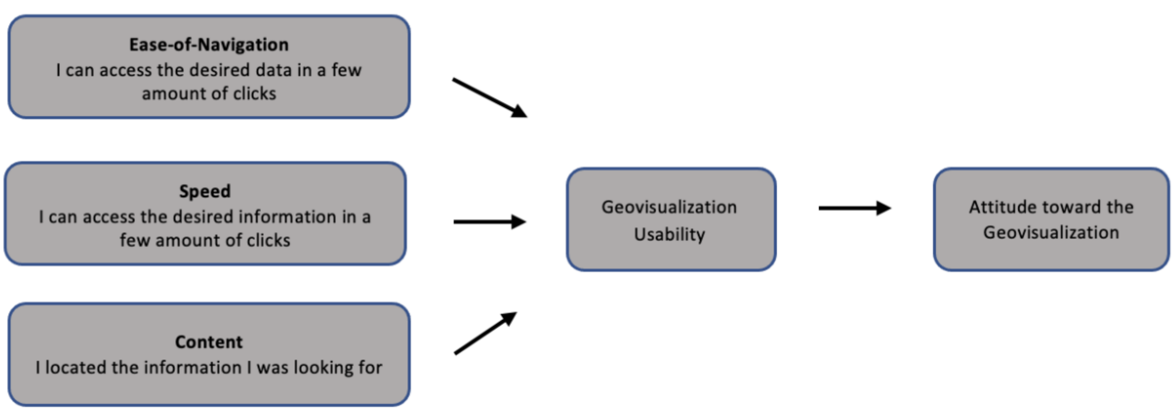


Figure 12. Novel geovisualization usability evaluation.

The metrics and statements are as follows: Ease-of-navigation – I can access the desired data in a few amount of clicks; Speed – The geovisualization navigation is fast; Content – I located the information I was looking for. Once each statement for the metrics has a binary value of 1 for Agree, or 0 for Disagree associated with it, the results are calculated. If the value from the statements is two or less, this implies that the usability is lacking. Depending on which metric did not achieve a score of one, the development team can revisit that aspect of the geovisualization and aim to improve it for the next iteration of the software. If a score of three is achieved during the user evaluation, it is reasonable to assume that a positive user attitude towards the visualization was attained.

4.4 Evaluation Framework Example Implementation

The proposed usability evaluation can be applied in one of the following methods. When implementing the binary evaluation within the context of the SSIC application, the evaluation could be presented to end-users after using the tool for a set amount of time, during which the participants are asked to perform intuitive tasks with the available functionality. These tasks may resemble open ended questions, like asking the users to compare different ice concentration threshold maps between specific seasons. This would stimulate the user to interact with the available data and to use this application for data exploration or new knowledge discovery. The participants would then have the opportunity to indicate their sentiments towards the application by responding to the evaluation questions. This method of evaluation is very generalized, and has an inherent short comings because of the binary nature of response. Participants are not able to indicate the extent to which they agree or disagree with a statement in the evaluation framework, and furthermore, they are not able to indicate a neutral sentiment or explain what specifically caused that attitude towards the service.

This use of this evaluation may be improved by implementing it within more specific aspects of a geovisualization, by subdividing the application's functionality or features. By breaking down the geovisualization to be evaluated into individual components, developers can gather more specific data that pertains exclusively to the component or aspect that was evaluated. This would indicate to the project manager or the development team that this particular part of the interface requires attention, while avoiding a full re-write of the project.

ViewExposed is an example geovisualization that may benefit from using the proposed evaluation framework to assess the usability in a component based manner (Bohman et al., 2015). ViewExposed (Figure 13) helps users to better understand exposure and vulnerability to natural hazards, through three distinct components: Map View, Parallel Coordinate Plot, and Datagrid. Instead of asking evaluation participants to assess the usability of the whole interface as a whole, it may be beneficial evaluate each of the three components individually. This recursive type of evaluation can be implemented within several levels of the interface, both going deeper within each component and evaluating the interface as a whole. This increases the quality and the amount of data that is gathered from the user during the evaluation stages, and can help improve the final user attitude and usability of the final product.

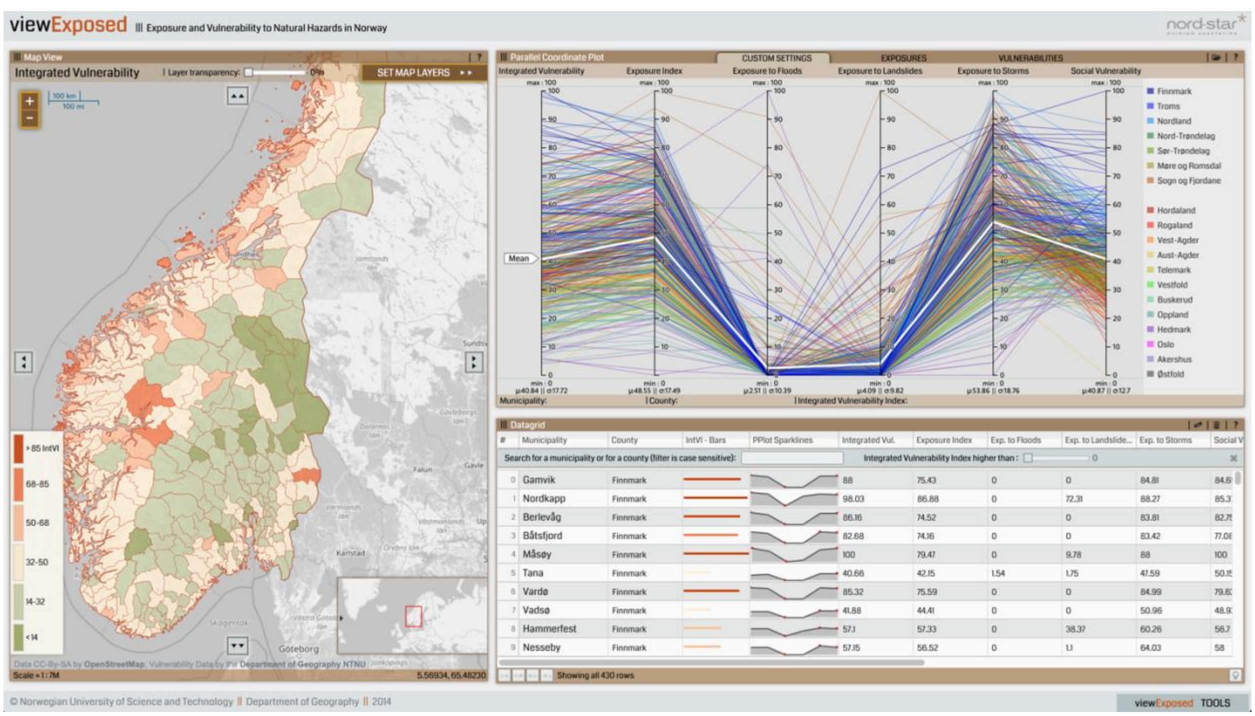


Figure 13. ViewExposed user interface. (Bohman et al., 2015).

4.5 Modern Website Evaluations

The proposed evaluation based on Wang & Senecal's (2007) conceptual framework is good starting point for assessing geovisualization usability, but it is also necessary to consider more recent and sophisticated website evaluation methods. Most of the previous studies that have focused on website or user interface assessment have included a user evaluation component within their methodology. While this is a worthwhile way of gathering data, it is often time and resource consuming, and may produce skewed data if there is participant bias.

Kaur & Gupta (2021), propose a framework to autonomously gauge the design quality of a website by assessing it with an index value. The Quality Index Evaluation Method (QuIEM) is a tool that parses the HTML code of the website to obtain quantitative measures for sub-criteria such as: initial segment, automated tool segment, weighing segment, and output segment. To perform the analysis and assess the website with a design quality index value, the QuIEM tool only requires the website address. This implies that this procedure can be performed repeatedly and gather data on a large scale, which may improve the quality of the results, and provide considerable time and resource savings when compared to traditional user evaluation methods. The results of Kaur & Gupta's (2021) work indicate that the framework is more efficient in terms of time, accuracy, and consistency, than that of user questionnaire methods. Furthermore, it is stated that the QuIEM tool can be used as a pre-deployment testing tool to predict (and subsequently enhance) the design quality of a website. Even though the proposed framework is not designed to evaluate web-map services, it is reasonable to assume that with some refinement the QuIEM tool may also be used to produce accurate quality index values for geovisualizations as well.

Usability increases user satisfaction (Nazir, Zafar, Shaheen, Maqbool, & Qamar, 2019), and is defined by how easy it is to use software. Therefore it is necessary that the usability of a system is high in order for everyone to be able to use, or to learn how to use the software in the least amount of time. Nazir et al., (2019) also state that usability may be often neglected to do factors such as a limited amount of development time, or the lack of usability knowledge possessed by the development team. The General Graphical and Structural Evaluation (GGSE) framework contains three main sections or categories, consisting of: general, structural, and graphical user interface (GUI). These evaluation categories are assigned weights or values based on the order of their relative importance. Within each category are website factors (which are also ranked relative to each other). The website usability is then evaluated through a formula, which produces a value between 0 and 10 (a higher value implies higher usability and user friendliness).

Combining aspects of both the automated QuIEM framework (Kaur & Gupta, 2021) and the GGSE framework (Nazir et al., 2019), could substantially benefit the evaluation of SSIC application as well as other geovisualization products within the CVAP framework. Furthermore, this notion does not imply that since user evaluations are more difficult to perform than automated testing and may produce less accurate or consistent results, they should cease to be replicated. In fact, combining traditional user evaluations methods alongside these more advanced evaluation frameworks can only improve both the fields of geovisualization and general website evaluation.

5. Summary & Conclusions

Geovisualizations are promising methods for communicating spatially related data to a user. Developing geovisualizations for a web-based format is often a suitable method for deploying and disseminating the product or service, however a set of principles or best practices should be adhered to, thus ensuring an effective geovisualization.

In this research, the development of the Seasonal Sea Ice Coverage (SSIC) application was detailed and analyzed in the context of a suggested six phase web development process and best practices. The web development process was then referenced in the context of varying types of geovisualizations as described in the Climate Visualizations for Adaptation Products (CVAP) framework, to identify expected barriers and potential solutions during the development of different geovisualizations. It was concluded that products with increased realism, such as 3D animation or virtual reality capabilities, require a larger infrastructure investment due to increased processing and deployment requirements. Simpler geovisualizations such as both static and interactive mapping applications, may benefit from an all-in-one proprietary software stack, as well as facilitated access to open-source mapping templates that can be re-used for different topics of research. Furthermore, the geovisualizations' content, as per Al-Hawari et al.'s (2021) framework for web development, is the essence of the website and therefore must be adequately considered and well planned, because it dictates the general purpose and message of the whole geovisualization project.

5.1 Future Research Recommendations

This thesis recommends that future research applies the proposed usability evaluation (section 4.3) to other types of geovisualizations to assess the usability and perceived user attitude towards those already developed geovisualization products. Furthermore, the web development best practices process may be applied to research outside of the contexts of university home page or geovisualization development.

It is also suggested that the SSIC application development continues, ideally through the adoption or acceptance of an online community of developers. The SSIC application can be used a starting point or a foundation, for a medium to display sea ice related data. Furthermore, the application should not be limited to sea ice layers exclusively, as there are many other factors that have an impact on Artic conditions such as: wind patterns, water temperature, ocean currents, and other isolated weather events. These are important factors to consider while using the SSIC application to plan a passage through Northern waters, because the conditions can change rapidly and currently available ice prediction models cannot accurately account for random and unpredictable weather anomalies.

A potential example where access to extra data layers may prove to be integral arises after significant wind events. There may be areas of refuge or passage ways that are typically described as safe or protected from sea ice, that become consolidated in a thick ice pack due to prevailing winds. If a qualified user has the ability to view current weather events, combined with ice condition prediction models, this may considerably improve their abilities to make an informed decision regarding the state of the ice-pack.

Chapter 4

Conclusion: Geovisualizations for Understanding Climate Futures

1. Geovisualizations

Producing meaningful and effective geovisualization products to communicate climate change related spatial data is important to promote discourse and stimulate climate change adaptation measures. It is useful to apply visual communication techniques, such as static and interactive maps, to present or communicate spatial data to the user because visualization tools increase information uptake and can present complex information in an easy-to-understand manner.

It is necessary to implement appropriate geovisualization techniques in order to widely disseminate research and to promote discourse and adaptation measures related to climate change. Due to the far-reaching implications of climate change impacts, a large majority of the planet’s inhabitants have ultimately become some form of stakeholder in the matter. This is why it is necessary to understand what features and qualities of geovisualization make them effective communication tools for varying audiences, within different circumstances or use-cases, and based on the intended purpose or goal that the geovisualization product is intended to achieve.

The increase in availability and access to sophisticated technologies and locational software has permitted the generation of a tremendous amount of spatial data. These data range from information on traffic congestion, to popular hiking trails, and including but not limited to fluctuations in weather patterns and other climate data. Even though geovisualizations can serve an imperative purpose in demonstrating a quick route through an unfamiliar city, their greatest potential may be the capacity for presenting complex geographical climate data in a format that may be understood by more than just the industry experts. Although scientific research has already demonstrated the benefits of using visualizations for spatial data presentation, it is not always as easily apparent exactly what type of geovisualization is most appropriate to implement.

This thesis presents a methodology to identify an appropriate format of a geovisualization based on the intended purpose of the geovisualization or the expectations for use towards a certain audience. This is achieved through conducting a structured literature review on the state of geovisualization science and thereby proposing a novel framework to aid researchers, stakeholders, and climate practitioners in discerning an appropriate form of geovisualization. The Climate Visualizations for Adaptation Products (CVAP) framework classifies geovisualization products based on amount of interactivity available to the user, the magnitude of risk or impact that is linked with the decision or outcome formed from using the geovisualization, and the level of realism or abstraction that is present in the geovisualization imagery. The geovisualizations were ranked relative to each other based on these parameters, which formed them into analogous clusters based on the framework. A set of four themes (Inform, Consult, Involve, and Partner) as well as a vertical axis (Exploration to Communication) partitions the analyzed geovisualizations, which facilitates the decision for choosing an appropriate form of a geovisualization.

The thesis then focuses on applying a series of phases and best practices for web development, within the context of geovisualization tool development. This is followed by the description and holistic analysis of the development of a novel geovisualization tool. The Seasonal Sea Ice Coverage (SSIC) application is a web-based interactive mapping service, created for the purpose of dynamically viewing the maximum sea ice cover extent in the Northern hemisphere. This is an open-source application that was developed with the JavaScript programming language, using the React and Leaflet libraries to provide the interactive mapping functionality. The theory and planning for this product is based on the groundwork established through the CVAP framework, and also Al-Hawari et al.'s (2021) website development best practices. The potential challenges and opportunities that may be encountered while adhering to these best practice guidelines while developing geovisualization products as demonstrated in CVAP are identified.

2. Limitations and Research Constraints

Limitations of the methods used in this research include aspects such as the coverage of peer-reviewed geovisualization research during the literature gathering stage, data availability, and limitations in time and resource constraints. It is necessary to acknowledge research limitations to recognize the research's shortcomings and gaps, and to identify potential ways of how these gaps can be addressed during future work.

Despite the fact that the coverage of literature during the formation of the CVAP was extensive, it can never be thorough enough. Especially due to the fact that the topic of geovisualization science is not as mature as some other geographical fields of research. This may indicate that a wide variety of unpublished research and topics are currently being studied or have not yet reached the publication stages. This research, may impact the state of the science, leading to new considerations or assumptions to examine in the future.

Data availability is also a pertinent aspect to consider in most projects and initiatives. The available sea ice data for the display in the SSIC application were gathered at a low resolution, which denied the ability of micro-regional analysis since each data point or pixel constituted a large geographical area. This is acceptable for certain use cases such as when comparing the observed seasonal sea ice patterns, however this hinders the ability of the tool to be used as a means of a Northern archipelago route planning system due to the displayed generalizations in sea ice cover. Furthermore, there is a significant issue with the map projection due to the web-browser environment for the application. A common coordinate reference system for browser-based maps is a Spherical Mercator projection (EPSG: 3857). This decision is beneficial for many online mapping interfaces, however it is the source of a substantial problem when it comes to mapping polar data. This projection is bound at a latitude of 85.06^{O} at both the Southern and Northern extents, as the error in the accuracy of the projection become too large. The SSIC application dealt with this issue by eliminating any data outside of the EPSG: 3857 bounding box. The expansion of libraries and application programming interfaces that permit for the mapping of polar coordinates, would have significant benefits for web development of polar region geovisualizations.

Lastly, constraints such as delivery deadlines and resource limitations had an impact on the outcome of the created geovisualization product. It is necessary to schedule the development in a way that allows for unforeseen circumstances like software issues, project changes, and other unexpected events. Furthermore, as suggested in the web-development best practices, separating the design and development teams, and over-all having a larger ensemble of individuals, may lead to a more intricate finished product.

3. Future Research

This research provides a necessary theoretical foundation for the field of geovisualization research, planning, and development, by providing a modernized framework and case study with a holistic analysis on the process of geovisualization production. This suggests that the sector of geovisualization and the associated research is still in its juvenile stages and merits a great deal more exploration. This thesis attempts at analyzing the highest amount possible of geovisualization projects and initiatives, however this is only the visible tip of the iceberg. Suggestions for future research include the implementation of the CVAP framework within future geovisualization planning and development projects, and providing detailed user evaluations to further assess the effectiveness of the suggested framework.

The desire to understand our surroundings is a part of human nature, and communicating that knowledge is the bedrock of maps and cartography. To harness the full extent of this historical knowledge, effective visual communication of geospatial data is fundamental to research, quantify, and understand. Advances in this field of scientific research have the capacity to promote environmental sustainability and increase understanding on the effects of climate change and options for adaptation. It has often been said that knowing too much of your future is never a good thing, but perhaps with geovisualizations, this is merely a fallacy in need of reassessment.

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