Interactive visualization of climate change: Characteristics, intentions, and metrics for success

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Abstract

Interactive visualization is becoming a widely used method for delivering information about climate change. In this thesis, I introduce the term climate visualization tools (CVTs) to refer to the interactive visualization of climate change data in web-based interfaces, such as climate data portals, decision support tools, data journalism articles, and educational climate models. Researchers and practitioners have argued that CVTs can play a critical role in making climate change data more understandable, actionable, and meaningful to non-scientists. Yet there remain open questions around how effectively CVTs deliver on their intended goals in real-use scenarios. To meet this gap, this thesis critically examines the characteristics of existing CVTs, the intentions of their creators, and the methods used to evaluate their success.

I begin by reviewing the literature on climate change visualization, tracing how interactive visualization methods have evolved to serve a rapidly expanding range of use cases. Past research on the effectiveness of CVTs in real-world scenarios has largely been restricted to individual case studies. Yet critical research suggests that there remain gaps between the expectations of designers and practical outcomes. I argue that it is therefore important to examine existing CVTs to determine whether increasing investments are well-founded in supporting urgent climate change goals.

Chapter 3 presents a content analysis of 41 existing CVTs. I analyze their objectives, data content, visualization techniques, interactivity, functionality, and technology architecture. The analysis reveals strong trends across CVTs, including a focus on meteorological impacts (e.g., temperature changes), the prevalence of maps to represent data, an emphasis on media sharing options, and the use of interactivity primarily to toggle variables and reveal supplementary information. This study also provides an annotated dataset of existing CVTs (available at https://github.com/smlum/climate-vis) which can serve future research and development by revealing commonly used techniques.

Chapter 4 presents the results of a semi-structured interview study with 22 lead designers of CVTs from government, research, non-profit, and news media. I investigate designers' backgrounds, expectations, conception of success, evaluation methods, and commonly faced challenges. The results reveal a high level of interdisciplinarity involved in CVT development, often requiring expertise across climate science and web development, as well as psychology, design, marketing, management, and community engagement. Designers emphasized several challenges, including measuring success directly, disseminating CVTs, developing long-lasting impacts and the simplifying complex climate change information. Chapter 5 concludes with implications for future research.

This thesis makes several contributions to climate change visualization research. First, the findings reveal techniques, intentions, and success metrics used in state-of-the-art practice. Second, it introduces an empirically derived typology for the analysis of CVTs to capture their interactive capabilities. Third, the findings suggest several gaps between research and practice in CVT development. In particular, practical measures of success and post-development tasks receive comparatively little attention in the visualization literature, despite their reported importance. Ultimately, I argue that better integrating interdisciplinary knowledge across research and practice will be critical in meeting the rising demand for climate change information among non-scientists.

Résumé

La visualisation interactive est devenue une méthode largement utilisée pour fournir des informations sur le changement climatique. Dans cette thèse, j'introduis le terme d'outils de visualisation du climat (OVC) pour faire référence à la visualisation interactive des données sur le changement climatique dans des interfaces utilisateur Web, telles que des portails de données climatiques, des outils d'aide à la décision, des articles de journalisme de données et des modèles climatiques éducatifs. Les chercheurs et les praticiens ont fait valoir que les OVC peuvent jouer un rôle essentiel pour rendre les données sur le changement climatique plus compréhensibles, exploitables et significatives pour les non-scientifiques. Pourtant, des questions demeurent ouvertes quant à l'efficacité avec laquelle les OVC atteignent leurs objectifs prévus dans des scénarios d'utilisation réelle. Pour combler cette lacune, cette thèse examine de manière critique les caractéristiques des OVC existantes, les intentions de leurs créateurs et les méthodes utilisées pour évaluer leur succès.

Je commence par passer en revue la littérature sur la visualisation du changement climatique, en retraçant comment les méthodes de visualisation interactive ont évolué pour servir un éventail de cas d'utilisation en expansion rapide. Des recherches critiques suggèrent qu'il reste des lacunes importantes dans les attentes des concepteurs et les résultats pratiques. Je soutiens qu'il est donc important d'examiner les OVC existantes pour déterminer si l'augmentation des investissements est bien fondée pour soutenir les objectifs urgents en matière de changement climatique.

Le chapitre 3 présente une analyse du contenu de 41 OVC existantes. J'analyse leurs objectifs, le contenu des données, les techniques de visualisation, l'interactivité, la fonctionnalité et l'architecture technologique. L'analyse révèle de fortes tendances dans les OVC, y compris une concentration sur les impacts météorologiques (par exemple, les changements de température), la prévalence des cartes pour représenter les données et l'utilisation de l'interactivité principalement pour basculer les variables et révéler des informations supplémentaires. Cette étude fournit également un ensemble de données annotées des OVC existantes qui peuvent servir la recherche et le développement futurs en révélant les techniques couramment utilisées.

Le chapitre 4 présente les résultats d'une étude d'entretiens semi-structurés avec 22 concepteurs principaux de OVC provenant du gouvernement, de la recherche, des organismes sans but lucratif et des médias d'information. J'étudie les antécédents, les attentes, la conception du succès, les méthodes d'évaluation et les défis courants des designers. Les résultats révèlent un haut niveau d'interdisciplinarité impliqué dans le développement de la OVC, nécessitant souvent une expertise en science du climat et en développement Web ainsi qu'en psychologie, conception, marketing et gestion. Les concepteurs ont mis l'accent sur plusieurs défis, notamment la mesure directe du succès, la diffusion des OVC, le développement d'outils durables et la simplification des informations complexes sur le changement climatique.

Cette thèse apporte plusieurs contributions à la recherche sur la visualisation du changement climatique. Premièrement, les résultats révèlent des techniques, des intentions et des mesures de succès utilisées dans la pratique de pointe. Deuxièmement, il introduit une typologie empirique pour l'analyse des OVC afin de saisir leurs capacités interactives. Troisièmement, les résultats suggèrent plusieurs écarts entre la recherche et la pratique dans le développement de la OVC. En fin de compte, je soutiens que l'intégration des connaissances interdisciplinaires dans la recherche et la pratique sera essentielle pour répondre à la demande croissante d'informations sur le changement climatique parmi les non-scientifiques.

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Contributions of authors

Contributions to Chapters 1, 2, and 5:

I wrote the introduction, literature review and conclusion chapters. Dr. Renee Sieber provided comments, feedback, and suggestions during the conception and writing processes. Dr. Robert Roth provided feedback on later drafts of the chapters.

Contributions to Chapters 3 and 4:

These chapter were co-authored with my supervisor, Dr. Renee Sieber, as peer-reviewed journal articles. I am the primary author and I conducted the studies, including question formulation, planning, data collection, analysis, and writing. Dr. Sieber provided guidance throughout the research and writing process. My supervisory committee, Dr. Nigel Roulet and Dr. Robert Roth, provided feedback on the initial formulation of objectives. Dr. Roth also provided feedback on the research design, and on later drafts of the manuscripts.

Chapter 1. Introduction

1.1 Research context and rationale

Since human-caused climate change entered the public and political agenda in the late 1980s, there has been a steep rise in the need to disseminate information and data about climate change, along with questions of how to do so most effectively (Moser, 2016). Information about the causes, impacts, and risks posed by climate change is needed by the general public to make informed choices, by decision makers to implement policy, and by communities to build resilience to future impacts (Overpeck et al., 2011). As climate change strategies are formulated by governments, industries, and individuals, there is a growing need for accessible, locally relevant information about climate change and its impacts (IPCC, 2019).

Graphical representations of information such as graphs, tables, and maps, known as visualizations, have long been a fundamental tool for understanding and disseminating climate change information (O'Neill & Smith, 2014). *Interactive* visualizations, which allow users to manipulate the display of data through a computer interface, can enhance understanding by allowing users to actively explore information (Anselin, 1996; Tukey, 1977) and can serve multiple audiences via the same interface (IPCC, 2016; Pickard et al., 2015). With the growing capabilities of web technologies and far-reaching connectivity of the Internet, interactive visualization of climate data in web-based interfaces has been framed as a powerful way to increase the accessibility and impact of climate change information, data, and models (Neset et al., 2016; Sheppard et al., 2011; Voinov et al., 2017).

Over the 2010s, such climate visualization tools (CVTs) have found a rapidly growing number of applications. Science organizations have created interactive data portals to make climate data more accessible (e.g., Gardiner et al., 2019; Pickard et al., 2015). Journalists have embraced interactive media to bring climate change impacts into everyday reality through data storytelling (e.g., Lee, 2018; Veltri & Atanasova, 2017). Interactive dashboards have been proposed to enable data-informed decision making and to amplify public voices in civic consultations (e.g., Bohman et al., 2015; Lieske, 2015). Climate change researchers are increasingly using interactive tools to increase visibility of their research (e.g., Ballew et al., 2019). CVTs have supported climate education by providing students with access to the data, models, and analytical tools used by scientists (e.g., Bush et al., 2016).

In some sense, the bar for developing and disseminating interactive tools has lowered significantly over time. Software packages such as Tableau and ArcGIS can be used to rapidly design and deploy CVTs (Girvetz et al., 2009). Developers can leverage a rising number of visualization web libraries to build complex, customized platforms allowing for data exploration and analysis (Batty et al., 2010; Roth et al., 2015). CVTs can potentially reach global audiences within days through news and social media to increase attention to climate issues (Fish, 2020; Olteanu et al., 2015). On the other hand, the design and dissemination of visualizations has evolved to be an increasingly multi-faceted process, incorporating critical insights from a range of disciplines such as design, psychology, and marketing. Research and development teams can include science communicators, designers, web developers, climate scientists, human-computer interaction researchers, managers, and outreach specialists (Glaas et al., 2015).

As the concept and application of CVTs rapidly ascends research and funding agendas, it will be increasingly important to understand their content, objectives, and efficacy. Yet, despite calls in the scientific community, research on the design and evaluation of CVTs has been relatively limited (Xexakis & Trutnevyte, 2019). Much of the literature on the implementation and evaluation of existing tools has been on a case-by-case basis. Whereas such work can highlight individual techniques, methods, and insights, comparative research is critical for assessing the efficacy of web-based interactive visualization as a medium, for revealing trends, and exposing commonly faced challenges (Neset et al., 2016; Roth et al., 2015; Stephens et al., 2017). There remain open questions as to what features CVTs should include to best suit their purpose, what they are being expected to achieve by their developers, and whether they meet such expectations (Hewitson et al., 2017; Voinov et al., 2017). Better understanding what it is that makes tools successful in their real-use contexts will be critical in realizing the potential of CVTs and addressing urgent climate change needs and challenges (Grainger et al., 2016).

1.2 What is a CVT?

In this thesis, I use the term "climate visualization tool," or CVT, to refer to a web-based user interface (often referred to as a web tool) containing a visual representation of climate-related information that gives users the ability to manipulate elements of the display. Whereas the term "data visualization" has been used to describe a process facilitated by interactive data exploration (e.g., MacEachren, 1994), we use "interactive visualization" to explicitly refer to displays of information that can be manipulated through a user interface. What constitutes "interactivity" in CVTs (and in visualizations more broadly) is a wide topic of discussion (e.g., Munzner, 2014; Roth, 2013; Shneiderman, 1996). In this thesis, interactions are understood in terms of user actions (e.g., mouse clicks), an interface that reacts to user actions (e.g., through checkboxes), and the resultant effects on the visual display (e.g., hiding of a data layer) (Roth, 2013). The nature and characteristics of interactivity in CVTs are further explored in Chapters 2 and 3.

Figure 1.1 shows a typical example of a CVT: The Carbon Map, developed by Kiln (Clark & Houston, 2014). It contains a visual representation of climate data (a choropleth map representing carbon emissions) that can be manipulated through interaction with its user interface (e.g., by clicking a dropdown selection menu) to change the information presented in the display (e.g., to change variable being mapped). Other examples of CVTs are included in data journalism articles such as the *New York Times*' "How Much Hotter Is Your Hometown than When You Were Born?" (https://www.nytimes.com/interactive/2018/08/30/climate/how-much-hotter-is-your-hometown.html), public climate change information websites such as Climate Central's Surging Seas Risk Zone Map (https://ss2.climatecentral.org/), and climate data exploration portals such as the U.S. Environmental Protection Agency's EnviroAtlas (https://enviroatlas.epa.gov/enviroatlas/).

CVTs such as the example shown in Figure 1.1 present many design challenges. What are the needs and capabilities of users? How should the interface be designed to best meet those needs? Which data should be displayed? Which visual representations best convey underlying patterns and meaning? What scientific information need to be expounded, simplified, or omitted? Which types of interactivity are necessary for users to achieve their objectives? How do users know what can be achieved using the tool? And what should users get out of using the CVT?

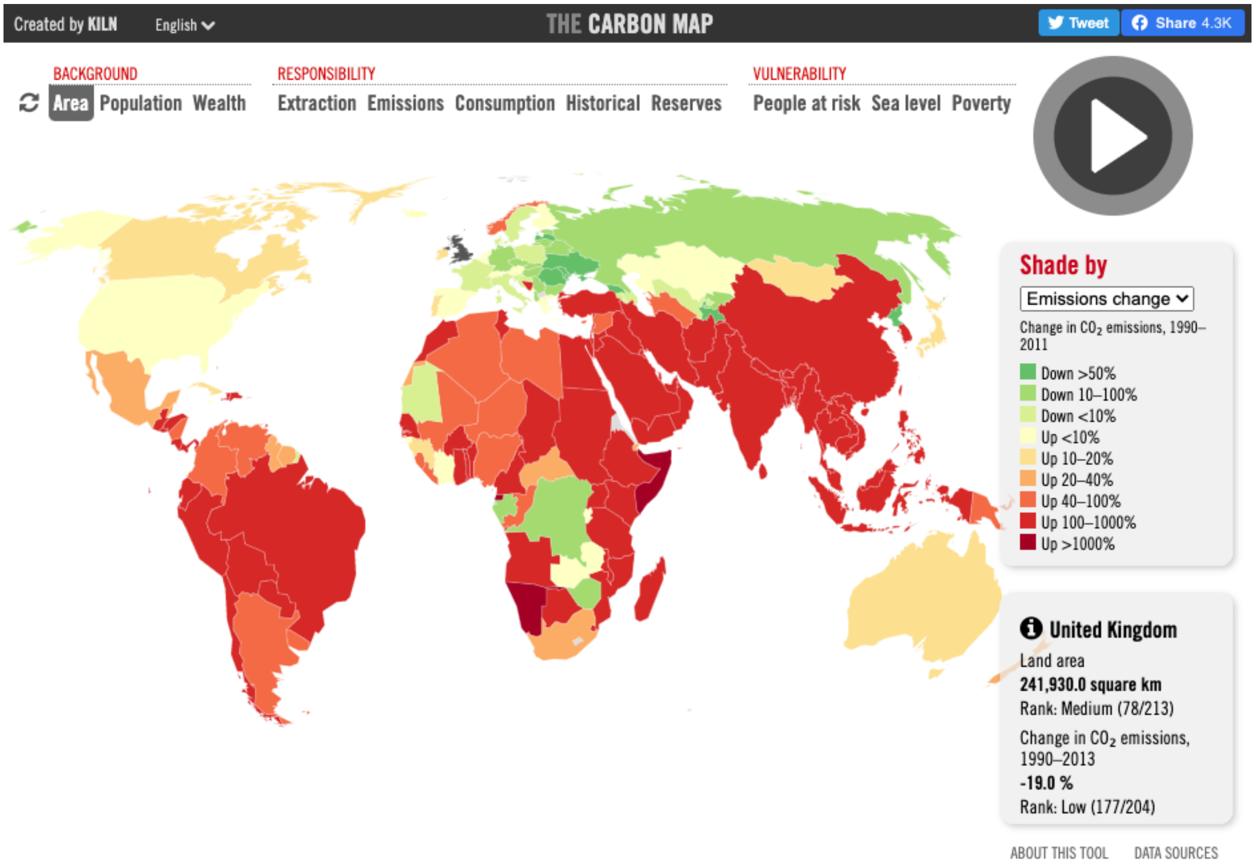

Figure 1.1 An example of a climate visualization tool: The Carbon Map, developed by Kiln (https://www.carbonmap.org/).

1.3 Aims of the study and research questions

The aim of this thesis is to critically examine how CVTs are being used to present and convey meaning from climate data. In particular, I explore three fundamental aspects of CVTs through the following research questions:

1. What are the characteristics of existing CVTs?
2. What are the intentions behind CVTs?
3. How do we know if CVTs are meeting our expectations?

The first research question is addressed in Chapter 3 through a content analysis of 41 CVTs. Drawing from visualization research, I divide this question into five core components: (1) What is the purpose of the tool? (2) Which data are being represented? (3) Which graphical representations are used to represent data? (4) Which technologies are used to implement visualizations? And (5) What functions can be accomplished with the CVT? This study identifies common approaches to visualization, discusses their strengths and limitations, and offers recommendations and future directions for the field.

The second and third research questions are investigated in Chapter 4 through an interview study with 22 lead designers of CVTs. I characterized designers' individual and organizational backgrounds, their intentions for CVT development, their understanding and measurement of success, and commonly faced challenges of using interactive web-based visualization for climate change data. This allowed me to compare widely held expectations of CVTs in practice to those expressed in the literature and to explore whether expectations were being met.

1.4 Research design

In contrast to much existing reporting on CVTs, this thesis takes a comparative approach to assessing design and evaluation practices. Comparison across multiple CVTs can give a clearer picture of the practice as a whole and reveal patterns across interactive tools. This serves researchers and practitioners in raising awareness of emerging techniques, technologies, and evaluation methods, as well as revealing unmet needs and exposing commonly occurring issues (Neset et al., 2016; Roth et al., 2015).

To answer the research questions, this thesis is organized into five chapters. Chapter 1 has provided rationale for the study of CVTs and identified three research questions. Chapter 2 traces the evolution of CVTs in meeting climate change challenges, examines motivations for CVT development, and explores approaches to evaluation. It surveys research disciplines including climate change communication, visualization, and human-computer interaction. Chapter 3 presents a content analysis of existing climate visualization tools to characterize the climate topics, data representations, interactivity, and visualization technologies used by developers. Chapter 4 presents an interview study with tool developers to characterize developer intentions and approaches to measuring success. Chapter 5 concludes by offering challenges and opportunities for future research on CVTs.

This thesis makes several contributions to the literature on the visualization of climate change. First, the findings reveal gaps between current design practices and recommendations. Second, the findings suggest a disconnect between the practice of tool evaluation and the research literature: practitioners were more focused on practical aspects of success such as the number of users, media attention, and the adoption of tools into users' lives, whereas research has focussed on tool efficacy, typically by assessing CVTs in controlled settings. Third, the repository of coded tools serves as a starting point for further research or CVT development. Ultimately, I argue that integrating existing knowledge and expanding research to dissemination phases of tool development will be important if researchers and practitioners are to meet the rising demand for effective methods to share of climate change information.

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Chapter 2. Literature review

2.1 Introduction

This thesis investigates the characteristics, rationale, and evaluation of web-based interactive visualizations of climate change, which implicates numerous fields of study. Climate science has long produced information which, having significant real-world implications, need to be interpreted and used by non-scientists, such as decision makers and the general public (IPCC, 2018; Overpeck et al., 2011). Climate change communication and related social-science fields have emphasized that experiences, mental models, and underlying values can shape (and hinder) the interpretation and use of such information. The field of visualization has proposed numerous techniques to explore and present climate change information and to meet emerging needs and challenges (Newell et al., 2016; Nocke et al., 2008).

In particular, the means to manipulate visualizations directly through computer displays and far-reaching connectivity of the Internet have supported a proliferation of interactive web-based climate visualization tools (CVTs). CVTs have found applications in scientific outreach, decision support, and digital journalism (Neset et al., 2016; Xexakis & Trutnevyte, 2019). More recently, CVTs have been examined by researchers in human-computer interaction, psychology, and geographic information science, which have provided critical insight into their efficacy as a medium by emphasizing the consideration of users with diverse needs, constraints, and expectations (Shneiderman & Plaisant, 2010). As techniques, technologies, and use cases rapidly evolve, it will be important for researchers to keep pace with existing practices, to understand whether CVTs are working as intended and to identify persistent challenges (Neset et al., 2009; Newell et al., 2016).

In this literature review, I first examine what visualization and interactivity have come to mean in the context of CVTs. Second, I trace the emergence of CVTs and examine how they have been proposed to meet needs for climate change communication, mitigation, and adaptation. Specifically, I explore how applications of interactive visualization have evolved from serving climate researchers in scientific analysis to a diversity of users and use cases including outreach, decision support, data provision, and online journalism. Third, I examine the rationale of developers and organizations in building CVTs by examining needs and challenges posed in climate change communication and related literatures. Finally, I examine how CVTs have been characterized and evaluated, highlighting differences in how "effectiveness" is understood between disciplines and intended use cases. I conclude by identifying needs and opportunities in climate visualization research; specifically, the need to better understand existing practices and intent in the development, dissemination, and evaluation of CVTs in real-world contexts.

2.2 Defining visualization and interaction in CVTs

Broadly, visualization describes the visual representation of quantitative information to generate qualitative meaning (Tufte et al., 1990). As explicated by Grainger et al. (2016, p. 301), in scientific contexts the primary aims of visualizations are to:

> Facilitate the communication of information; aid understanding through presentation, exploration, or analysis; and … to raise awareness and elicit affective responses.

Some fields, such as information visualization, have also defined visualization as a process involving both representation and interaction, mediated through computer displays (Buja et al., 1996). MacEachren (1992, p.101) describes visualization as "an act of cognition, a human ability to develop mental representations that allow us to identify patterns and create or impose order." For these authors, visualization is not only a visual artifact for presenting information, but a process driven by particular objectives; specifically, the use of manipulatable visual elements to aid thinking and hypotheses generation. Because of the differences between disciplines, in this thesis we opt to use the term "interactive visualization" to explicitly refer to displays of information that can be manipulated through a user interface.

As defined in the field of information visualization, interactions involve three components: the user, the visualization, and a mediating interface that can be used alter the display (Roth, 2013). In general, computer hardware is used to provide a visual display (e.g., through a monitor) and the means to alter the display (e.g., a keyboard or a mouse). Interactivity can be characterized in terms of user actions (e.g., clicking a mouse, typing, scrolling, or hovering), components of the user interface that invite and react to actions (e.g., a checkbox, slider, or button), and resultant effects (e.g., toggling a visual element) (Norman, 1988). The systems of visual displays and the components used to manipulate them are referred to as being contained within a wider user interface (MacEachren & Kraak, 2001). Such interfaces often contain contextual information as well as interactive elements which can be used to manipulate the display of information in the visualization. Such interfaces have been presented as flexible, easy-to-use means for data exploration (Shneiderman, 1996).

Interactive visualizations have increasingly been incorporated into web-based interfaces (Grainger et al., 2016), often referred to as web tools (Netzel & Stepinski, 2017). In the context of climate change, web tools incorporate interactive visualization within user interfaces to present information and deliver climate data services (Xexakis & Trutnevyte, 2019). Often these web tools have a geographic component, leading to the subdivision of web-mapping tools (e.g., Neset et al., 2016; Stephens et al., 2014). As discussed, we use the term climate visualization tool (CVT) to refer to the collection of visualizations as well as their user interface. However, the types of visualizations, the interactivity they afford, and their embedding in user interfaces have not been static in time; in the next section, we explore their emergence and evolution.

2.3 The emergence and evolution of CVTs

Visualizations such as maps, charts, and graphics have long been intended to communicate and extract meaning from climate data (Friendly, 2008). Starting in the mid-1980s, methods were developed that allowed instantaneous and direct manipulation of data visualizations via computer inputs and displays (Becker & Cleveland, 1987). This interactivity meant that data could be explored within a visual interface, allowing the user to make immediate adjustments to explore different parts of a dataset. Interactive elements such as sliders, selection boxes, and dropdowns could make it more efficient to explore multidimensional climate data by filtering spatial layers, zooming in on a feature, or reading off precise data values (Anselin, 1996). The visualization and interaction techniques facilitated by software such as Ferret and Vis5D became important for scientists conducting climate research, who routinely needed to explore large heterogeneous datasets with multiple spatial and temporal components (Nocke et al., 2008). For example, Treinish (1994, p. 671) described the capabilities of the IBM Visualization Data Explorer in allowing different visual representations to illustrate different aspects of multi-dimensional climate data, thereby "promoting visual exploration and … facilitating the extraction of knowledge from complex, diverse data sets."

In the 1990s CVTs were also proposed as means to meet needs outside of scientific research contexts. For example, Gordin et al. (1994) saw novel interactive visualization techniques as an opportunity to promote learning in climate sciences. The authors outlined their Climate Visualizer as providing a visual interface to data from the US National Meteorological Center. Their CVT included a map presenting climate data variables and functionality to change variables and display options, such as the color mapping (shown in Figure 2.1). By allowing users to create, inspect, and annotate scientific visualizations, the tool was intended to "assist students' appropriation of the practices of scientists, thus allowing for more situated learning in the manner of cognitive apprenticeship" (Gordin et al., 1994, p. 203).

The 2000s saw growing access to computer and network resources among the public alongside mounting concern about the challenges of delivering climate information to non-scientist audiences (Stamm et al., 2000). A growing number of researchers proposed interactive visualization as a method for the dissemination of climate change information (e.g., Sheppard, 2005). Many newly possible techniques were advanced; for instance, landscape visualizations that mapped climate change impacts onto depictions of real-world environments and allowed users to navigate through different scenes were proposed as a way to increase personal concerns about climate change by illustrating impacts to familiar places (Nicholson-Cole, 2005; Sheppard, 2005). For example, in the field of science education Chandler et al. (2005) developed EdGCM, a user interface to global climate models that was intended to expose students to the methods and processes of climate research. Beyond viewing a pre-determined dataset, users could adjust input parameters and run simulations on their own computers. This greater flexibility and access to tools was thought to improve learning about the climate system by allowing users to experiment with an external representation of the climate system.

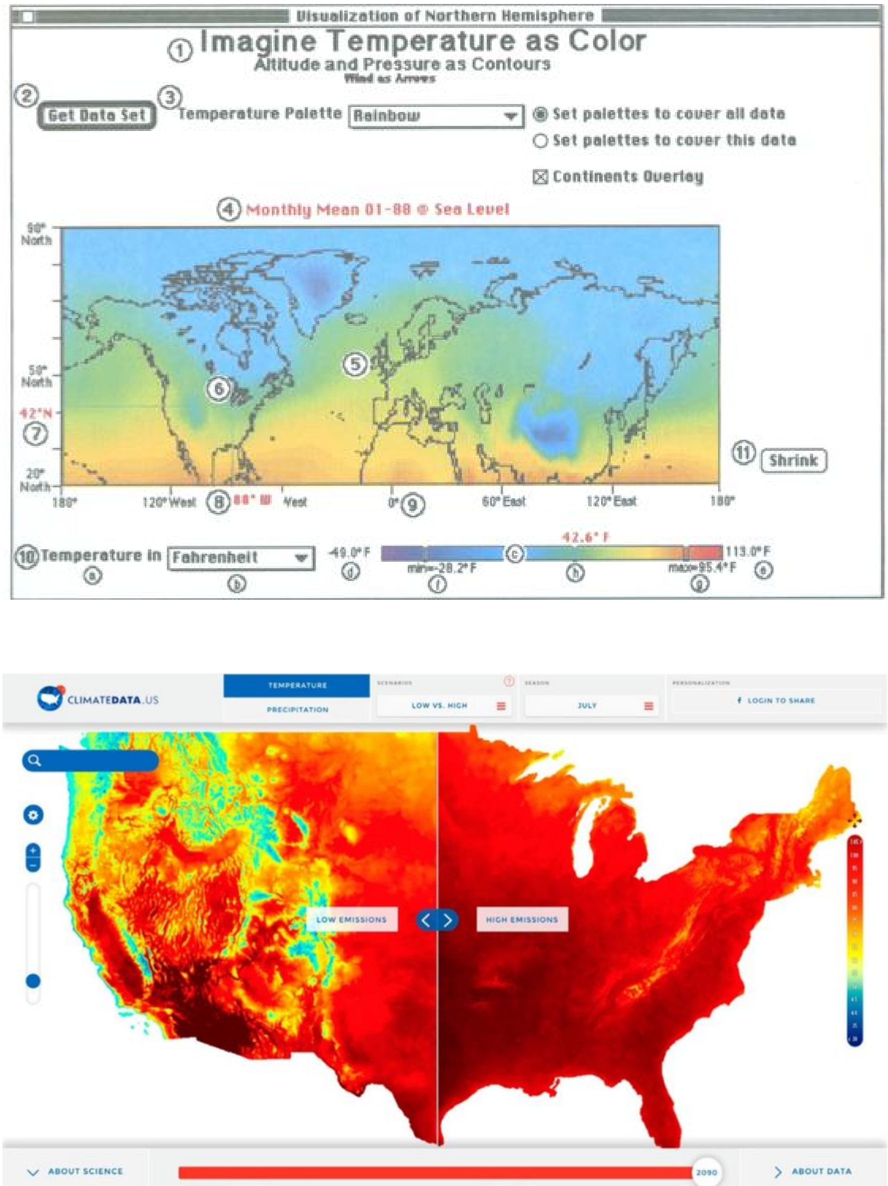

Figure 2.1 Evolution of CVTs: The user interface for Gordin et al.'s (1994) Climate Visualizer (top) and Herring et al.'s 2017 ClimateData.us (bottom).

The latter half of the decade saw a technological inflection point that greatly expanded the power of web technologies available to developers of CVTs. The growing availability and capabilities of application programming interfaces (APIs), modular packages of remotely accessible code that allowed developers to incorporate external functionality into their own applications, meant that maps and other complex visualization techniques no longer needed to be developed from scratch in web applications. Newly available APIs, such as Google Maps, meant that developers could rely on an API to display geospatial data on a basemap and provide interactivity such as panning and zooming, which were non-trivial technical tasks (Erle et al., 2005; Haklay et al., 2008). APIs and software that supported visualization applications, along with advances in collaborative development (e.g., the launch of code-sharing version control platform, GitHub, in 2007) and cloud-based web infrastructure (e.g., the launch of Amazon Web Services, in 2006), meant that developers of CVTs could more readily build advanced functionality, such as visualizing data layers on interactive scalable maps (Batty et al., 2010). However, Nocke et al. (2008) noted that developments in visualization techniques were not yet widespread. Thus, a major research priority was further bridging the gap between climate and visualization expertise (Neset et al., 2009).

As the feasibility of delivering dynamic content over the web increased, many national science agencies began to incorporate interactive visualizations into their public websites (Carpendale, 2008). For example, Gardiner (2009) described the NOAA Climate Services Portal dashboard as including a set of trend charts for which the time period could be adjusted via a slider, intending to make information more transparent and engaging. CVTs were also increasingly proposed to support decisions and inform policy; for example, through the use of local 3D visualizations of flood maps to illustrate local impacts of global climate change (Burch et al., 2010; Shaw et al., 2009).

In the 2010s, the number of CVTs and the diversity of use cases dramatically increased. In a content analysis of climate visualizations in major online news outlets, Lee (2018) observed the increasing uptake of interactive visualization in online climate change journalism to allow users to access additional information, filter data, and guide navigation. In government outreach, Herring et al. (2017) described the interactive map interface for ClimateData.us, shown in Figure 2.1, as presenting high-resolution climate data and allowing users to search or zoom in to local areas to compare differences between low- and high-emissions climate projections. Relative to early examples, CVTs began to incorporate standardized design procedures to encode visual representations (such as dynamic and scalable maps), though many of the interaction paradigms remained the same (e.g., buttons, sliders, selection boxes, and text inputs), as shown in the comparison in Figure 2.1.

CVTs also were increasingly used in the delivery of application-focused climate services to meet demand for climate information serving specific user needs in decision making by individuals and organizations (Lemos et al., 2012; Lourenço et al., 2016). For example, Johansson et al. (2014) created VisAdapt to build adaptive capacity in Nordic homeowners. They designed an online interface to calculate user specific adaptation measures which could be explored through navigation menus, interactive maps, and infographics. Pickard et al.'s (2015) EnviroAtlas embedded analysis tools within their interactive map interface to allow resource managers to explore the impacts of policies and regulations. Non-climate scientist users, such as decision makers, planners, journalists, and researchers in other domains represented a growing audience for climate data services and CVTs (Moss, 2016). Correspondingly, a growing number of climate change researchers began to adopt CVTs with the intention of making their results more widely accessible through visual data portals, and thereby increasing their potential impact (Ballew et al., 2019; Netzel & Stepinski, 2017).

2.4 Rationales for using CVTs in meeting climate change challenges

The development of CVTs has been driven by the rationale of their creators in meeting challenges presented by climate change. Xexakis & Trutnevyte (2019) consider two broad types of usages for serving non-climate scientist audiences: (1) outreach and education, and (2) provision of data and services for applications. First, CVTs have been made to explicate environmental issues by providing interfaces for the public to actively explore information (e.g., Herring et al., 2017; Newell et al., 2016). Second, CVTs have been developed to support decision making and research by delivering climate data and analysis capabilities through interactive interfaces to assist with use of climate data to inform decisions or for other applications (e.g., Lemos et al., 2012; Moss, 2016). Across both use cases, CVTs can range from presenting known information to facilitating user-led exploration of a dataset (MacEachren, 1994). We consider the ways in which CVTs have been proposed to meet challenges in each of these contexts in the following two sections.

2.4.1 CVTs for communication, outreach, and education

The use of CVTs has largely been driven by needs and challenges considered in the domain of climate change communication (Schroth et al., 2014). Climate change communication literatures are concerned with informing, warning, persuading, and mobilizing non-scientist audiences in their engagement with climate change issues (IPCC, 2016). At a deeper level, climate change communication considers how experiences, cultural models, and human values can shape the production of knowledge about climate change (Newman et al., 2018). Changes in communication can lead to shifts in societal beliefs, motivate political action, influence individual behaviors, and change economies, thereby making significant contributions to alleviating the impacts of climate change (Nerlich et al., 2010). Effective communication is important for political leaders to factor climate risks into governance; in contrast, poor communication can lead to critical issues being ignored (Sarewitz, 2004).

Making communication more challenging, climate science and human involvement in the climate system are widely recognized as complex topics (Nocke et al., 2008). Projections of future scenarios depending on global human behavior contain multiple types of uncertainty. Acting on what is perceived as uncertain information can often fail to compete with certain and immediate challenges, such as meeting basic economic needs (Budescu et al., 2009). Early efforts were often communicated as a matter of fact by research scientists and transmitted through mass communication channels. Such “top-down” approaches have been criticized in science communication research as often being ineffective, potentially leading to public and political misunderstanding of climate issues (Lee et al., 2008). CVTs have long been thought to help understanding of data by allowing users to navigate and explore information of their own accord (Andrienko et al., 2014; Nocke et al., 2008). It has been argued that these attributes can, in some cases, foster a deeper engagement with abstract climate change subjects and make complex scientific results more accessible (Alder & Hostetler, 2015; Herring et al., 2017).

Another challenge in presenting climate change information is that the “invisible causes” of climate change, namely greenhouse gas emissions, are not visibly linked to the actions that produce them (Lazarus, 2008). Similarly, many of the impacts of climate change are psychologically distant in both time and space (Spence et al., 2012). CVTs have been proposed to meet these challenges by illustrating local impacts to increase their familiarity (Nicholson-Cole, 2005). For example, Sheppard (2005) argued that by visualizing climate change impacts on realistic and familiar scenarios such as local landscapes, visualizations could help to create cognitive and emotional connections between users and distant impacts of climate change. For instance, sea-level-rise viewers could allow users to explore flooding of neighborhoods during projected storm surges (Burch et al., 2010; Stephens et al., 2014). Others have argued that visual imagery can trigger affective responses that can engage people in issues of environmental change and motivate personal action (Slovic et al., 2007).

The presentation of climate change issues in news media has also been critically examined within climate change communication research (Boykoff & Boykoff, 2007). Studies have found that focusing on global or distant impacts, such as the warming of Arctic regions, could make it challenging for individuals to connect their everyday lived experience to global scale impacts (Nerlich et al., 2010; O'Neill & Smith, 2014). This contributed to climate change being seen as a low priority in news-media stories and reader apathy to climate change news (Moser, 2007). CVTs have been proposed as a way to increase visibility and salience of climate issues by making climate news more compelling (Fish, 2020) and persuasive (Pandey et al., 2014). However, others have pointed out that sensationalist representations of climate can create a tension with the scientific nature of climate change content (Scharrer et al., 2016).

The political contentiousness of climate change also presents a communication challenge (Doyle, 2007). Action can conflict with the vested interests of powerful groups actively engaged in lobbying and mobilizing climate-change-skeptic discourses (Scheufele & Krause, 2019). Although questions have been raised about the effects of scientific literacy on climate change beliefs (e.g., Drummond & Fischhoff, 2017), increased scientific literacy has been argued to help public audiences in understanding uncertainties and discounting misinformation (Linden et al., 2017). Researchers have argued that CVTs can contribute to scientific literacy by allowing a greater amount of transparency into the methods used by scientists (Niepold et al., 2008). Particularly in education, interactivity can help to provide access to scientific models to support a deeper understanding of climate systems via experimentation and independent scientific inquiry (Bush et al., 2016).

As awareness and concern about climate issues have increased in recent years (Leiserowitz et al., 2020), others have argued that it is important to focus on enabling collective action. Inaction can stem from the practical challenges of being unaware of potential solutions (Neset et al., 2009), the delayed or absent gratification of adopting emission-reducing behaviors (Moser, 2016), and feelings of personal insignificance (Chapman et al., 2017). Leiserowitz et al.'s (2011) "Six Americas", demonstrated that significant parts of society are concerned with climate change issues but are unsure how to act. Other research has suggested that even relatively small but actively participating groups of individuals can initiate large-scale societal changes (Chenoweth et al., 2011). CVTs have been proposed to motivate and support individual action by suggesting personalized and manageable actions (Johansson et al., 2014), as well as fostering widespread engagement with climate science and science communities (Gardiner et al., 2019).

2.4.2 CVTs for delivering climate data and services

Another critical need identified for addressing climate change issues is ensuring relevant data and information are incorporated into decisions scenarios to support planning by governments, industries, and communities (Moser & Ekstrom, 2010). International commitments like the 2016 Paris Agreement have increased demands from decision makers at national and local levels for climate data and expertise to set emissions targets, curate adaptation policies, and communicate risks (Lourenço et al., 2016). However, research has shown that significant work is needed to translate scientific assessments into actionable information usable by decision makers, businesses, and communities, leading to a "usability gap" in the provision of information and services (Lemos et al., 2012, p. 789). Improved uptake and application of scientific knowledge within environmental decision making has prompted growing consideration for, and investment in, new modes of dissemination such as CVTs (Moss, 2016).

Moser & Ekstrom (2010) raise data accessibility as a central barrier to incorporating climate data in non-science contexts. The data output by climate models is often complex and multidimensional, requiring significant background knowledge and technical skills to interpret and operate with (Nocke et al., 2008). However, the accessibility of data is critically important in determining how readily it can be incorporated or understood (Lemos et al., 2012). Moss (2016) argues that narrowing such usability gaps requires the re-orientation of existing platforms towards their end use. CVTs have been increasingly proposed as a way to meet this challenge by making large climate datasets and models more accessible by letting users explore data within a web browser, as opposed to needing specialist software (Alder & Hostetler, 2015). In particular, being able to explore data without needing to download it has been proposed as a means to lower the level of expertise needed to understand and apply climate data (Pickard et al., 2015).

Another key barrier identified by researchers is the extent to which conclusions from the data can be used to support actual decisions (Kirchhoff et al., 2013; Moser & Ekstrom, 2010). It may be unclear to decision makers how climate change information should factor into their workflow. Further, there is often a need for data relevant to particular locations, sectors, or stakeholders. As climate data of increased resolutions has become more readily available, how best to share it with various end users of different backgrounds has been raised as a non-trivial problem (Borgman, 2012). Delivering localized data specific to particular application-oriented audiences has been a central intention of many CVTs (e.g., Ballantyne et al., 2016). Interactive displays can allow a user to navigate variables, filter irrelevant information, and explore subsets in more detail (Nocke et al., 2008). More recently, CVTs have been designed to meet specific and evolving needs of individual sectors (e.g., Palutikof et al., 2019).

Another motivation driving the development of CVTs has been the delivery of functionality: to go beyond data provision to allow analytical or modeling functionality specific to a user's inputs (Moser & Ekstrom, 2010). CVTs have been proposed as a way to give access to analytical functionality while reducing user requirements (Pickard et al., 2015). In other contexts, CVTs can provide access to dynamic simulations without the need to install software or deal with complex file types, and can be used to make projections about real-world scenarios based on input parameters (Sterman et al., 2012). For example, simulations can allow users to learn about an environmental system and compare options by running "what if" scenarios (Schroth et al., 2014).

A final but critical aspect of CVTs are qualitative user perceptions such as their credibility, salience, and scientific legitimacy (Li et al., 2018). Andrienko et al. (2007) observed that the confidence in data used can significantly alter its influence in decision-making scenarios. Access to relevant and reputable data and resources is particularly important for communities in holding governments and industries accountable if they fail to address climate change problems (Ford et al., 2016). For example, a specific aim of some CVTs is to increase data transparency to encourage journalists to bring issues into public view (e.g., Howe et al., 2015). Providing communities with access to scientific resources has been proposed as a way to empower them to challenge decision makers using scientific evidence. In particular, scientifically trustworthy data can serve as a strong rhetorical and legal device. In this sense, CVTs have been proposed as a way of increasing the role of citizens by enhancing participation in decision making (Lieske, 2012).

2.5 Assessing whether CVTs deliver on their intended use

CVTs have been proposed to meet a wide diversity of use cases and many benefits have been claimed. However, even taking into account advances in theory, techniques, and technologies, building effective CVTs can take considerable resources, leading to important questions in a context of urgent climate change issues: Are CVTs worth the effort? What does it mean for a CVT to be effective? And how do we know when a CVT is effective or not? Such reflections on what has been achieved are critical for the development of effective tools (Norman, 1988).

Given their variety of purposes, a discussion of what it means for a CVT to be effective requires some level of generalization. Roth et al. (2015) proposes three components of interface success for interactive maps, which can apply more broadly to interactive visualization tools. They are: (1) utility, or the usefulness for assisting with given tasks; (2) usability, or the ease of use; and (3) appropriateness for a target user group. CVTs contain many components that can influence their interface success. Two such components were discussed in Section 2: the choice of visual encoding to represent information (e.g., a map versus a line graph), and how interactivity is encoded (e.g., to allow a user to zoom in on a map location) can determine what can be achieved with a CVT and how readily tasks can be achieved. Similarly, the data content of a CVT can determine its utility to particular user groups (e.g., the requirement for up-to-date or scientifically rigorous data) or its usability (e.g., whether a high level of expertise is required to understand caveats).

Evaluation of CVTs is challenging because there is often great variability between users even within a single system in terms of ability, domain experience, and familiarity with the interface (Lam et al., 2012). In addition, users may be trying to accomplish different tasks via the same interface. Therefore, understanding utility and usability requires consideration of the target user groups, as argued for by Roth et al. (2015), by expanding the utility/usability paradigm to explicitly include consideration of the user. In CVT evaluations, precise characterizations of user groups are uncommon (Hewitson et al., 2017), although many developers reported targeting broad user groups (Alder & Hostetler, 2015; Pickard et al., 2015). User characterization could lead to important design insights; for example, in the development of VisAdapt, Glaas et al. (2015) employed user testing and focus groups to identify key barriers to their target audiences, including low risk perception and a lack of clarity on appropriate adaptive actions. These findings informed their tool design decisions to present anticipated climate change impacts and compile existing adaptation guidelines.

A central approach to understanding whether CVTs meet their goals has been to assess their utility for target users and the extent to which user tasks are supported by their functionality (Stephens et al., 2015), although what is considered to be useful can depend significantly on the intended purpose of the tool. For example, Bush et al. (2017) evaluated learning outcomes for an educative global climate modeling CVT, finding higher levels of engagement and improved understanding of scientific methods among students. In particular, the authors found that interactive capabilities allowing students to test their own climate experiments made their tool more useful in an educational context. In the domain of climate communication, Herring et al. (2017) assessed the utility of ClimateData.us in eliciting changes in understanding and beliefs of users, using pre- and post-test measures. Evaluations of utility and performance could also reveal shortcomings in existing visualization approaches. For example, Xexakis & Trutnevyte (2019) found that interactivity features in four surveyed decision-support CVTs showed no benefit compared to their static counterparts in terms of understanding or engagement with climate data.

Another important consideration in the evaluation of CVTs was their ease of use, or usability. A tool might be useful for completing tasks, but little may be achieved if users are unable to readily access functionality (Shneiderman & Plaisant, 2010). Roth et al. (2015) emphasizes the dependence of usability on target users accounting for their needs, abilities, domain knowledge and use cases. Wong-Parodi et al. (2014) proposed a method to assess usability of CVTs for decision support, judging user preferences, understanding of the tool's functionality, and ability to make inferences. Applying usability evaluations, Zikmund-Fisher et al. (2011) and Voinov et al. (2017) found that virtual environments could distract from user objectives making them counterproductive in decision making. The choice of data, graphics, and interaction encodings can strongly impact ease of use (Kirchhoff et al., 2013).

Other researchers have emphasized the importance of a user's subjective feelings about the CVT and the experience of using it in determining its successful real-world application (Chapman et al., 2017). Feelings such as enjoyment, trust, satisfaction, and perceptions of usability can greatly affect the interpretation of information presented in CVTs and the extent to which they are incorporated into workflows. For example, Gardiner et al. (2019) emphasized trust and satisfaction as being key goals of the U.S. Climate Resilience Toolkit. Fogg et al. (2003) emphasized the importance of credibility in presenting web-based information, whereas Fish (2020) found that vividness could affect the impact of online climate change news.

Some assessments of CVTs evaluated multiple factors across users, utility, usability, and user experience to meet their specific objectives in evaluating tools. For example, Stephens et al. (2015) assessed the communicative effectiveness, usability, and user satisfaction of a sea level CVT via stakeholder consultations. Gardiner et al. (2019) measured several aspects of their CVTs' progress toward their goals through user feedback and measurement of site visitors via web analytics. By triangulating informal feedback from their users through webinars, public speaking, and workshops, alongside quantitative measures of uptake, they were able to build a more comprehensive judgement of its overall success.

On the other hand, Ellis & Dix (2006) found that in many cases the choice of evaluation criteria and methodology was not always appropriate for the claims made. In an examination of user study practices of information visualizations, the authors found there were issues with evaluation practices used by many researchers. They identified recurrent issues with the majority of evaluations they sampled, including the use of flawed methodologies to measure performance, the use of inappropriately small sample sizes and limited testing of visualizations in their real-use contexts. They concluded that evaluation was often an ad hoc process and that generalizability was often claimed without sufficient evidence. Even in studies without evaluations, they observed that attempts were often made to justify the significance of application by means of examples but could not substantiate arguments that their particular approach had advantages over existing methods.

Finally, theory-based evaluations examine CVTs using theoretical frameworks established through scientific research (Roth, Ross, et al., 2015). Whereas user evaluations are often specific to a visualization's objective and users, theory-based evaluations can more easily be applied to multiple tools with different purposes. For example, Neset et al. (2016) critically assessed the data content and interactivity features of 20 map-based climate adaptation tools, finding that tools could be divided into serving exploratory or explanatory user goals based on their interactivity features, as described by MacEachren (1994). Further, the authors found, based on their analysis of data content, that there was a lack of adaptation tools that provided integrated adaptation guidelines as opposed to general information relevant to climate change. In a competitive analysis of sea level mapping CVTs, Roth, Quinn, et al. (2015) observed that existing climate adaptation maps and sea-level-rise viewers could be made more effective by following established design principles, such as representing uncertainty with appropriate color mappings. In data journalism, Lee (2019) applied content analysis methodology to question whether CVTs in online journalism actually gave more control to users as they were purported to do. Similarly, Appelgren (2018) found that the restrictive types of interactivity included contributed to an "illusion of interactivity" in data journalism. Despite the appearance of giving users more agency, user experiences were in fact highly constrained. Interactivity also left the potential for users to miss important results, misinterpret information or be distracted from important features (Voinov et al., 2017).

The results of such evaluations emphasize the challenges facing developers in designing and gauging the success of CVTs. With important insights from a wide range of disciplines such as visualization, climate change communication, web design, GIScience, HCI, and psychology, integrating knowledge to select appropriate techniques and criteria for evaluation continues to pose significant challenges in research and practice (Lam et al., 2012).

2.6 Conclusions

According to the literature, web-based visualization has been promoted as an effective way to communicate and derive meaning from climate change data. CVTs were considered important in supporting climate education, public awareness, policy decisions, and data access (Newell et al., 2016). Visualizations can help the sharing of information by exposing patterns, condensing ideas and creating meaning from abstract data (Sheppard, 2012). Another proposed advantage of CVTs is their ability to provide individually relevant information to multiple users through the same interface, addressing a key challenge in climate change communication research (Shaw et al., 2009). Web-based technologies have provided access to a rapidly expanding array of new techniques, which can improve functionality and access to climate data. If used effectively, the resulting tools should have unique characteristics that can support tasks essential to climate change mitigation and adaptation (Moss, 2016).

Whereas many rationales have been advanced for using CVTs, critical evaluations suggest that neither visualization nor interactivity is guaranteed to be beneficial for achieving climate change goals (e.g., Xexakis & Trutnevyte, 2019). Disseminating climate research is a non-trivial problem implicating a wide range of disciplines. There remain significant gaps between intentions and practical outcomes in CVT development (Grainger et al., 2016). Better understanding the effectiveness of different visualization and interactivity techniques for achieving objectives will be important for the success of future applications.

A first step in addressing these gaps will be understanding current practices of development, dissemination, and evaluation of CVTs. The rapidly diversifying set of audiences, technologies, tool creators, and use cases, pose critical questions about what CVTs actually constitute in terms of their content, visual representation of information, and interactivity. Second, with the application of evaluation techniques from many disciplines and large variance within the literature, it will be important to articulate the goals of developers and understand whether and how CVTs are meeting their expectations.

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Preface to Chapter 3

Chapter 3 presents a content analysis to assess the first research question: "What are the characteristics of existing CVTs?" This study was motivated by the literature review presented in Chapter 2, which revealed research gaps in understanding of the purpose, design, and functionality of existing CVTs.

This chapter was co-authored with my supervisor, Dr. Renee Sieber, as a peer-reviewed journal article. We plan to submit the manuscript to *IEEE computer graphics and applications*.

Chapter 3. Interactive visualization of climate change in web-based interfaces: A content analysis

Abstract

Web-based data visualizations have become widely adopted across science outreach, journalism, and decision making, with the goal of making climate change information more accessible, actionable, and meaningful. Despite the rapid uptake of climate visualization tools (CTVs), little research has been done to understand the characteristics of CVTs that underpin their efficacy in meeting climate change needs. To meet this gap, this paper presents a content analysis of 41 CTVs, assessing their objectives, data content, visual representation, interactivity, functionality, and underlying technologies. The analysis reveals strong contrasts in content and functionality between tools, with several trends, including a focus on climate change impacts, the prevalence of maps, and the use of interactivity to filter data or reveal supplementary information. The widespread inclusion of social media sharing prompts also suggests an intention to increase distribution across social and news media. The findings suggest that CVTs are contributing to making climate data more accessible and transparent but also indicates an evolving practice. Our repository of 41 coded tools has been made accessible to support further analysis and insights to improve the capacity of CVTs to support climate change goals.

Key words: Climate visualization, climate web tools, content analysis, interactive visualization, climate change communication

3.1 Introduction

Interactive visualization has become a prevalent method for sharing information and data about climate change. Interactive visualizations of climate data increasingly appear in web-based interfaces, which we refer to as climate visualization tools (CVTs). By allowing users to directly interact with visual representations of climate change information, CVTs have been presented as improving cognition of large complex datasets. CVTs have made a significant contribution to closing gaps between scientists and non-scientists, who grapple with understanding distant impacts, evaluating risks, and implementing policies (Moss, 2016). CVTs have found increasingly diverse applications across climate journalism (Lee, 2018), decision making (Bohman et al., 2015), scientific outreach (Herring et al., 2017), and education (Bush et al., 2016).

The rapid proliferation of CVTs and increasing demand for climate change information warrants examination, since the presence of climate visualizations contribute to real-world consequences and commitments (Hewitson et al., 2017). However, research on CVTs has largely been carried out on a tool-by-tool basis across different disciplines. This discrete and non-standardized reporting makes it challenging to draw conclusions about the practice as a whole (Lee, 2018). Existing comparative analyses have largely focused on tools with expert users, despite the growing number targeted at the general public (Neset et al., 2016). Better understanding the diversity of existing tools is important for increasing the effectiveness of CVTs by highlighting design innovations and exposing gaps between theoretical and practical value (Pretorius et al., 2017; Roth, Quinn, et al., 2015).

To address this gap, we analysed 41 web-based CVTs by their objectives, audience, data content, visualization techniques, interactivity, outputs, and technologies. We collected a purposeful sample of tools that were freely available on the web and were aimed at non-scientist audiences. Each tool presented climate change data but served a variety of different use cases and contexts. Our sample included climate data portals, data journalism articles, decision support tools, and science outreach platforms. The aims of this study are: (1) to capture the diversity of existing practices in using web-based tools for climate change visualization, and (2) to identify key issues needing more attention in research communities.

The paper is structured as follows. We first discuss related literatures to inform a framework to analyze the visualization content of our sample of tools. We next describe our content analysis method and outline a typology for assessing CVTs. The results section presents the analysis of tools and relationships between variables, and the discussion describes emergent characterizations of tools, practices, and their implications for research and practice. We conclude with avenues for future research.

There are three main contributions of this work. First, we draw out key issues for consideration in visualization and climate change research by characterising existing CVTs. Second, we discuss the implications of tool characteristics for the intentions behind CVT design. Third, our typology and coded repository of 41 CVTs can serve as an entry point for others to contribute insights into the design, implementation, and value of CVTs in addressing climate change goals.

3.2 Related work characterizing climate visualization tools

We reviewed climate change visualization and related literatures to examine how researchers have approached the characterization and assessment of CVTs. Although reporting varies significantly between studies, disciplines, and tools, there are several aspects of CVTs that are important for their characterization, including their rationale, underlying datasets, visualization methods, interactivity, and implementation, as discussed below.

Whereas studies reporting on individual tools can give detailed information, because of their highly non-standardized reporting it is challenging to gain a picture of the range and variety of CVT techniques across the practice. Relevant knowledge is often dispersed, being discussed in various domains such as psychology (e.g., Harold et al., 2016), risk communication (e.g., Corner et al., 2015), and geosciences (e.g., Kaye et al., 2012). More significantly, as a widespread practice often driven by governments, non-profits, and commercial organizations, only a fraction of CVTs used in practice are likely to be formally reported in the literature (Lee, 2018).

A number of comparative studies on the content of CVTs have been conducted more recently. Those that have been conducted often focussed on specific applications of CVTs. Notable examples include Roth, Quinn, et al.'s (2015) competitive analysis of 25 sea-level visualizations tools, Neset et al.'s (2016) critical analysis of 20 map-based climate change adaptation web tools, Lee's (2018) content analysis of 547 interactive online climate change visualization news stories, Hewitson et al.'s (2017) review of 42 climate change information websites (19 of which were considered to contain interactive visualizations), Stephens et al.'s (2017) evaluation of the design features of 20 sea-level-rise viewers, and Fish's (2020) content analysis of 242 climate change maps (38 of which were considered interactive). Evaluations of CVTs required the establishment of assessment criteria, which break down the aspects of CVTs that are to be examined, depending on the objectives of the study. The purpose, data representation, interactivity, and implementation were assessed across many of these studies.

CVTs had a diversity of purposes that often were difficult to discern from their documentation alone (Hewitson et al., 2017). One common approach to classify purposes was to distinguish explanatory tools from exploratory tools (Munzner, 2014). This distinction is reflected in MacEachren's (1994) visualisation cube, which differentiates explorative, privately used "data explorers" from public-facing and more tightly constrained, "data viewers." For example, Neset et al. (2016) applied MacEachren's (1994) framework, to contrast adaptation maps that primarily allowed users to view climate-related data from maps which allowed users to both analyze data, inspect geographic objects, and display supportive visualizations.

A review of individual case studies revealed that CVTs serve a diverse set of objectives and user/provider groups. For example, Johansson et al. (2014) constructed a tool to support public adaptation to climate change and Gardiner et al. (2019) sought to facilitate the use of climate data in decision making. Describing the purpose was important for establishing how a tool related to climate change needs and how it was suited to meeting the needs of its users. On the other hand, target audiences were often loosely defined. Hewitson et al.'s (2017) comparative analysis of climate change websites found that their main providers were governments, researchers, and multinational entities, with commercial and not-for-profit entities playing a smaller role. However, their analysis focused on climate information websites, fewer than half of which contained interactive visualizations of climate data. The contextual information about developers from other comparative studies (e.g., Neset et al., 2016; Roth, Quinn, et al., 2015; Stephens et al., 2017) have focused largely on application-oriented tools (e.g., decision-support platforms) rather than CVTs used for more public or casual audiences.

CVTs present or provide climate change data, which can vary from meteorological climate model projections (Alder & Hostetler, 2015) to sector-specific impacts (Bohman et al., 2015);

particular use cases necessitated different data requirements (Moss, 2016). For example, tools modeling the average temperature of the earth did not require high geographic precision (Chandler et al., 2005), whereas tools used by local decision makers often needed localized impact data (Gardiner et al., 2019). Climate data was also often accompanied by complex caveats and uncertainties which required significant amounts of contextual understanding (Stephens et al., 2017). Describing the type of data being represented was thus a characterizing function of CVTs in establishing them within a broad, interdisciplinary field. The aspects of data content reported varied greatly. For example, Pickard et al. (2015) emphasized the breadth and variety of their dataset covering 150 indicators. In contrast, Netzel & Stepinski (2017) presented a single global climate similarity index dataset as a key innovation underlying the ClimateEx climate comparison tool.

Neset et al. (2016) compared choices of data topics and visual representations in CVTs. Analysis of data topics suggested that most tools show either climate model data or data on hazards, vulnerabilities, and risks, whereas few tools directly help users to take concrete actions. Similarly, CVTs that emphasize climate change causality and its underlying science have not been well studied, despite being highlighted as central topics in climate communication and decision making (Moser, 2016). Many studies have focused on web-mapping tools (e.g., Neset et al., 2016; Roth, Ross, et al., 2015; Stephens et al., 2017) but there has been little work assessing prevalent non-cartographic types of visualizations. Their findings exposed several design gaps between practice and established cartographic principles, such as the use of inappropriate colour schemes to represent data in maps (Brewer, 2015).

A defining aspect of CVTs is how visual representations are used to depict climate information. A poor visualization choice can hamper understanding of climate data, whereas an effective one can play a central role in its usefulness for conveying information, revealing patterns, or creating meaning from data (Munzner, 2014; Nocke et al., 2008). Display types were seen as a method to balance the need to make information accessible to an audience without obscuring the underlying complexities. For example, Bachelet et al. (2017) intended to enhance data exploration through the use of charts embedded in maps in the CBI Climate Consoles interface.

CVTs provide functionality through user interaction with the interface, although what constituted interactivity differed between tools and between studies. Across different CVTs, interactivity could allow users to filter, query, and re-symbolize multidimensional climate datasets (Alder & Hostetler, 2015), run modeling simulations to make "what if" future projections (Sterman et al., 2012), and deliver individually relevant information about risks and impacts (Burch et al., 2009). On the other hand, interactivity could also complicate usability: effective use required that a user know what functions were available and how to access them (Roth, Ross, et al., 2015). Making it clear to users what functionality was available and how functionality could be accessed represented a critical design consideration (Norman, 1988).

Interactivity was examined by several of the comparative studies but with significant difference in the interpretation of interactivity and the types of interactivity measured. Hewitson et al. (2017) used a binary operator to determine whether a climate change information website contained "static" or "interactive" graphics. Comparison of with subjectively assessed usability for each site suggested that complex interfaces could present barriers to achieving user goals. More detailed classifications could provide deeper insight into what interactions allowed users to do with the tool. Assessing visualizations in online climate journalism, Lee (2019) examined the degree of freedom visualizations gave users by distinguishing interactivity actions (clicking, typing, and hovering) and effects (access, provision, and transference) using Adami's (2015) semiotic framework, challenging disciplinary assumptions that data journalism improved the user's ability to draw independent conclusions. Roth, Quinn, et al. (2015) categorized potential user interactions using Roth's (2013) cartographic operators, finding that most sea-level visualization tools supported basic web map interactivity (e.g., pan, zoom, and retrieve), signalling a growing adoption of modern web technologies by tool developers.

There were aspects of interactive web tools that had little precedence in the visualization or related literatures and required new criteria and typologies. For example, to assess interactivity, Knight, (2015) adapted Yi et al.'s (2007) information visualization typology by adding in operators to describe narrative features of interactive journal articles (Boy et al., 2015). Another commonly unreported aspect was what user were expected to do after using the tool, such as sharing via social media or exporting saved configurations. Such considerations speak to an important objective of CVTs in raising the visibility of climate data (Lee, 2018).

Finally, the software architecture used to implement visualizations played a large role in their design, appearance, and interactivity (Knight, 2015). Tools are typically created using a "stack" of different software and web libraries, although the level of detail with which technologies were reported could vary greatly. For example, Koy et al. (2011) described the architecture of Cal Adapt by listing the libraries they used, including Django, MapServer, and Google Maps API. Adoption of particular technologies over others could impact the stability of tools and could simplify or complicate the development process, which was an important consideration given the resource constraints across many climate change visualization projects.

3.3 Methods

To better understand the evolving landscape of existing CVTs, we conducted a content analysis of a purposeful sample of CVTs. Content analyses are a systematic method of describing the content of textual or visual information, coding them into categories to make inferences through shared characteristics and variables (Neuendorf & Kumar, 2015; Rose, 2016). In this section, we describe how we collected our sample of tools, derived a typology to structure the analysis, and applied the typology to the sample.

3.3.1 Sample

To collect a purposeful sample of CVTs, we conducted an extensive web search using combinations of the keyword phrases "climate," "climate change," "interactive," "tool," "visualization," "graphic," "web tool," and "viewer." We supplemented this list with a structured search of peer-reviewed literature using the same keyword phrases. Finally, we used snowball search methodology to include tools that were encountered during the search, such as from the documentation or literature of tools that we had already identified (Biernacki & Waldorf, 1981).

As part of this search we applied the following inclusion criteria:

1. Focuses on climate change topics
2. Contains interactive visualization
3. Is aimed at non-scientists
4. Is freely and openly available on the web
5. Is available in English

Our criteria and search methodology were similar to those used by Neset et al. (2016) for climate adaptation maps, Hewitson et al. (2017) for climate information websites, and Stephens et al. (2017) for sea-level-rise viewers. The search was conducted between May and November 2019.

The list of 41 CVTs surveyed is shown in Table 3.1. We consider the list to be representative of existing CVTs used in practice at the time of assessment. Our sampling strategy includes tools that would likely be encountered in a user's search for data and information on climate change. Our full coded dataset is included in Supplementary Material. This dataset includes several additional coded properties that are not discussed in this paper, such as the types of guidance given to users, a search engine optimization (SEO) ranking of each site, and the number of time each CVT was linked in online news articles.

Table 3.1 The 41 climate visualization tools reviewed.

Climate visualization tool	Link
C-ROADS World Climate Simulator	https://croadsworldclimate.climateinteractive.org/
CAIT Climate Data Explorer	http://cait.wri.org/historical/US
Cal-Adapt	https://cal-adapt.org/tools/maps-of-projected-change/
Canada Climate Action Map	http://climate-change.canada.ca/climate-action-map
CBI California Climate Console	http://climateconsole.org/
Climate Analytics RegioClim	http://regioclim.climateanalytics.org
Climate Atlas of Canada	https://climateatlas.ca/map/canada
Climate Central Risk Zone Map	https://ss2.climatecentral.org
Climate Impact Map	http://www.impactlab.org/map/
Climate Ready Boston Map Explorer	https://www.boston.gov/departments/environment/climate-ready-boston-map-explorer
Climate Signals	https://www.climatesignals.org/
Climate Watch Data Explorer	https://www.climatewatchdata.org/data-explorer/
Climate Wisconsin Stories from a State of Change	https://climatewisconsin.org/story/temperature-change
ClimateData.us	http://climatedata.us/
ClimateEx	http://sil.uc.edu/webapps/climateex/
DECC 2050 Pathways Calculator	http://2050-calculator-tool.decc.gov.uk/#/calculator
EarthTime	https://earthtime.org/explore
EnviroAtlas	https://enviroatlas.epa.gov/enviroatlas/interactivemap/
Exposure to Climate Change App	https://maps.esri.com/MoraLab/CumulativeChange/
Fitzlab City App	https://fitzlab.shinyapps.io/cityapp/
Future Cities App	https://hooge104.shinyapps.io/future_cities_app/
Global Carbon Atlas	http://globalcarbonatlas.org/en/CO2-emissions
"How Much Hotter Is Your Hometown?" *NY Times*	https://www.nytimes.com/interactive/2018/08/30/climate/how-much-hotter-is-your-hometown.html
Monash Simple Climate Model	http://monash.edu/research/simple-climate-model
NASA Climate Time Machine	https://climate.nasa.gov/interactives/climate-time-machine
ND-GAIN Country Index	https://gain.nd.edu/our-work/country-index/
NDC Explorer	https://klimalog.die-gdi.de/ndc/
NOAA Global Climate Dashboard	https://www.climate.gov/maps-data#global-climate-dashboard
NOAA Sea Level Rise Viewer	https://coast.noaa.gov/slr/
"Precipitation in the 2050s" *The Revelator*	https://therevelator.org/interactive-map-precipitation-2050/
PREPdata	https://prepdata.org/explore
SNAP Data for a Changing Climate	http://mapventure.org/#/map/snap-data-intro
The Carbon Map	http://www.carbonmap.org/
The Climate Explorer	https://crt-climate-explorer.nemac.org/
The Global Carbon Budget: 1960 to 2100	https://galenmckinley.github.io/CarbonCycle/applet/
The Very, Very Simple Climate Model	https://scied.ucar.edu/simple-climate-model
	http://regclim.coas.oregonstate.edu/visualization/gccv/
Vermont Climate Change Mapping Tool	https://climatechange.vermont.gov/climate-tools
VisAdapt	http://visadapt.info/
"What's Really Warming the World?" *Bloomberg*	https://www.bloomberg.com/graphics/2015-whats-warming-the-world/
Yale Climate Opinion Maps	https://climatecommunication.yale.edu/visualizations-data

3.3.2 Procedure: the coding scheme

Informed by our analysis of the literature, we identified the following five questions that were important to characterising a CVT:

1. What is the purpose?
2. What is the data content?
3. How is data represented?
4. What functions can be accomplished?
5. What visualization technologies were used to implement the CVT?

We broke down each question into specific criteria to be assessed for each tool, as shown in Table 3.2. For each assessment criterion we established a set of categories. The scope of these categories needed to cover the entire set of possible answers and bridge the inevitable tension between being specific enough to say something of value while being general enough to apply across the diversity of CVTs.

We took a hybrid deductive/indictive approach to establishing categories (Fereday & Muir-Cochrane, 2006). We began with a predetermined set of categories informed by the literature and our own research experience (deductive), which we updated as we encountered new content during the coding process to better fit our data (inductive). This approach complemented the characterizing questions by allowing us to draw from established visualization research, while allowing for themes to emerge where there was little or no precedent in the visualization literature. As part of the coding process, we exhaustively explored the contents of each CVT and tested the interactivity features in Mozilla Firefox and Google Chrome browsers. We report the categories of the final coding scheme in Table 3.2. We describe categories generated deductively in the remainder of the Methods section below and report emergent categories generated inductively in greater detail in the Results section.

Table 3.2 Criteria, categories, and sources for the content analysis.

Research question	Assessment criteria	Categories	Source of analysis
1. Purpose	Organization type	University, non-profit, government, commercial	Organization website
	Target user group	Climate stakeholders, public, education	CVT website
	Goal	Explanation, exploration	CVT Website
2. Data content	Data types	Meteorological, environmental impacts, social impacts, causes, adaptation	CVT
	Geographic extent and precision	Global/continental, country/state, county/city, neighbourhood/individual	CVT
3. Data representation	Visualization types	Map (raster, choropleth, dot, proportional symbol, isoline, cartogram, connected), Chart (line, bar, timeline, pictorial, area chart, projection graph, stacked bar, bubble, flow, network, sparkline), Table	CVT
4. Functionality	Interactivity types	Reexpress, resymbolize, overlay, pan, zoom, filter, search, retrieve, calculate, narrate	CVT
	User inputs	Checkbox, dropdown select, slider, text field, scroll, file import	CVT
	Outputs	Data download, data subset download, tool download, social media share, share configuration, image snapshot, HTML embed	CVT
5. Technology	Visualization web libraries used in implementation	Library names	CVT source code

The purpose question aims to establish a sense of what the tools were designed to do. We used broad categories given the high variability in CVTs' use cases, target users, and content. To assess the goal of each tool, we drew from MacEachren's (1994) geovisualization framework to determine if the CVT was "explanatory" or "exploratory." The framework characterizes explanatory tools as targeting public audiences, having low interactivity, and presenting known information, whereas exploratory tools are characterized by private audiences, higher interactivity, and the discovery of previously unknown information. This distinction is well established in the visualization literature (Munzner, 2014) and was used in other comparative analyses (e.g., Neset et al., 2016; Roth, Quinn, et al., 2015). We also coded for the target user groups based on the CVTs' online documentation and any accompanying research literature. The diversity and vagueness of tool developers' target audiences necessitated broad categories, including the public, climate stakeholders (public or private groups with specific use cases), and education (students and teachers). These distinctions also helped us to locate this study in terms of existing research, which largely focuses on stakeholder use cases. Coding details about the organization primarily responsible for the CVT's development also helped to illuminate its context and purpose.

In answering "What is the data content?" we first distinguished thematic types of climate change data. Because some tools contained hundreds of variables, it was necessary to categorize broad thematic groups. We used categories similar to (Lee, 2018), including: meteorological (e.g., average temperature), environmental impacts (e.g., sea level rise), social impacts (e.g., a vulnerability index), causes (e.g., carbon emissions), and adaptation (e.g., climate change adaptation policies). If a tool contained more than one data type, then we recorded all that were present. Since the chosen climate data tends to be strongly geographic, another important aspect was its spatial scale, which could suggest different use cases. We coded for two significant aspects of scale: extent and resolution (Goodchild, 2011). For vector data (such as country-level carbon emissions), this category was straightforward to apply. Raster data, such as a temperature field, required a greater degree of judgement in assessing its resolution. To minimize the level of judgement required, we adopted four coarse ranges for the scale categories: global/continental, country/state, county/city, and neighbourhood/individual.

We coded for the visualization types used to represent data, which constituted a significant design choice. Coding for visualization types was also important for comparing our findings to past work that has largely focused on mapping applications (e.g., Neset et al., 2016; Roth, Quinn, et al., 2015; Stephens et al., 2017). We first recorded whether each CVT contained maps, charts, and tables. We then exhaustively recorded all visualizations types used in the CVT (as shown in Table 3.2 and illustrated in Figure 3.2).

We analyzed the interactivity functions afforded by CVTs, which had a strong bearing on their usefulness and ease of use. To examine visualization interactivity, we drew from Roth's (2013) taxonomy of interactive work operators. Despite being targeted at mapping applications, we found Roth's taxonomy to be the most comprehensive of those we considered, since it reconciled concepts from many extant visualization typologies (e.g., Buja et al., 1996; Crampton, 2002; Shneiderman, 1996; Yi et al., 2007) and had a close correspondence with more recent typologies (e.g., Boy et al., 2015; Brehmer & Munzner, 2013; Young et al., 2018). Roth's twelve operators included: reexpress, arrange, sequence, resymbolize, overlay, pan, zoom, reproject, search, filter, retrieve, and calculate. We excluded "arrange" and "sequence," which are primarily used to analyze rather than visualize data, as well as "reproject," which was mainly relevant for global-scale maps. We added Boy et al.'s (2015) "narrate" to describe simple user interactions that sequentially automated other visual operations (e.g., guiding a user through data exploration). To code our sample, we defined our 10 data interaction operators as follows:

- Reexpress – *change the data representation type (e.g., switch from a table to a map)*
- Resymbolise – *change the design parameters (e.g., change the colour palette used)*
- Overlay – *display a different variable (e.g., display temperature instead of precipitation)*
- Pan – *change the spatial centre (e.g., move a map to a different location)*
- Zoom – *change the scale or resolution (e.g., zoom in on a location in a map)*
- Filter – *show a subset conditionally (e.g., display data within a specific time range)*
- Search – *query a specified data point (e.g., identify a data value at a geographic address)*
- Retrieve – *show specific details about a data element (e.g., reveal a data value on hover)*
- Calculate – *derive new data from user configuration (e.g., run a climate model)*
- Narrate – *display a new section (e.g., scroll to automate a data reconfiguration)*

Next, the user input criterion examines the means by which users could enact interaction operators, such as text input boxes or checkboxes, in the spirit of Shneiderman & Plaisant's (2010) "interface styles" for InfoVis applications. The output criterion asks what users can take from their interaction with the tool. The categories included downloading the underlying dataset, downloading data subsets, downloading the CVT itself, exporting screenshots, sharing user configurations, sharing the CVT on social media, and links to embed the CVT on another webpage. Since there were a limited number of input and export options, we were able to code with a high degree of specificity. Because they were derived empirically, we describe the input and output categories in more detail in the Results section.

Finally, we analyzed the CVTs' software architecture. The choice of libraries used to implement a CVT could have a strong influence over its visualization and interactivity features. We developed several techniques to uncover the libraries that developers had used. First, we used browser developer tools to detect any external scripts being requested during the page load. Second, we inspected underlying HTML and JavaScript to examine data visualization elements for library-specific syntax. Finally, we inspected the packages listed in configuration files in sites made using a build tool (e.g., npm's package.json file). We created a final list of libraries for each tool accounting for dependencies between libraries. This allowed us to explore industry trends and compare technologies with those observed in other studies (e.g., Roth, Quinn, et al., 2015; Young et al., 2018).

To analyze the CVTs, we developed an initial set of codes which were refined through several iterations into a codebook with labels, descriptions, qualifications, exclusions, and examples for each criterion (Roberts et al., 2019). After reviewing the codebook on half of the tools, the completed template was applied to the whole dataset by exhaustively exploring and testing the features and interactivity of each CVT. The coding analysis was conducted between January 2020 and March 2020.

3.4 Results

This section presents the results obtained from the content analysis of CVTs structured by our characterizing questions: purpose, data content, data representation, functionality, and visualization architecture.

3.4.1 Purpose

3.4.1.1 Organization type and target audience

The main providers of CVTs were universities, non-profits, and government agencies, as shown in Table 3.3. The remaining six providers were categorized as commercial (three news

Table 3.3 Providers, target audiences, and tool purposes of the CVTs.

Criteria	Categories	Number of CVTs
Organization type	University	14
	Non-profit	11
	Government agency	10
	Commercial	6
Target audience	Climate stakeholders	18
	Public	12
	Education	7
	Multiple groups listed	4
Goal	Explanation	13
	Exploration	28

organizations and three web visualization companies). This finding may be reflective of the fact that the provision of freely available services is largely led by non-commercial organizations, as found by Hewitson et al. (2017). However, the majority (29/41) of tools were made by partnerships of multiple organizations. For example, the World Resources Institute's Climate Watch listed 10 partners, ranging from the Stockholm School of Environment's provision of data to Google's provision of support in developing concepts. According to their documentation, such partnerships could involve funding, data provision, development, or dissemination.

Based on descriptions from each tool's documentation, we classified target users into three broad groups: climate stakeholders, the general public, and education (students and teachers), as shown in Table 3.3. We used "climate stakeholders" to describe application-oriented users with a professional or community need for climate data, such as journalists, planners, community organizations, policymakers, or researchers. The "public" also represented a broadly defined audience of users described in many CVTs' documentation. Seven of the tools were designed for use by students or educators and were typically designed to be incorporated into lesson plans or to assist with independent study. Finally, four tools were explicitly described as serving multiple user groups. For example, the EPA's EnviroAtlas and CREATE Lab's EarthTime were explicitly targeted at casual users, decision makers, and educators; interestingly, the developers of these tools created separate sections of their interface for each audience.

3.4.1.2 User goal

Two-thirds of CVTs (28/41) primarily supported the goal of exploration; for example, the World Resources Institute's CAIT Climate Data Explorer enabled users to navigate several climate datasets. Of these, seven also allowed users to simulate a model; typically, climate models were targeted at education applications. For example, UCAR's The Very, Very Simple Climate Model allowed users to run a one-dimensional model of earth's average temperature. Thirteen CVTs explained climate change, which included interactive journalism articles such as the *NYT*'s "How Much Hotter Is Your Hometown?" They also included the sharing of results by several university research laboratories (e.g., Crowther Lab's Future Cities App) and public outreach by science organizations such as NASA's Climate Time Machine.

There were several CVTs for which the distinction was less clear-cut. For example, *The Revelator*'s "Precipitation in the 2050s" included linear narrative content but gave users access to an interactive map at the end to let them explore. Four tools gave access to large climate datasets, but in their documentation described their intention for the tool to be to present a particular dataset (e.g., by allowing users to export a static screen capture of the interface). For example, the websites of CREATE Lab's EarthTime indicated "[it] is regularly used to share data-driven stories with the public," such as in classrooms or conference presentations. Such CVTs served a dual purpose: they allowed presenters (e.g., instructors or public speakers) to explore a dataset and generate their own analyzes and gave them functionality to use the tool as part of presentations. Such CVTs could be used in community planning and outreach sessions in which users (e.g., policy makers) could add their own narration layered on to frame discussions.

These categories aligned closely with the target audience categories: 10 of the 13 explanation tools were aimed at public audiences, whereas 22 of the 28 explorations tools were aimed at climate stakeholders. For cross-tabulations with other variables (presented in the following Results sections), the explanation/exploration distinction was nearly synonymous with public/private distinction, where private refers to both stakeholder and educational audiences.

This aligned with MacEachren's (1994) characterization of data explorers as serving private audiences.

3.4.2 Data content

3.4.2.1 Climate data type

We categorized data types into five categories: meteorological, environmental impacts, social impacts, causes, and adaptation. Figure 3.1 shows the distribution of climate data types in the CVTs across public and private audiences. Explanatory CVTs targeted at the general public tended to focus on meteorological impacts and, on average, included only one data content type. In contrast, exploratory CVTs accounted for the majority of other data types and had a higher average number of data types of 1.5.

Most common across all CVTs was meteorological data, which mainly consisted of air temperature data, but also included precipitation and extreme weather event frequency. The statistical representation of temperature data varied between CVTs and could impact their interpretability to users. Some CVTs presented absolute values for temperature, such as HabitatSeven's ClimateData.us. However, such yearly or monthly averages may have little interpretability to audiences and can make deviations hard to distinguish. Visualizing temperature changes (or anomalies) between periods represented an alternative to absolute temperatures that better emphasized differences. Other CVTs such as the Carbon Atlas of Canada presented data products intended to be more meaningful to public audiences, such as changes in the number of days above 30°C. Finally, two CVTs translated future changes in climate conditions into present day climate analogues. For example, the Fitzlab City App linked current and future climates between North American cities.

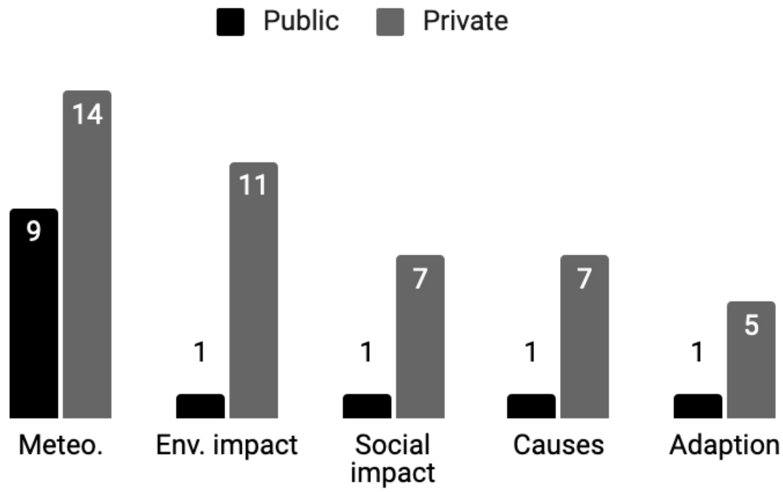

Figure 3.1 The types of climate data represented in CVTs split by audience.

The next most common data type were environmental impacts, found in 12 CVTs, the majority of which were exploratory tools. A common topic was sea level rise, with three CVTs coming under what Stephens et al. (2014) call "sea level rise viewers," such as Climate Central's Surging Seas and NOAA's Sea Level Rise Viewer. Other environmental impacts included changes to biology and landscapes, as found in CBI's California Climate Console. Next, eight tools contained social or economic impacts data, which included risks to human systems such as agriculture, infrastructure, and livelihoods, as well as indices for human vulnerability to climate impacts. Like environmental impacts, social impacts tended to be representative of CVTs with more specific user groups or use cases.

Next most common were data on the causes of climate change, all of which focused on greenhouse gas emissions or energy consumption. For example, DECC's 2050 Pathways Calculator allowed users to compare the costs and benefits of various energy-emissions mitigation strategies. Finally, six tools included climate adaptation data, which typically included comparisons of different countries' adaptation policies. For example, The German Development Institute's NDC Explorer allowed users to compare the numerical aspects of countries' Nationally Determined Contributions as part of The Paris Agreement, such as the quantified adaptation targets. In contrast, NordStar's VisAdapt allowed Nordic homeowner users to calculate individual-level adaptation advice based on their specific inputs.

3.4.2.2 Geographic scale

We adopted coarse categories to assess geographic extent and resolution of data shown, which included: global/continental, country/state, county/city, and neighbourhood/individual. Table 3.4 shows that just over half of CVTs (24/41) covered a global/continental extent. Of these, six also had a global/continental resolution, all of which included meteorological data and focussed on the earth's average temperature. For example, Climate Interactive's C-ROADS allowed users to model the influence of continental emissions on the average temperature of the earth. Seven CVTs had a global/continental extent and a country/state resolution. These generally focussed on comparing country-level data, five of which focussed on causes (country-level carbon emissions). The remaining 11 of the CVTs at the global/continental extent and a county/city level resolution. Most of these (8/11) included climate data but with a greater focus on impacts, either environmental (5/11) or social (3/11). Of the 10 explanatory CVTs aimed at public audiences, seven had a global extent.

Of the remaining 17 CVTs, 15 had an extent at the country or state level. Thirteen of these had the goal of data exploration and 11 of these were aimed at climate stakeholders. Nine CVTs had data at a neighbourhood or individual level of precision, notably including all three CVTs showing the impacts of sea-level rise, three municipal planning tools and two tools telling individual-level human stories. These findings suggested that geographic scale is associated with the type of climate data being displayed and the purpose of the tool.

Table 3.4 Geographic extent and resolution of each CVT, represented by shaded rows.

3.4.3 Data representation

We found 19 different visualization types used in CVTs as shown in Figure 3.2. We grouped these into three overarching categories: maps, charts, and tables. We then distinguished sub-categories for maps (raster, choropleth, dot, proportional symbol, isoline, cartogram, and connected points), charts (line graph, bar chart, timeline, pictorial, area chart, projection graph and stacked bar chart, bubble chart, network map, sparkline charts, and flow diagrams), and tables. Exploratory CVTs contained on average three types of data visualization types, whereas explanatory CVTs contained an average of two different visualization types.

Alongside the illustration, Figure 3.2 includes the frequency with which each type was found in our sample. The most common visualization type in our sample were maps, which were included in 36 of the 41 CVTs, emphasizing the centrality of cartography to climate visualization. Most common were raster maps, found in 20 CVTs, which typically presented climate temperature data. The next most common were choropleth maps (11/41) and dot maps (8/41), which were used for a wider variety of climate data topics. Less common were proportional symbol maps, connected maps, and cartograms (such as Kiln's The Carbon Map).

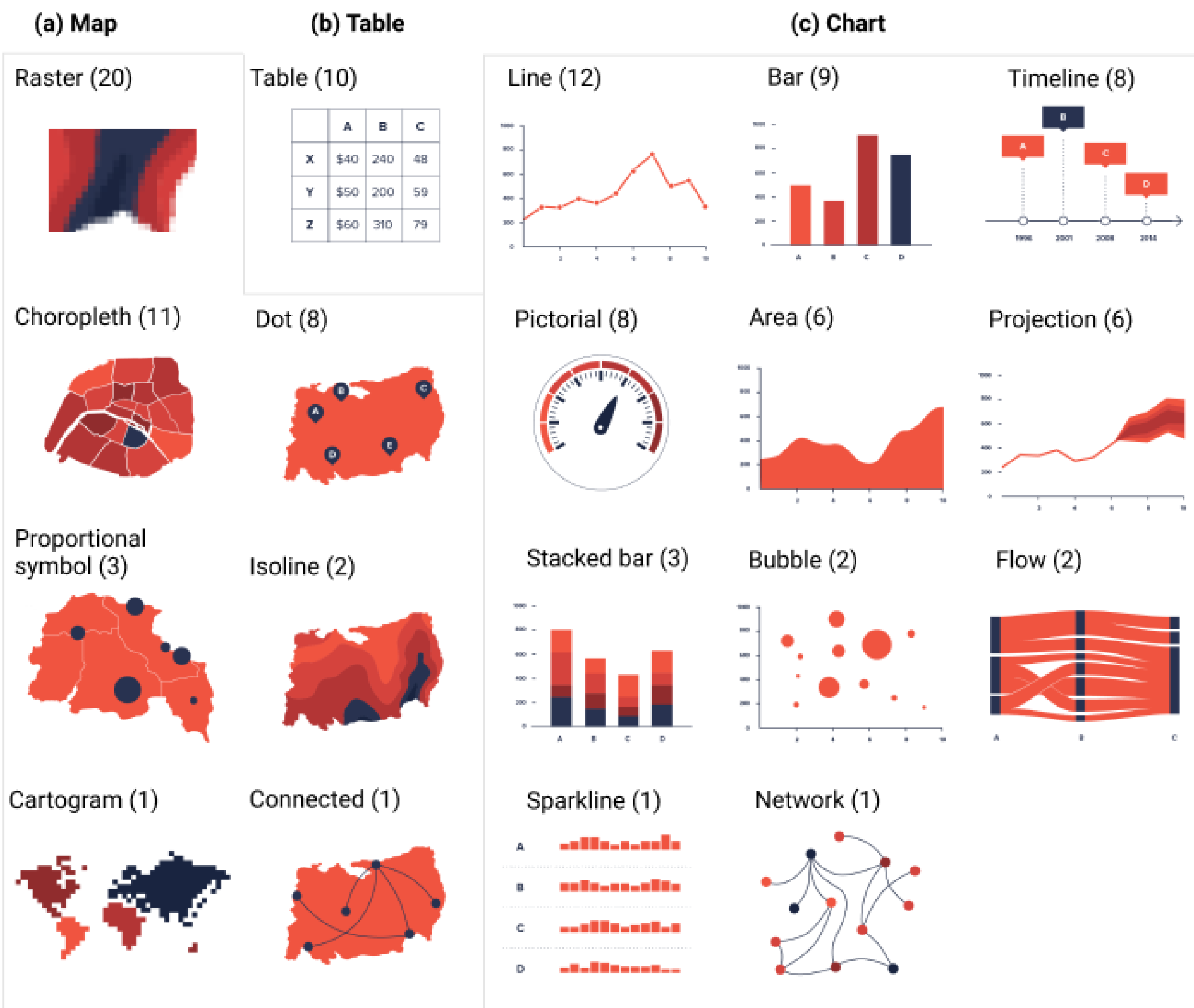

Figure 3.2 Types and frequencies of visualization use to represent climate change data.

(Source of icons: https://datavizproject.com/, CC By-NC-ND 4.0 International License).

The most common chart visualization type was the line graph, found in 12 CVTs, in all cases to represent the change of a variable over time. A total of 9 CVTs featured bar charts, but they were generally not the focal part of the interface; often they were included in pop-outs or additional information sections, such as in a side panel of CBI's California Climate Console. There was not a significant difference between the explore and explain categories for line and bar charts. Less commonly used visual encodings included pictorial and flow diagrams. Pictorials were used in eight CVTs, often to make data visualization elements look more like recognizable or real-life objects (e.g., sea level dials in Climate Central's Surging Seas). Against our expectations, all eight pictorial diagrams were included in exploratory CVTs, which may reflect that although they were targeted at private use cases, the audiences could still be considered non-experts in climate science. For example, NordStar's VisAdapt was targeted at Nordic homeowner and used dials to represent changes in air climate variables.

Ten CVTs displayed data in tabular form, often to assist users in viewing data prior to downloading. Contextual information about the data was important for climate data that could contain complexities, caveats, and uncertainties. As might be expected, the majority (9/10) of tables were included in exploratory CVTs, which were more focused on allowing users to view raw underlying data values.

Five CVTs juxtaposed multiple visualizations of the same variable to allow users to compare visualization elements side by side (e.g., comparing social vulnerability under different emission scenarios). A more visually compact approach to juxtaposition was to superimpose two versions of a data visualization (typically a raster map) and to use a slider to overlay one version over the other, such as in HabitatSeven's ClimateData.us. This could potentially make point by point comparisons easier, since the user could look at the same part of the screen (as suggested by Kinkeldey et al., 2017).

3.4.4 Functionality

3.4.4.1 Interactivity types

We used 10 interaction operators to describe the kinds of interaction functionality available to manipulate data. Similarly to Roth (2013), we grouped operators based on what they let the user do: change what variables are presented (overlay, narrate), change how data is presented (reexpress, resymbolize), adjust their viewpoint (pan, zoom), and access additional detail (retrieve, filter, search, calculate). Table 3.6 shows the relative occurrence of each operator across explanatory and exploratory CVTs.

The most commonly used interactivity type was overlay (36/41), which allowed users to change the variable being shown in the visual display. Most frequently this meant changing data thematically (e.g., from a temperature to precipitation). Some CVTs also allowed users to toggle the statistical representation being used to represent the same variable. For example, the Climate Impact Map allowed users to toggle between absolute temperature values and changes from historical levels. The other operator that allowed users to change what was being displayed was narrate. Six CVTs had interactivity that guided the user through automated steps of data manipulation or analysis through basic input from the user. An approach to encoding narration used in two explanatory CVTs (both data journalism articles) was scroll storytelling (or "scrollytelling"), in which a user scrolls to automate the manipulation of data representations alongside textual analysis. For example, Bloomberg's "What's Really Warming the World?" emulates scientific steps of reasoning for the user by analyzing different potential causes of the earth's change in temperature. We also observed guided storytelling elements in four of the exploratory CVTs. For example, CREATE Lab's EarthTime allowed users to create guided walkthroughs for their own presentations; data stories could be recorded to automate zooming, filtering, highlighting, and text annotations via next buttons.

There were relatively few occurrences of operators that allowed users to change the type of visualization used (reexpress) or the design characteristics of the visualisation (resymbolize). Some exploratory CVTs (12/29) allowed users to reexpress the same underlying dataset using different visualization types. This could help to emphasize different aspects of the data. For instance, WRI's Climate Watch allowed the user to view emissions data as different types of line charts and as a data table. In contrast, there were no explanatory CVTs that facilitated changes of visualization type for the same data. Similarly, only two of the 41 CVTs allowed users to resymbolize data elements. Both examples allowed the user to adjust the opacity of data layers on map.

Operators that allowed users to alter their viewpoints (pan and zoom) were common across all CVTs (28/41 and 29/41 for panning and zooming respectively). In all but one case, viewpoint operators were used to navigate web map interfaces. Zooming could allow users to view a particular area in more detail and panning allowed them to view a different subset of the data based on its geographic location. The most common (and conventional) method for encoding viewpoint interactions was to use dragging for panning and scrolling for zooming. However, some CVTs used both dragging and scrolling for panning operations, causing redundancy, and requiring users to click a button to zoom (e.g., the Canada Climate Action Map).

Zooming and panning encodings presented several usability problems across CVTs. First, zooming via scrolling could interfere with page navigation for maps that were embedded in long webpages (rather than full-page applications), since scrolling could be used to encode both zooming into a visualization and vertical movement up or down the page. For example, in *The Revelator's* "Precipitation in the 2050s," the effect of scrolling depended on mouse location; when the mouse was outside the map, scrolling had the expected behaviour of controlling vertical page position, whereas when the mouse was inside the map, the user could not scroll down the page, obstructing page navigation. Panning via dragging in touch screen devices presented a similar issue. Second, the sensitivity of zooming and panning interactions impacted ease of navigation. Most issues stemmed from zooming being overly sensitive. Small user actions could lead to unexpectedly large changes in zoom level, making it hard to reach a desired zoom level. Third, the smoothness of panning and zooming could lead to undesirable user experience; slow loading tended to be a problem where many data layers were layered at one time or for older raster base maps. Finally, many CVTs allowed unrestricted panning and zooming. For all mapped variables, there were certain scales at which the data was relevant (e.g., determined by the extent and the resolution). While navigating CVTs that had few restrictions on zooming or panning, such as the EnviroAtlas, it was easy to lose track of the data, particularly when zoom sensitivity was high. This presented a particular challenge for designer of CVTs presenting information across multiple scales, such as Surging Sea's Risk Zone Map, which showed neighbourhood-level sea level rises for coastal cities globally.

Four operators were used to provide users with more detail, by revealing specific details about a data element (retrieve), showing a subset of the data based on conditions (filter), identifying a specific data value (search), and generating new data based on user input (calculate). Retrieve (also known as inspect in Yi et al., 2007) operators were commonly used across explanatory (8/13) and exploratory (24/28) CVTs. The most commonly used format were tooltips (i.e., a small pop-out window connected to the mouse location) accessed by hovering or clicking on an element in the display to provide additional information about the underlying data (e.g., a precise value at a point on a raster map). Another commonly used format was to provide additional information about a clicked data element in a separate part of the interface. For example, upon clicking a region in CBI's California Climate Console map, users were provided with supplementary charts, infographics, and text descriptions specific to the region. A downside of displaying large amounts of information via retrieve operations was that the user might not be aware of content that is initially hidden. The Yale Climate Opinion Maps represented a particularly strong example of retrieve operators by compactly representing the data label, value, and significance. Hovering over a region on the map revealed the name of the region, the value of the data variable for the region, and the population of the region. Clicking on the map zoomed into the particular region and updated a second linked data visualizations below the map (stacked horizontal bar charts). Hovering allowed a user to quickly assess data points across the map, whereas clicking allowed a conscious exploration of the region in more depth.

Filter and search represented similar operations to reduce the range of data displayed or identify specific features of interest. Filtering was less common in explanatory (4/13) than exploratory (16/28) CVTs. Filtering was most commonly used to display data depending on geographic areas or time periods. Location based filtering had a similar effect as panning and zooming in maps, by adjusting the geographic boundaries of displayed data. However, filtering could specify non-rectangular boundaries (e.g., country outlines) and more readily applied to visualizations that were non-cartographic. Though similar, search represented a distinct operation because a user specified a known feature rather than narrowing based on conditional parameters. A search implied a query based on a known feature, whereas a filtering was more likely to imply a more exploratory intention. Searches were most commonly used to specify a particular location through a text-based input box. Search was similarly less common in explanatory (2/13) than exploratory (17/28) CVTs.

Finally, calculate signified the generation of new data based on a user input. Seven of the nine instances of calculate occurred in exploratory CVTs. Four of the seven exploratory CVTs were aimed at educational use cases, allowing users to explore models of the earth's climate or energy balance. For example, the Global Carbon Budget allowed users to project future temperature rises based on carbon budgets. Also included were decision-support tools such as Climate Interactive's C-ROADS, which allowed users to run climate projections based on countries' GHG emissions. An interesting explanatory example was found in the *NYT*'s "How Much Hotter Is Your Hometown?" article, in which users were guided through climate projections specific to a location they entered. Calculate operators often gave the impression that the user input was being used to dynamically generate new content. However, inspection of several CVTs documentation revealed that this was often not the case, where model results had been pre-run.

Across operators, browser and device compatibility complicated how interactions were encoded, particularly for zooming and panning. The use of phones, tablets, and trackpads requires touch-based encodings, whereas desktops require mouse-based encodings. Browsers also led to inconsistencies. For example, the Climate Ready Boston Map Explorer web map could be zoomed via scrolling in Google Chrome but not in Mozilla Firefox. Incompatibility and interaction issues were alleviated in some CVTs by including navigation buttons that offered alternative methods for panning and zooming.

Some types of interactivity were largely a product of the libraries used to implement them. Web-mapping libraries often determined panning and zooming capabilities. Whereas many options were possible within individual libraries, default options were most often used. CVTs implemented with D3 frequently incorporated tooltips to show specific data values when a user hovered over a corresponding part of the display. Interaction techniques could therefore be strongly influenced by the choice of visualization technology; some interactivity may have been a by-product (intended or unintended) of the choice of architecture.

Table 3.5 Interactivity, user inputs, and tool output categories, split by the tool purpose.

Criteria	Categories	Number of CVTs		
		Explain (/13)	Explore (/28)	Total (/41)
Data interaction operations	Overlay	10	26	36
	Retrieve	8	24	32
	Zoom	8	21	29
	Pan	9	19	28
	Filter	4	16	20
	Search	2	17	19
	Reexpress	0	12	12
	Calculate	2	7	9
	Narrate	2	4	6
	Resymbolize	1	1	2
User inputs	Select dropdown	6	15	21
	Slider	5	15	20
	Checkbox	3	13	16
	Search box	1	12	13
	Scroll	2	0	2
	File import	0	1	1
Download outputs	Data download	4	20	24
	Download subset	0	7	7
	Tool download	0	4	4
Sharing outputs	Social media share	6	16	22
	Share configuration	0	14	14
	Export graphic	2	11	13
	Embed snippet	0	8	8

3.4.4.2 User input

We recorded the web elements that users could use to enact interaction operators and to input information into the tool, as shown in Table 3.6. Inputs included click options such as checkboxes (16/41), select dropdowns (21/41), and sliders (20/41). These were typically used to overlay variables (via checkboxes and select dropdowns) or to adjust a parameter (via sliders). Many such input methods were functionally the same. For example, an overlay layer could be toggled using a checkbox, a dropdown select menu, or a slider. However, different input options could give different user experiences. Another grouping were text fields requiring keyboard entry. Of these, one was numeric and the remainder (12/41) were text-based search bars, all to search for locations. Scrolling represented a simple interaction that was used in two data journalism articles to guide users through steps of data analysis. Finally, one CVT allowed users to upload files, suggesting that the CVTs surveyed were directed for exploring data rather than data analysis.

3.4.4.3 CVT output

To describe what the user could output from the CVT, we deduced and applied the following categories:

- Full dataset download – *download the entire underlying dataset*
- Data subset download – *download a subset of the underlying dataset*
- Tool download – *download the entire tool*
- Social media share – *share on social media (e.g., via a share button)*
- Share configuration – *share a configuration (e.g., through a URL)*
- Snapshot – *export a static image of the visualization*
- Embed – *export a snippet to embed in another site*

Such outputs represented an important part of what users can gain from using a CVT but are rarely captured in existing visualization typologies. The output categories fell under two groups: downloading (the first three bullets) and sharing (the latter four). One common output function was to download the underlying dataset, with 25/41 CVTs allowing the user to download the entire dataset. Of these, seven data exploration CVTs allowed the user to filter data within the CVT and download a specific subset of the data. This was particularly important for CVTs that had tens or hundreds of variables contained in terabytes of underlying data. It also reflected intentions behind the tool: whether the tool was seen by its developers as an intermediate step before the end user's application of the data outside the tool or the final stage of data exploration.

The majority of CVTs supported at least one method for sharing information. The most common output type, and one specific to web-based tools, was the ability to share the tool on social media, typically through a share button, and was present in 22 CVTs. More advanced examples (14/41) allowed users to share their configuration of the CVT as part of the post. For example, The Global Carbon Project's Global Carbon Atlas included the option to share selected options, data filters or specific queries entered by the user inside the tool. Another way of exporting user-specific information from CVTs was exporting a graphic. This consisted of a static image or PDF that could be downloaded or shared through a share button. Perhaps calling into question the explain/explore distinction, the majority of sharing options came from CVTs we labelled as "exploratory." To some extent this might be expected, since users may often want to share specific configurations found through exploration, or to save them by copying the share link for future use.

We also observed eight CVTs that allowed users to embed a version of the tool in their own web page by copying a snippet of HTML code. This could be useful for increasing the visibility of the tool by allowing (and encouraging) others, such as journalists, to include copies of the tool in their own web pages or articles. Lastly, four CVTs provided open access to their project repositories so that the tool in its entirety could be downloaded. This included two projects supporting open source decision making (DECC and SNAP) and two projects supporting open learning (UCAR's Very, Very Simple Climate Model and Monash University's Simple Climate Model). In conclusion, CVTs included a range of output options that could reflect a diversity of use cases, even within the same interface.

There was a significant difference in output options between explanatory/public and exploratory/private CVTs, as shown in Table 3.6. Of the 12 output options recorded in the 13 explanatory CVTs, six were social media share options, four were data download links and two were the ability to export graphics. In contrast, exploratory CVTs included on average three times more output options. In particular, downloading a subset of the dataset, downloading the tool itself, sharing a configuration, and embedding snippets were all exclusively included in exploratory CVTs. Such contrasts might be expected, since exploratory CVTs allowed more customization, targeted users with more practical use cases, and were sometimes designed as a platform for others to work from rather than a final product themselves.

3.4.5 Visualization technology architecture

Of the 41 CVTs, 36 called on at least one external library to support visualization, as shown in Table 3.5. Analyzing the libraries used by developers gave insight into how visual and interactive encodings were implemented. Most commonly used (15/41) was the JavaScript library D3 to create custom interactive data visualizations in the web browser, primarily for the implementation of static maps, dynamic maps, time graphs, and bar charts. Unlike many of the other charting libraries, D3 does not have "ready to ship" charts and graphs and required developers to adapt existing applications or create components from scratch. However, eight of these CVTs used a library that had D3 as a dependency, indicating that developers could instead using D3 via a dependent library, such as Plotly, rather than directly. A variety of charting-specific libraries were used to implement bar charts, time graphs, and flow diagrams, including Highcharts (3) and Chart.js (3).

Several web mapping libraries were used, including: Leaflet (11), Esri (11), Google Maps (5), Open Layers (4), Carto (3), and Mapbox (3). Web map libraries provided base maps, web map interactions (e.g., panning and zooming), and data visualization features (e.g., points and other geometries added as layers). Web map libraries were often combined to provide different functionalities. For example, PREP's PrepData explorer used Esri, Mapbox, and Leaflet to implement its map data interface. The web map libraries had a significant influence on interaction operators and associated usability issues. For example, Esri web maps corresponded with the panning usability issues discussed in Section 3.5.4.1. The use of libraries to produce non-cartographic visualizations was common but not universal. Most notably, Kiln's Carbon Map implemented a highly stylized cartogram without external visualization libraries by using scalable vector graphics (SVG, the markup language upon which D3 is based) and custom JavaScript. The choice of mapping technologies had significant design and functionality implications. For example, static maps kept the extent of the map fixed, whereas dynamic maps allowed the user to zoom and pan to view specific parts of the map in more detail.

Table 3.6 The frequency of the 12 most common visualization libraries.

Library	Programming language	Visualization types supported	Frequency
D3	JavaScript	Chart, dynamic map, static map, animation	15
Esri	UI, python	Web map, chart, table	11
Leaflet	JavaScript	Web map	11
Google Maps	JavaScript	Web map	4
Mapbox	JavaScript	Web map	4
OpenLayers	JavaScript	Web map	4
Carto	JavaScript	Web map	3
Flash	ActionScript	Chart, map, infographic, animation	3
Highcharts	JavaScript	Chart, dynamic map, static map	3
Chart.js	JavaScript	Chart, animation	3
Shiny Apps	R	Chart, web map, dynamic map, static map	2
DataTables	JavaScript	Tables	2

3.5 Discussion

Our analysis of 41 CVTs suggests that interactive web-based visualization already plays an important role in climate change communication, decision support, community data access, and education. The diversity of CVTs surveyed indicates an expansion from their early use in climate change outreach by scientists (Moser, 2010), to a more diverse set of creators and applications, both mainstream (e.g., climate journalism) and specialist (e.g., municipal climate planning support tools). This also was also reflected in the partnerships of organizations involved in their development, although government and researchers were still involved in most projects, as noted by Hewitson et al. (2017).

A simple characterization of CVTs split them into explanatory and exploratory categories (MacEachren, 1994; Neset et al., 2016). Explanatory CVTs were primarily targeted at public audiences and presented users with known information about climate change. Exploratory CVTs were characterized by more sophisticated functionality which facilitated a variety of uses by stakeholders, decision makers, students, and researchers. In the exploratory group, we further distinguished CVTs that allowed users to explore known information from those that facilitated data analysis, modeling, and the generation of new information. Our analysis of data content, interaction operators and output functionality demonstrated significant differences between these two groups. Specifically, exploratory CVTs covered a more diverse set of climate topics (e.g., social impacts and climate science), contained a greater number of data representation options, included a greater number of user input to manipulate the visual display, and facilitated outputs such as data downloads. In other instances, we found that a distinction was less clear-cut. We found that many exploratory CVTs were also intended to be used to present data to public audiences, such as CMU's EarthTime. Climate data exploration tools also included the highest number options to share CVTs on social media or via embed snippets, indicating they were intended to serve more diverse purposes than data exploration alone.

We also observed that a higher degree of complexity did not necessarily lead to more effective tools. In fact, some of the most compelling and usable designs had the simplest interfaces with the most restricted functionality, even in the case of exploratory CVTs. On one hand, a greater degree of interactivity can give the user more agency over data exploration, a quality shown to be important for helping with climate change education (Bush et al., 2016). On the other hand, unnecessary functionality could complicate interfaces and require a greater degree of guidance, making tools less intuitive to use, as found by Hewitson et al. (2017). Designers of CVTs face a significant challenge in balancing functionality with ease of use. Ensuring usability was particularly important for explanatory CVTs, for which a user may be expected to dedicate less time to learning functionality.

The analysis suggested that CVTs are aiming to make data more accessible and personalized. Our analysis of the geographic scales suggested that a moderate number of CVTs included social and personal layers (e.g., personal property damage), which past research has suggested can increase the salience of climate change information by presenting a more familiar entry point (Shaw et al., 2009). However, a limitation of even the more advanced datasets and models is that even regional climate models remain contested. There is a tension between the uncertainty of climate projections and the need for local-scale data. One way several CVTs approached this problem was by allowing users to explore a range of future scenarios. For example, two of the sea-level-rise viewers allowed users to visualize the impact any specified level of sea level rise and provided secondary information about the likelihood of such given levels under different scenarios.

Many characteristics of CVTs can be interpreted, to some degree, as reflecting the intent of their developers. For example, including functionality that let users embed the tool elsewhere on the web could indicate an intent to have the tool shared in news articles or adapted by third parties. Similarly, the inclusion of social media share buttons indicated a desire to have users share the CVT using their social media. The frequent occurrence of such functionality suggested that media visibility was important to many organizations creating CVTs.

In analyzing CVTs from the past 10 years, longevity also emerged as an important challenge. The rapidly evolving technology landscape continues to present challenges to developers, as has been suggested by Roth, Donohue, et al. (2015). Indeed, during a review of the CVTs eight months after the initial survey, three had been depreciated, and one had undergone a full version upgrade. Choosing a durable technology stack represents a significant challenge in building lasting climate change tools. Technical maintenance likely increases with the complexity of the interface and with the number of dependencies relied upon. CVTs could also depreciate in terms of their content. For CVTs whose purpose is delivering climate change data, having up-to-date datasets could require frequent updates to be useful to end users. In contrast, CVTs illustrating a concept in climate science, such as how climate models worked, had lower requirements for frequent content updates.

This study also tested the usefulness of existing typologies in assessing CVTs, and web visualization tools with non-expert audiences in general. We found that many existing typologies for interaction in information visualization were focussed on expert data analysis use cases. Such typologies emphasized operations that were more common in research or professional use cases, such as resymbolizing design elements, making annotations, and deriving new data elements (e.g., Brehmer & Munzner, 2013; Yi et al., 2007). We found Roth's (2013) typology of interaction work operators to effectively capture interactions, with several adjustments that included the addition of a narrate operator. We found it necessary to introduce new typologies to describe the input and output functionalities of tools which may be useful for future analyses of web tools. In particular, we found it important to capture outputs such as data downloads and media sharing since they represented significant objectives for CVT development and use. Our overall framework to characterize CVTs (purpose, data, representation, functionality, and technologies) and the empirically derived categories we developed to assess them could be applied both inside and outside of the domain of climate change to assess visualization web tools.

3.6 Conclusion

This study provided a systematic evaluation of 41 climate visualization tools, using a content analysis to analyze the objectives, data, techniques, and technologies used by developers. We adapted existing visualization frameworks and developed new typologies to analyze the defining characteristics of CVTs. We found that characterizing web tools as data explorers and data presenters was useful in distinguishing the functionality features of tools. We also found that data explorers were increasingly being aimed at non-scientist audiences. Our findings suggest that the CVT landscape is variable and prolific. This heterogeneity may help to address specific gaps between scientists, decision makers, climate stakeholders and the public. However, the rapidly evolving landscape means that earlier innovations risk being overlooked.

The growing use of visualizations on the web makes analysis of web-specific characteristics more important but will require that existing visualization frameworks and methodologies be extended to include web-specific interaction types, such as new types of outputs (e.g., social media sharing), interactivity types (e.g., scrolling to simulate data manipulations), and inputs (e.g., auto-populated location search bars). In this study, expanding visualization typologies for web-specific content was useful in revealing unique aspects in the context of climate change objectives. Specifically, web paradigms can help to identify metrics such as user inputs and outputs, which can complement climate visualization research.

A limitation of our analysis is that it did not capture the user experience, which is critical to the value of climate visualization tools. Empirical research can complement this type of work to connect the content of tools and intentions of developers to the experience of users. We encourage others to publish these findings and help to deepen our collective understanding of climate change visualization. To assist in future research, we made available our coded repository of 41 climate visualization tools. We hope that our analysis can help to stimulate discussion on the efficacy of CVTs and to improve their ability to serve climate change goals.

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Preface to Chapter 4

Chapter 4 presents an interview study to assess the research questions: “What are the intentions behind CVTs?” And, “How do we know if CVTs are meeting our expectations?” This chapter builds on the results from the previous chapter. Interviewing designers themselves allowed us to further investigate gaps between the design of CVTs and their real-world outcomes. To increase consistency between studies, we used the sample of tools from the previous chapter to inform our contact list for potential interviewees.

This chapter was co-authored with my supervisor, Dr. Renee Sieber, as a peer-reviewed journal article. We plan to submit the manuscript to *The Professional Geographer*.

Chapter 4. Interactive visualization of climate change: Who, why, and does it work? An interview study with designers

Abstract

Many organizations rely on interactive web tools to disseminate climate change research, communicate risks, inform decision making, and support scientific outreach. Despite the growing number of climate visualization tools (CVTs), there has been little work to understand what creators intended of their tools and how they gauged whether they met their expectations. To better understand the intentions of those behind CVT development, we conducted semi-structured interviews with CVT designers from 22 organizations across a variety of sectors, including government, journalism, science outreach, and research. We asked designers about their backgrounds and roles in CVT development; why they made their CVT; how they gauged whether it was working; and what successes or challenges they encountered. Based on our interview data, we distinguished five broad intentions: increasing the use and influence of climate data, supporting community participation, improving climate change literacy, increasing the visibility of climate change issues, and making climate data more meaningful. In gauging success, designers needed to triangulate a diversity of metrics since direct measurement against objectives often challenging. Designers adopted a range of formal and informal measures such as the number of active users, user observations, and feedback. Designers also faced significant challenges in CVT development, including simplifying complex climate information appropriate for their audience, ensuring the durability of their CVT given resource constraints, and disciplinary challenges given increasingly diverse tasks involved in CVT development and dissemination.

Key words: Climate visualization, climate web tools, designer interviews, interactive visualizations, climate change communication

4.1 Introduction

Interactive visualization has become an important means for disseminating information about climate change (Lemos et al., 2012; Voinov et al., 2017). In contrast to traditional means of dissemination, such as journal articles and reports, the use climate visualization tools (CVTs) to display and explore data had been argued to make climate change information more accessible to wider audiences (Newell et al., 2016), increase the salience and proximity of risks (Herring et al., 2017), increase the actionability of climate change data and services (Moss, 2016), and foster scientific literacy (Niepold et al., 2008). With the growing capacity of web services and the reach of the Internet, interactive visualizations have found rapidly growing uses in online climate journalism (Lee, 2018), scientific outreach (Herring et al., 2017), decision support (Palutikof et al., 2019), and education (Bush et al., 2016). The creators of such CVTs represent an increasingly diverse group of actors, whose intentions are a central driver of CVT development.

Despite the growing number of CVT applications, there has been little work done to understand who their creators are, what they intended at their initial stages, how they gauged success, and what challenges they faced in doing so. Rationales for development as reported in the literature or the documentation of CVTs may not reflect the actual expectations that designers had when initially embarking on tool development (Hewitson et al., 2017). Similarly, the extent to which CVTs met such initial expectations are largely unreported (Xexakis & Trutnevyte, 2019). Understanding the designer's perspective may be critical in determining whether CVTs warrant the allocation of resources to serve mounting climate change challenges.

To better understand the intentions behind CVT development, we interviewed 22 of their creators from varied organizations, including news media, national science agencies, non-profits, web development agencies, and universities. We asked respondents about their background and role in development; which problems their CVT was intended to address and how it was expected to solve them; how they conceptualized and measured success; what lessons they learned about the usefulness of interactive visualization as a medium; and what challenges they faced in realizing their intentions through CVT development. In this paper, we present the results and analysis of these interviews. We conclude with a discussion of emergent themes and implications for research and practice.

We argue that CVT development constitutes an increasingly interdisciplinary pursuit, which raises persistent challenges for designers who often have input across the design, development, and dissemination of their CVTs. Moreover, the dissemination stages represented a significant component of real-world success but often goes overlooked in current research. To meet these challenges, we encourage a wider discussion on the gaps between intention and real-world success and a more integrated articulation of the insights, guidelines, and best practices from across relevant disciplines.

4.2 Related work

Many rationales for using interactive visualization CVTs have been advanced. First, interactive tools have long been thought to help understanding of climate data by allowing users to navigate and explore information of their own accord (Andrienko et al., 2014; Nocke et al., 2008). In contrast to static visualizations, interactives can allow a user to navigate variables, filter irrelevant information, and probe subsets to uncover details (Shneiderman, 1996). Such explorative functionalities are particularly useful for climate contexts, which often involve large, multidimensional datasets (Nocke et al., 2008). Interactivity can also provide access to dynamic models or simulations, which can be used to make projections about the real world based on input parameters (Palutikof et al., 2019; Sterman et al., 2012), or to deepen understanding of the system being represented via experimentation (Chandler et al., 2005). It has been argued that these attributes can foster a deeper engagement with complex and abstract climate change subjects and make scientific results more accessible and transparent (Alder & Hostetler, 2015; Herring et al., 2017).

Interactive visualization has been proposed as an effective means for attracting diverse public audiences in climate change research dissemination (Newell et al., 2016). CVTs have been contrasted with traditional means of distribution (such as academic articles, reports, and press releases) in terms of making scientific impacts more tangible (Nicholson-Cole, 2005), accessible (Schroth et al., 2009), and compelling (Fish, 2020). Sheppard (2005) made the case that by imposing climate change impacts on realistic and familiar scenarios such as local landscapes, visualizations could help to create cognitive and emotional connections between users and the psychologically distant impacts of climate change. These deeper connections have been argued to have the potential to lead to changes in attitudes and behaviours (Shaw et al., 2009).

CVTs have also been presented as an effective means of delivering user-specific information. In particular, CVTs have been used increasingly to support the use of climate data in specific decision-making scenarios (Moss, 2016). CVTs have been proposed to make large climate datasets and models more accessible by letting users explore data within the platform itself rather than needing specialist software (Alder & Hostetler, 2015; Pickard et al., 2015). More recently, CVTs have become tailored to individual and evolving needs of specific sectors, making data more actionable in specific use cases (Palutikof et al., 2019). Similarly, CVTs have been proposed as a way of increasing the role of citizens and communities as stakeholders by facilitating participation in decision making (Lieske, 2012) and building resilience within communities (Johansson et al., 2017). Despite these descriptions, the problems of specific use cases, which designers envision their CVT addressing, are often not articulated.

Researchers have reported many challenges specific to disseminating climate change information (e.g., Moser, 2010; Moser & Ekstrom, 2010). Studies in the climate change communication literature point to distance in time and space as a potential communication barrier (e.g., Pidgeon & Fischhoff, 2011; Spence et al., 2012). For climate data applications, Glaas et al. (2015) argue that a low actionability of climate data makes it challenging to use in real-world applications. Lemos et al. (2012) identify a "usability gap" between current approaches to disseminating information about climate science to meet the specific needs of decision makers. The authors argue that narrowing the usability gap will require better framing platforms towards their specific end uses. On the other hand, Scharrer et al. (2016) found that simplification of science can lead to a discounting of expert guidance, pointing towards a tension between making tools more usable and overgeneralizing important scientific information.

Moreover, effective CVT development poses resource and technical challenges that are common across other fields of visualization and software development. Johnson and Sieber (2017) argued that despite framings of geospatial technologies (which often underly CVTs) as rapidly deployable, low-cost and low-expertise, concerns of resource requirements for implementation remained, particularly when considering their development and sustainability within organizations. Roth, Ross, et al. (2015) highlighted the challenges of keeping pace with emergent web technologies as posing issues concerning long-term durability. However, little has been discussed as to how such challenges influence the design and success of CVTs, which, given that the providers making them are often from government, research, and non-profit backgrounds, may be subject to particularly stringent budget and time constraints (Hewitson et al., 2017). Nor has there been much discussion about their long-term sustainability.

In the context of these challenges, research on climate visualization has become increasingly interdisciplinary. Whereas early communication efforts were largely undertaken by scientists themselves, tool development has come to involve input from science communication research which has identified specific barriers to communication (Moser, 2010) and provided guidance on representation and language (Corner et al., 2015). The increasing role of technology has come to implicate the fields of visualization and web design as foundational in CVT development. The fields of cartography and geography have provided insight into specific challenges presented by spatial climate data and provided new methods for data representation (e.g., Neset et al., 2016; Voinov et al., 2017). Recent work in the fields of geovisualization, human-computer interaction, and GIScience have refocused research onto users and introduced principles for user-centred design to ensure CVTs meet their design objectives (Roth et al., 2015). However, it is not clear how (or whether) these disciplinary insights are being adopted into practice.

There have been relatively few evaluations of the ability of CVTs to meet their real-world objectives. Some evaluation studies have reported positive results by examining specific dimensions of effectiveness through the study of individual cases, such as increasing understanding and beliefs about climate change (Herring et al., 2017), improving scientific learning outcomes (Bush et al., 2016), improving usability in decision aids (Wong-Parodi et al., 2014), and eliciting persuasive and emotional responses (Pandey et al., 2014). Others have presented more problematic findings, suggesting that the use of interactive displays could complicate decision-support tasks rather than improve performance, understanding or engagement (Voinov et al., 2017; Xexakis & Trutnevyte, 2019). Such studies highlight the potential of CVTs as well as the difficulties in realizing intentions.

Despite the wide variety of intentions and applications focused on real-world outcomes (e.g., increasing visibility of climate issues and influencing public policy), there have been even fewer discussions of the creators of CVTs, their intentions, and the methods they use to assess the prevalence and adoption of their tools in real-world scenarios. Such evaluations may be critical for uncovering potential problems in the real use of climate visualization tools.

4.3 Methods

We conducted semi-structured interviews with CVT designers to better understand their disciplinary backgrounds, their intentions for tool development, how they assessed their success, and what challenges they faced. We use the term "designer" broadly to refer to individuals who had an influential role in the creation of a CVT. We sought to speak to designers who had the greatest amount of creative oversight across their CVT's conception, design, and dissemination.

We contacted designers based on the CVTs they had made. We identified a purposeful sample of 41 CVTs (described in a corresponding study; Lumley & Sieber, 2020) using search engines and a structured literature search using combinations of the keyword phrases "climate," "climate change," "interactive," "tool," "visualization," "graphic," "web tool," and "viewer," as well as snowball sampling . We selected CVTs which: (1) focussed on climate change topics; (2) contained interactive data visualization, defined as a graphical display of information which users can manipulate (Munzner, 2014); (3) were not aimed at experts in climate scientist; (4) were freely available on the web; and (5) were available in English. We identified the responsible organizations for each CVT, leaving us with a shortlist of 44 organizations. We examined each organizations' websites to identify the person we determined to have significant creative oversight over the CVT's development. We contacted designers via email, giving the option to indicate if there was a more appropriate contact in their organization.

We interviewed 22 CVT designers from 22 organizations. Participants held a number of job titles that included "directors," "data journalists," "professors," "climate research scientists," and "web developers". Of the organizations we spoke to, six were government or federal agencies, five were private-owned or news-media corporations, five were non-profits, and six were research laboratories at universities. The CVTs that they had developed included three interactive news articles, three climate model simulation tools, two public information websites, and 14 CVTs which could be generically categorized as data exploration tools (Lumley & Sieber, 2020). A list of the organizations and their corresponding CVTs is given in Table 4.1.

We conducted semi-structured interviews via Skype or telephone calls. Each interview lasted between 40 minutes and two hours; there was some variation depending on the participant's availability and the speed with which questions were covered. We asked open-ended questions about specific CVTs that they had built and encouraged interviewees to describe their own experience and opinions using examples from their work. In each interview we asked designers the following questions:

- How would you describe your professional background?
- What role did you play in your CVT's development?
- Which problems did you intend to address by developing your CVT?
- How did you envision your CVT solving those problems?
- How did you gauge the success of your CVT?
- In which ways did the results match your intentions?
- What about CVTs makes them effective for achieving climate change objectives?
- What challenges did you face in realizing your intentions?

We recorded the interviews for later analysis and took extensive notes while interviews were taking place. We used Mozilla DeepSpeech (https://github.com/Mozilla/DeepSpeech), an open-source, offline speech-to-text engine, to provide rough transcriptions of the interviews. We used Scription, a custom-made transcription editor (https://github.com/smlum/scription), to listen to each interview in full, make corrections to the transcript, and highlight material relevant to each research objective. We followed an inductive approach to code our data (Boyatzis, 1998). First, we first labelled segments of text to create categories for commonly shared ideas. We then grouped similar categories to reduce redundancies as we worked through our data. Finally, we refined categories for each research question and applied them to the entire dataset. The final set of categories used to assess each criterion is given in Table 4.2. Human subjects approval was obtained for the research and respondents had the option of having their input remain anonymous or to be presented with attribution.

Table 4.1 Names of interviewees' organizations, CVTs, and organization type.

Organization	CVTs discussed	Organization type
Boston Planning and Development	Climate Ready Boston Map Explorer	Government
Environment Canada	ClimateData.ca, Climate Atlas of Canada	Government
NASA Jet Propulsion Laboratory	Climate Time Machine	Government
NASA GISS, Columbia University	EzGCM, EdGCM	Government
NOAA Climate Program Office	U.S. Climate Resilience Toolkit Climate Explorer	Government
UCAR Center for Science Education	The Very, Very Simple Climate Model	Government
US Environmental Protection Agency	EnviroAtlas	Government
USGS	National Climate Change Viewer	Government
The New York Times	How Much Hotter Is Your Hometown?	Media
Bloomberg	What's Really Warming the World?	Media
Carbon Brief	Carbon Brief Interactives	Media
Climate Analytics	Climate Analytics Interactive Tools	Non-profit
Conservation Biology Institute	Climate Consoles	Non-profit
Global Carbon Project	Global Carbon Atlas	Non-profit
Prairie Climate Centre	Climate Atlas of Canada	Non-profit
World Resources Institute	Climate Watch, CAIT Data Explorer	Non-profit
HabitatSeven	ClimateData.us, ClimateData.ca, U.S. Climate Resilience Toolkit Climate Explorer	Commercial
Vizzuality	Climate Watch	Commercial
CREATE Lab, Carnegie Mellon University	EarthTime	University
Linköping University	VisAdapt	University
University of Maryland	What will climate feel like in 60 years?	University
Yale University	Yale Climate Opinion Maps	University

Table 4.2 Criteria and categories for the interview coding.

Criterion	Categories
Designer background	Natural science, social science, technology, management
Designer roles	Orchestration, coding, dissemination, advisory
Organisational context	Large/ multi-partner, small/ independent
Intentions	Visibility of climate issues, use of climate data, meaning from climate data, climate literacy, community participation
Success metrics	Number of users, engagement, feedback, interface success, media coverage
CVT benefits	Personalization, user exploration, visual illustration, visual/ emotional appeal
Challenges	Resources, durability, complexity

4.4 Results

This section presents the results obtained from the interview study, including the backgrounds of designers, the intentions behind development, the conception and evaluation of success, the benefits of CVTs in meeting climate-specific objectives, and the challenges of CVT development. Throughout the presentation of our analysis, we use representative quotes to support our analytical claims and use block quotes to emphasize key summative ideas. We have anonymized or attributed quotes based on the interviewee's preferences.

4.4.1 Designer backgrounds and organizational context

We asked designers to describe their professional backgrounds, the roles they took related to their CVT's development and the organizational context in which the CVT was made. Designer backgrounds generally fell into four disciplinary categories: natural sciences, social sciences (including science communication), technology, and management, as illustrated in Figure 4.1. Eight respondents described their backgrounds as being in the pure and applied physical sciences, with four specifically involved in climate research. Thirteen described themselves as having social science or communication backgrounds, including three data journalists, six scientific outreach directors, and four researchers across the fields of climate communication, education, and human-computer interaction (HCI). Two respondents had backgrounds primarily in management and planning, both within government agencies. Although all respondents were involved in developing CVTs, five designers described having had a formal technology background in areas such as software engineering, data visualization, and web development.

In spite of specific job titles, most designers took on a wide range of roles during their CVT's development. We distinguished four broad roles played by respondents: orchestrators, developers, disseminators, and advisors. Orchestrators took a leading role in decision making across the lifecycle of the CVT and provided vision, set objectives, and managed teams. As a product of our sampling strategy, this described most respondents' primary role (20/22). Developers (9/22) were responsible for the implementation of the CVT, as well as its deployment and technical maintenance. Disseminators were involved in the application of the CVT in real-world settings, such as creating teaching materials for schools, establishing relationships with user communities, or promotion of the CVT to decision makers. Two respondents' primary responsibilities were in dissemination, whereas many orchestrators (9/20) played an active role. Finally, most designers (15/22) played an advisory role providing disciplinary expertise; for example, ensuring the scientific rigour of the CVT, establishing its efficacy in meeting user needs, ensuring technical feasibility, or producing the underlying dataset.

Designers worked in a wide variety of organizational contexts for CVT development, ranging from self-led operations to large teams spread across multiple partnering organizations. Twelve respondents worked in teams of more than five members, all of which involved multiple partner organizations. In such teams, decision making was often described as being a collaborative process managed across partners, although responsibilities were typically divided. Most respondents who were part of large teams (11/12) were not involved in the technical implementation; rather, they played orchestrating and advisory roles. Indeed, larger teams tended to be structured with well-defined roles, such as designers, developers, and outreach staff.

In contrast, the remaining 10 respondents worked in smaller teams with fewer than five core members. All operated within the context of a large organization, which included three universities, three online news distributors, three government science agencies, and one non-profit. Within such organizations, CVT development was typically not the organization's primary focus and could represent just one of many objectives. Such designers often described working with a higher degree of autonomy over their chosen topic than those in partnership contexts, although they were often still subject to organizational constraints. For example, data journalists could exercise a large degree of creative freedom over the topic of an article but were still required to fit within their organization's style guidelines. Such designers also often took on multiple roles; seven were the primary orchestrator, coder, and distributor of their CVT.

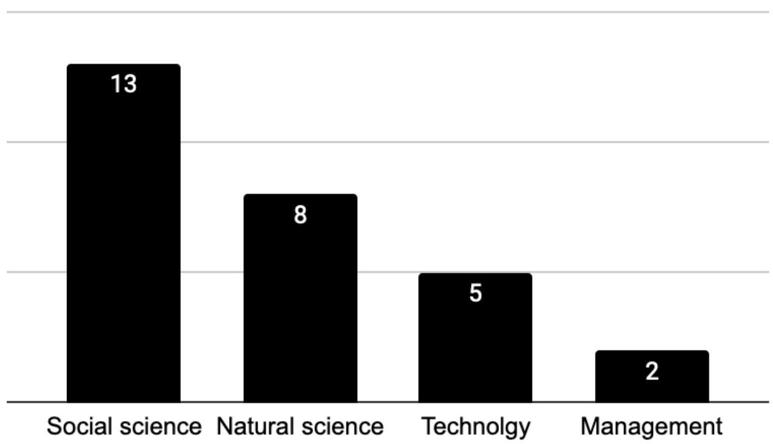

Figure 4.1 The primary disciplinary backgrounds of respondents.

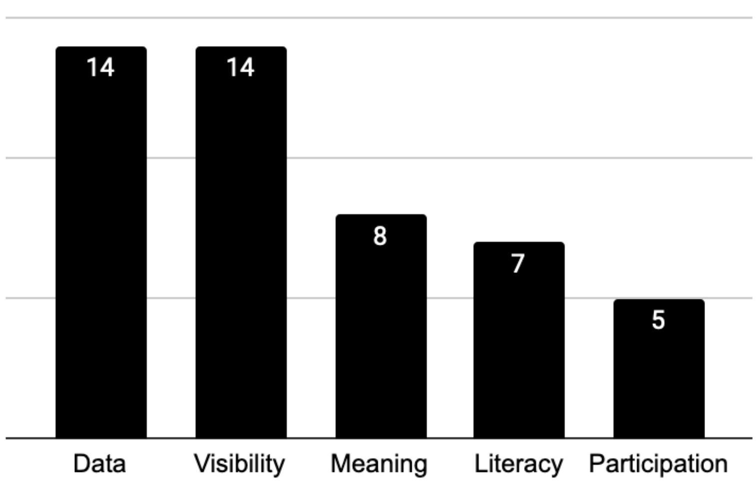

Figure 4.2 The number of designers describing each intention category.

4.4.2 Intentions behind development

To explore the intent behind CVT development, we asked designers which problems they intended to address and how they envisioned addressing those problems. There was a large diversity in the answers given, but several recurrent themes emerged. They included: increasing the visibility of climate change issues; supporting the use and influence of climate data; making climate data more individually meaningful; improving climate change literacy; and enhancing community participation in climate change activities. The number of designers reporting each intention is shown in Figure 4.2 and discussed below.

4.4.2.1 Increase the visibility of climate change issues

Many designers (14/22) intended to increase the visibility of climate change issues or results. CVTs were seen as a more accessible means to traditional scientific outlets, such as academic journals, in terms of the expected background knowledge and language. As explained by one designer, “You can access information in a few clicks, rather than having to go to academic literature.” A primary component of increasing visibility of climate change results described by 10 designers was getting stories and information in news and social media cycles. Higher visibility was seen as a means to “create conversation and dialogue about climate change,” and to “put pressure on decision makers to act.” However, fast-paced news cycles were perceived as being not well adapted to report on long-term climate change issues. Further, competition for media attention was characterized as “information warfare” by two designers. One designer framed well-funded climate change skeptic groups as actively and effectively using news and social media to discredit scientific results: “Scientists fighting for hearts and minds are losing to corporate, big time.”

One intended strategy for appealing to news media was to present climate information specific to a location, sector or individual. This could make the visualization more personally relatable; for example, by linking the visualization to memorable event and places. Starting from a personal perspective and then moving to the bigger picture could help to build empathy with distant places. For example, a part of Ian Mauro’s strategy for the Climate Atlas of Canada was to create city-specific reports directly from the platform to allow local news networks to display city-specific implications, citing science communication research that suggested that locally relevant results were more salient and more likely to be emotionally engaging.

4.4.2.2 Increase use and influence of climate data

The application of climate data in real-world settings was an objective of 14/22 designers. Designers perceived needs for climate change data in a wide range of applications, such as research, education, agriculture, decision making, and journalism, each of which "could bring in their own expertise to expand the impact of the data." There were several perceived barriers to climate data being applied that designers aimed to address. First, climate data was seen as having low usability for non-scientists, as explained by one designer:

> Raw climate change data can be complex, multidimensional, incomplete, with many caveats that need to be understood. It can require expertise, specialist software and a lot of patience to find and retrieve relevant information from terabyte-size files.

A second challenge was that different user groups often had different backgrounds and capabilities. This presented a challenge to designers who aimed to serve multiple audiences (9/22). These barriers were seen as making climate data less likely to be used, even in situations where its use could be critical. A specific goal of a number of designers (10/22) was to have climate change data to factor into planning and decision making. Johannes Friedrich of WRI described being motivated by the observation that climate data was being "underused in decision scenarios where it could be highly important." Whereas three designers targeted national-level policy makers, others saw a need for data that was specific to a sector or location: "specific data at the smallest unit is critical."

4.4.2.3 Make climate data more meaningful

A significant barrier to climate change communication raised by eight designers was connecting climate change information with everyday lived reality: "People may be aware and concerned about climate issues but feel unable to translate them into their personal lives and behaviours." In particular, the psychological distance of climate change was seen as a key barrier to connecting individual and societal behaviours with global-scale issues. Illustrating human stories and local impacts could make them more relatable and help to translate the full meaning projections and temperature changes to real people: "We need to remind people that data points are humans or related to human experience."

For example, Ian Mauro described storytelling as being a central design element of the Climate Atlas of Canada, envisioning a multimedia platform to connect climate projections to individual and community stories. This could "help people walk in other people's shoes to create empathy […] and create spaces for nuanced, authentic, face-based conversation." Digital media was seen as a way to reveal human climate change stories that might not otherwise be seen.

4.4.2.4 Improve climate change literacy

Improving science literacy in climate change was described as an objective by seven designers. Science literacy was seen as important in helping students and the public understand environmental policy decisions. One designer said that literacy was particularly important with climate change being a politically contentious topic that is subject to widespread misinformation. Three designers described frequent low-quality reporting or outright misrepresentation of climate science across news outlets, complicating the communication landscape and making it challenging for non-scientist individuals to interpret complex information. These designers saw an increase in science literacy as a way to help non-scientists decode conflicting messages that they saw about climate change and to better discount misinformation.

As exemplified by designers of two education applications, CVTs were seen as a way to provide access to data and functionality similar to those used by scientists, such as climate models. Exposing users to the tools used by scientists could help them to understand scientific inquiry, as well as the challenges facing scientists in their work:

> We wanted to make people go through all the options: the years, variables, statistics, colors. We force you to make all these decisions because that's the way science really works – you can't just push a button.

In contrast, a designer of a journalism article described intending to guide readers through a step-by-step process of scientific reasoning to make the "science more digestible." In both cases, increasing transparency in the scientific method was seen as having the potential to convince people of the reality and seriousness of climate issues, as summed up by one designer: “You can’t argue with the raw numbers.”

4.4.2.5 Support community participation

The central objective of five designers was to empower communities to participate in climate-related activities. This often included the provision of data, but also encompassed wider goals of building resilience within communities. One designer argued that often communities that were taking the brunt of climate impacts often lacked agency in local decision making. Citizens were also often seen as having lower access to resources and expertise than decision makers. There was therefore a need to provide “relevant and reputable information about climate change.” For example, one designer envisioned citizens bringing visualization printouts to town hall meetings, sending information to their local representatives, and supporting activist community networks. In these scenarios, their CVT could be used to bolster citizen empowerment by allowing them to “present facts backed by scientists.”

David Herring of NOAA's Climate Program Office aimed to advance users up a “ladder of participation” in climate science, motivated by the research literature: “It only takes a few actively involved citizens to enact social change, so enabling a small number of people can do a lot.” He further argued that a feeling of engagement in science could make citizens more likely to engage in pro-environmental behaviours, such as discussing issues within their social circles, messaging representatives, and participating in decision-making processes. This informed an intention behind NOAA’s interactive tools to allocate digital resources to support individuals who had demonstrated a level of interest, rather than to change the minds of climate skeptics.

4.4.3 Gauging success

We asked designers whether and how they judged the success of the CVT that they had made. All designers described a desire to understand whether or not their CVT was working as intended. Evaluations could help them to answer fundamental questions of what had worked, what could be improved in future development, and what lessons could be shared with the wider research community. Six designers also highlighted evaluation as being central to securing and sustaining funding.

On the other hand, measuring success was seen as a significant challenge: one designer described it as "*the* problem in climate visualization research." In most cases, measuring outcomes directly was impractical. For example, one designer said it was "nearly impossible" to know whether an article had changed a user's long-term behaviour; another described the difficulty of attributing the role a CVT had in influencing a national policy decision. Assessment of success was typically confounded by many other factors. Often, therefore, gauging success required identifying indirect metrics and determining practical methods to measure them. Whereas there was a wide range of approaches described by designers, there were five broad metrics that were widely reported: the number of users, the level of user engagement and application, feedback about the CVT, the theoretical efficacy of the CVT in experiments, and the amount of media attention received. The full list of metrics and methods described are summarized in Table 4.3.

4.4.3.1 Number of users

Nearly all designers (18/22) described the number of people using their CVT as an important metric of their CVT's success. Having people interact with a CVT in the real use scenarios was seen as a fundamental condition to having an impact: "Even if the tool was perfect, it couldn't have an effect unless it was actually being used."

The number of users could also be seen as a basic proxy for other types of success. One designer argued that the number of users was an indicator of the CVT's usefulness, saying, "People wouldn't use it if it wasn't useful." Other designers emphasized the importance of use by particular audiences. One digital journalist said that their interactives "doesn't have to be viral to be successful – sometimes it's more suited to a professional audience, or people who self-select as being interested." Similarly, two designers of educational CVTs described that knowing the number of teachers using their CVT in their lessons was more useful than knowing their total number of visitors.

Table 4.1 Metrics for success and evaluation methods used by designers.

Metric	Methods of assessment
Number of users	Web analytics, user accounts, informal tracking
Engagement/Application	Web analytics, user stories, user observations, educational studies
Feedback/User relationships	Informal conversation, surveys, workshops, webinars, awards, conferences
Interface success	Controlled experiments, benchmark testing, interviews, focus groups
Media coverage	Media tracking, media impact assessment

The number of site visits was typically one of the most straightforward methods to track. The availability and low cost of web analytics (particularly Google Analytics), mentioned by all but four designers, provided a straightforward estimate of the number of visitors. Some designers also used analytics to observe patterns in activity, such as spikes during launch or increased usage when climate change was in the news. This persuaded one data provider to plan their yearly release of climate data around a major climate conference, which was helpful in establishing themselves as a reliable source of information. To track small, specific audiences, four designers described maintaining informal lists of active users, which provided them with precise information but required a greater amount of upkeep.

4.4.3.2 Level of engagement

Many designers (13/22) described the importance of *how* users were interacting with the CVT and how it was applied in real-world scenarios. One designer emphasized that receiving a high number of visitors was "great, but not the end game." The quality of user interactions was conceptualized in terms of how long they spent with the CVTs, how fully they explored the interface, how deeply they interacted with the functionality, and how frequently they returned. One designer said, "Adoption into people's routines distinguished tools that were an interesting novelty from tools that genuinely helped users," although this varied depending on the intended use cases. Questions specific to different intended purposes asked by designers included: "To what extent was data incorporated into a decision?"; "Was downloaded data used in a new research study?"; "Did a user share their results on social media?"; and, "Are communities implementing plans?"

Measuring the nature of user interactions was typically more challenging than tracking the number of users. Seven designers used web analytics or logging to evaluate aspects of engagement with their site; for instance, to "trace which parts people are visiting and how long they spend." This provided information about the topics that users were interested in and which parts of the CVT they were first drawn to, from which designers could infer usefulness or appeal of different parts of the site. For example, one designer described using the regular recurrence of a cluster of visitors at a particular location to identify that their CVT was being used in a university class. However, designers found it "harder to measure what people are doing after using the tools," and often relied on feedback from users. One designer added a survey question before data could be downloaded that asked users their purpose and which revealed use cases that they "could never have thought of [themselves]." A digital journalist designer described a key measure of success for them was seeing people share personalized versions of the CVT on social media; "it suggested [users] are not just passively reading this, they're really interested."

4.4.3.3 User feedback

Thirteen designers cited user feedback as being central to gauging success (both as a metric and a method). For example, Ian Mauro described their team as "maintaining a constant dialogue between [themselves] and the community over whether it's working." User feedback was used to provide information on many aspects of success such as the usefulness of the CVT, its value to users, and the extent to which users felt actively involved in its development. User feedback could come in structured formats such as surveys, or through informal interactions, such as discussions, casual encounters, and unsolicited emails. One notable example came at presentations of a CVT mapping climate change opinions:

> For live audiences, a particular sequence of maps would [elicit] an audible gasp in the audience – that kind of feedback was useful. Seeing people having an "ah ha" moment tells you you're sharing something new with them.

User feedback also provided many designers with their strongest personal feelings of success about the CVT. David Herring described the feeling of accomplishment when they "received user emails saying how inspired they were, how unique [the CVT] was, how it became a part of their day." On the other hand, designers found limitations to conversational feedback; for example, one designer reported that people often felt the need to portray the CVT positively: “You don’t get much on usability from unprompted feedback – I think it’s not the kind of thing that most people anecdotally will come up and say.”

4.4.3.4 Efficacy of the interface

Another measure of success described by 10 designers was the efficacy of the interface itself in solving intended problems. Examples of metrics specific to particular intents included scientific learning outcomes, user attitudes towards climate issues, and the usability of climate change information. It was often not practical to assess these questions for the entire user base; instead, evaluations assessed a sample of users. The CVT’s effectiveness for accomplishing particular tasks was often actively assessed as part of the development stages as well as after the launch. One method described by five designers was passive user observations. One such designer described the value of informal observations in encountering problems that they may miss as designers:

> We see what users miss and the capabilities they don’t notice, like scrolling down to see more data or clicking a legend. My mother-in-law didn’t know you could click it at all!

Other designers (7/22) conducted controlled studies such as benchmark tests, focus groups, and interviews. Measurement focused on a sample of users (either real or recruited): testing before-and-after outcomes, and aspects such as the potential usefulness (6/22), ease of use (4/22) or subjective feeling of using the CVT (2/22). Active measures were described by one designer as complementing passive measures by allowing designers to understand the reasons why someone used the CVT in a particular way, which could help to reveal gaps in understanding between the designers and the users.

Another method of assessing the effectiveness of an interface described by four designers was through feedback from experts through consultation, peer review, conferences, casual encounters, and awards. This implicated various fields such as science communication, psychology, and human-computer interaction. Johannes Friedrich described gaining as much as

75 percent of the design insights for Climate Watch from expert feedback, compared to 25 percent from user testing, which, while important, was more expensive and more time intensive.

4.4.3.5 The amount of media coverage

Whereas media visibility was an explicit intent of 10 designers, 14 described success in terms of the media coverage they had received. Coverage in news and social media was a critical factor in reaching diverse audiences and giving designers a wider platform to increase visibility of climate change information. As summed up by Ian Mauro: "Creating attention in itself has huge value." Indeed, if a CVT went viral, "it could gather enough momentum to reach hundreds of millions of people in days."

The simplest methods of gauging media coverage included tracking references to a CVT in news or social media, as described by five designers. A formal media analysis was described by Ian Mauro, whose team contracted a third party during the initial launch phases of their CVT to trace the presence of the CVT across social, online, and traditional news media. This calculation estimated the potential views of the Climate Atlas of Canada as over 150 million, which helped them to confirm the reach of their CVT.

4.4.4 The benefits of interactive visualization

We asked designers which features of interactive visualizations made them effective for addressing climate change challenges based on their tool evaluations. We identified the following widely cited benefits: personalization, user exploration, visual illustration, and emotional appeal.

4.4.4.1 Personalization

The ability to personalize information to users was seen by 13 designers to be a key feature facilitated by interactivity. Particularly in local decision-making contexts, precision was seen as critical to data being useful in real-world scenarios. CVTs were described by one designer as unique in meeting the need to deliver high-resolution, local-, and sector-specific data to decision makers in a format that was usable by non-scientists: "There's simply no other way to deliver that amount of information."

Five designers reported localization as being central to the salience of their CVT with users or news media. For example, Ian Mauro described a "huge media uptake" in response to city-specific reports generated by the Climate Atlas of Canada. Another designer found that delivering location-specific climate forecasts as helping to increase the personal significance to individual users: "Personalization gives people a new view into a topic that they might otherwise have glazed over." Matt Fitzpatrick of the University of Maryland found that despite not having considered visual appeal at the forefront of their designs, their reimagining of a climate dataset that personalized it to individual users attracted "significantly more media attention than [they] had anticipated."

4.4.4.2 User exploration

Another key aspect of interactives highlighted by 10 designers was that CVTs gave users freedom to explore data on their own accord using functionality like filtering, zooming, or reconfiguring data representations. This was important for linking individual views of data with broader views, particularly in climate change contexts that operate across individual and global scales. As described by Johannes Friedrich: "If you've just got the data you're going immediately to the deepest level – with an interactive it helps you look from a very abstract level." Based on education assessments, one designer also found user autonomy to have significant benefits for student-learning outcomes:

> You can start asking questions you didn't even know existed. This is the main difference from statistics or infographics – they don't stimulate your thinking processes in the same way.

User exploration was important for specific users and use cases but could complicate other CVTs. Flexibility was found to be a key attribute for teachers (to adapt their lesson plans) and students (to practice testing their own research questions). Similarly, it could give the user a sense of "ownership" over their own experience, leading to a greater level of engagement. However, other developers emphasized the importance of restricting options in clarifying their messages, particularly in data journalism articles.

4.4.4.3 Visual illustration

Ten designers found interactive visualizations to be an effective and efficient method for illustrating complex climate concepts and data. Visualizations could quickly convey patterns in data that would be cumbersome to describe in words: "You can see things immediately – stories immediately pop out." Another designer summarized: "A graph can convey something that would take 1,000 words. An interactive can do that for 1,000 graphs."

One setting in which illustration was found to be particularly important was collaborative decision-making scenarios such as group meetings or public consultations. Ensuring parties had quick access to information could help make agreements more efficient. Many designers argued that interactives could "lower the bar of participation." This was particularly useful for a topic like climate change, where often expert knowledge was needed to understand technical details. Visualizations allowed groups of users to see what was being discussed and interactivity allowed scenarios to be viewed in real time or explored individually. Other designers offered a critical view that interpretation is always present in visualization, from the choice of data to the choice of how to represent it.

4.4.4.4 Visual and emotional appeal

Finally, interactives were described by five designers as making climate data more appealing, both in terms of visual appearance and creating engaging user experiences. Whereas they considered truthful representation of data to be the primary design consideration, one designer said, "There's definitely a cool factor to it – some appeal to the slickness of design." Another designer found that striking designs were more likely to be shared on news or social media, which was particularly important given that climate issues often were seen as competing with other immediate issues in news cycles.

4.4.5 Challenges to CVT development

Finally, we asked designers about the challenges they experienced in reaching their objectives. Whereas, on balance, designers emphasized the positive aspects of visualization, they also described recurrent challenges and caveats.

4.4.5.1 Resources

The most commonly reported challenge (15/22) was managing to develop a CVT using limited resources (e.g., time and funding). CVT development was described by eight designers as a high-cost process, particularly for projects which implicated partnerships between multiple organizations. The majority of designers described resources as having limited their activities, which was significant in a climate change context where designers described funding as often being scarce or constrained by fixed, one-off timescales. Five designers described resource constraints as particularly affecting later stages of projects, implicating their long-term sustainability:

> The phases after launch are often underestimated. Even we [as a highly-funded project] don't have enough resources for them – storytelling, blog posts writing, user-community building – these are things we need to build so that people will come back regularly.

4.4.5.2 Durability

Closely related to resource constraints was ensuring lasting durability in CVTs, which was described as a critical challenge by seven designers. There were several aspects of durability discussed, including its long-term usefulness to users, its stability over time (e.g., as dependencies are depreciated by browser software updates), and relevance of the data content over time. One designer argued that the durability of the project was central to establishing a strong relationship with users: "It's not just a one-off; the launch is just the start. Once the data is out there it doesn't mean it will be impactful." One benefit of multiple-agency networks mentioned by one designer was that it could give more long-term sustainability by sharing responsibility of tasks, expertise, and long-term funding. Actively involving multiple stakeholders could make a project more durable, more institutionalized, and less impacted by individual disruptions. This contrasted with "one-off" CVTs, such as web articles, which had a "hands-off approach once the tool was released." On the other hand, many of the larger-scale, long-term projects had significantly higher maintenance requirements. The designers of simpler "one-off" CVTs often reported a lesser degree of concern about long term durability, since there were much fewer components to maintain.

Five designers described the challenge of keeping pace with the speed of change in web development technologies. Choosing a technology stack could represent a significant design concern. For example, the depreciation of Flash in modern web browsers meant that one designer was currently in the process of rebuilding their CVT from scratch.

4.4.5.3 Interdisciplinarity of skills in CVT development

The development and dissemination of CVTs included many activities such as design, project management, web development, scientific consultation, marketing, promotion, user outreach, and maintenance. While not every designer (or project) engaged in every activity, many CVTs required a wide range of relevant skills which could fall outside their formal area of experience, especially for smaller teams. Intuition was described as being critical by five designers. Many designers also reported being unsure about which guidelines were appropriate or available. On the other hand, one designer trained in social science found that, relatedly, many established results were not being incorporated into CVT development:

> I often read papers in top-tier InfoVis venues presenting ideas that are well-documented in the psychology literature. I feel there's a lot of re-inventing the wheel.

4.4.5.4 Representing the complexities of climate change

Finally, seven designers described a fundamental tension between making information accessible to their audience and representing the complexities of climate change information. Peter Pfleiderer of Climate Analytics said, "It's complicated to fit everything into a simple interface with all the necessary background information, data caveats, and uncertainties." Particularly for media or public-facing applications, this could mean leaving out particular details: "We try to cram in as much information as possible, but we had to leave out some of the nuance."

The complexity of climate change information was also described as raising usability problems. For instance, one designer found that "too much data leaves users paralyzed." Another described being frustrated by users not using the full functionality of their CVT, using the analogy of "a race car being driven at half speed." For this reason, David Herring argued against one-size-fitsall approaches, saying, "You cannot have a Swiss army knife – you need to think discretely." Serving a smaller number of user demographics and use cases allowed designers to target language and functionality. Since evaluations were mostly imperfect, designers had to continue while often not knowing if their CVT was actually having the intended effect: "That's the nature of the work."

4.5 Discussion

The results of this interview study suggest that CVTs are intended to meet a broad diversity of objectives. It was evident that they were, in many ways, meeting many of their intended goals. Many CVTs received far-reaching media attention, had tens of thousands of users, and had visible effects on their users. Several unique advantages of CVTs were emphasized from designers' experiences and evaluations: the ability to deliver personalized information through the same interface, the provision of data exploration functionalities, the simplification of access to data and functionality through the web, and the demystifying of data and tools used by scientists. On the other hand, CVTs raised significant challenges for designers: the high resource costs of development, many potential pitfalls in design, the requirements for a diverse range of skills, and the difficulty of direct evaluation.

One significant finding from the interviews was the interdisciplinarity of CVT development and the challenges it presented to designers. The academic research referenced by designers as important sources of information included climate science, public participation, science communication, geovisualization, human computer interaction, and psychology. Similarly, designer backgrounds ranged across social science, natural science, technology, and management. The full teams responsible for CVTs would likely be more diverse than those represented in our sample, which targeted those leading design and development. Development processes required identification of appropriate data, design decisions, implementation, deployment on the web, and a method for distribution among target audiences. Many teams also invested significant effort in assessing user needs, conducting market research, incorporating insight from research literatures, evaluation, prototyping, and iterative assessment; such tasks required a wide range of expertise. A diverse set of skills was also often implicated in post-development activities, such as promotion, maintenance, user training, and support for real-world use. This could indicate, as has been suggested, the growth and professionalization of CVT development across its applications (Hewitson et al., 2017; Moss, 2016).

This interdisciplinarity also presented challenges to designers. In some sense, CVT development could be considered more accessible, with a growing number of available technologies (Johnson & Sieber, 2017). Yet at the same time, results from psychology, HCI, and usability engineering have suggested that many elements of design decisions can significantly impact the effectiveness of CVTs. Designers typically had years of experience in their field, multidisciplinary expertise, and in-depth knowledge of academic literatures. Yet many respondents, particularly in small self-led teams, expressed a feeling that they lacked expertise in specific aspects of CVT development. In response, designers often described using their intuition, engaging with appropriate communities, or enlisting consultants, depending on the scope of the project. There was a reported need to better integrate design recommendations from different disciplines and to make them more readily accessible to researchers and designers. High-level frameworks may be necessary to integrate this interdisciplinary knowledge and to make it more readily accessible to researchers and designers. One solution used by practitioners was to enlist casual consultations from expert colleagues, who could quickly point out appropriate design choices or resources.

A second significant finding concerns the importance of dissemination in terms of designer intentions and metrics of success. In many cases designers reported that making data available was insufficient to ensure its use; a significant amount of time and resources were necessary to make climate information useful to real-world users, in alignment with findings from past research (e.g., Lemos et al., 2012; Moss, 2016; Wong-Parodi et al., 2014). This differed significantly for CVTs with a “one-off” use and those with a continual use, as suggested by Johnson and Sieber (2017). For CVTs being continually developed, dissemination and real-world applications often took up the greatest portion of resources within a project but were also a significant source of feedback for success and future development. Dissemination played a significant role in the perception of success of many CVTs, such as the number of users and adoption of the CVT into user workflows. Despite their importance in the practical success of CVTs, post-development stages of maintenance, evaluation, user support, and durability are rarely discussed in the literature. In particular, individual reports often come quickly after the

CVT has been published such that its real-world reception goes underreported (e.g., Pickard et al., 2015). Similarly, evaluations in the literature usually focus on the efficacy of the interface (e.g., its utility for supporting desired tasks, or its usability for particular audiences), rather than on the success of a CVT in attracting users or appealing to news media.

Finally, designers highlighted the importance of informal feedback methods used to evaluate success during development. Controlled formal tests were useful in fine-tuning CVTs through user-centred design and providing valid evidence after the CVT had been completed. However, informal forms of feedback such as casual conversations, interactions with colleagues, and discussions within the community were also crucial in guiding intuitions throughout development. It is unclear how such informal methods could be better reflected in research (Gardiner et al., 2019, offer a good example), but it is important to note their strong influence on CVT design. One approach was to triangulate qualitative and quantitative information: individual-level testing can show where confusion occurs and reveal why a user behaves in a certain way, but it is usually not practical to test for every user or even a representative sample, whereas a survey might reveal a behaviour is prevalent but not the reason it occurs. Combining the two was found to enable a fuller understanding of the quantity and quality of CVT usage.

4.6 Conclusions

This paper presented the results of an interview study with 22 designers of climate visualization web tools to understand their backgrounds, intentions, evaluation metrics, and success in realizing their goals. By speaking directly to designers, we were able to better understand the diversity of roles in CVT development, to discern intentions that were often unrepresented in the literature or CVT documentation, and to understand the aspects of success important to designers. Our characterization of intentions, success metrics, and challenges provides an overview of how CVT designers understand and measure success in practice.

We identified several research gaps between practitioners and the visualization literature. First, designers emphasized the importance of real-world outcomes such as use and adoption, which implicated methods of evaluation infrequently reported in the literature such as web analytics and media analysis. Since these are closely related to widely reported intentions, closer alignment with these evaluation priorities in visualization research can better inform the full cycle of effective CVT development, including design, distribution, dissemination, evaluation, and continued use. Second, the diversity of development teams is a sign of a quickly evolving practice; future research will need to find ways to integrate relevant knowledge to ensure its application in real-world development of CVTs.

Being based on a limited number of interviews and open-ended questions, our descriptions of objectives and methods are not exhaustive. Whereas we tried to capture the diversity of responses, we were inevitably unable to articulate the full details described by designers. Paraphrasing one such designer: "We tried to cram in as much information as possible, but we had to leave out some of the nuance." We encourage future work to broaden and substantiate the ideas presented in this study and encourage close collaboration between researchers and designers to share insights on the development of climate visualisation tools.

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Chapter 5. Conclusion and outlook

The aim of this thesis was to examine the characteristics of interactive visualizations of climate change and the intentions behind their development. Specifically, I examined the following three research questions: What are the defining characteristics of CVTs? What are the intentions behind CVTs? How do we know if CVTs are meeting their expectations? I answered these questions through a review of related literatures, a content analysis, and an interview study.

In Chapter 2, I identified the evolution of CVTs from scientific analysis in the 1980s to serving a diversity of use cases and audiences. Correspondingly, researchers and practitioners across climate communication, education, outreach, decision support, and journalism have advanced strong rationales for developing CVTs to help address climate change goals (e.g., Dockerty et al., 2005; Shaw et al., 2009; Sheppard, 2005). However recent evaluation research suggests that there are gaps between intentions and practical outcomes of CVTs (Lemos et al., 2012; Moss, 2016; Xexakis & Trutnevyte, 2019). Further, there is no established code of conduct for the development of CVTs and much existing knowledge is dispersed over multiple fields, including climate change communication, cartography, climate science, psychology, user experience and web development (Roth, 2013).

Chapter 3 presented a content analysis of 41 existing climate change tools to understand the characteristics of existing CVTs. I analysed a sample of 41 state-of-the-art CVTs on the basis of their purpose, data content, visualization types, interactivity, functionality, and technical implementation. The results revealed the techniques and technologies used by practitioners. The analysis suggests that CVTs are contributing to the needs to make climate data more accessible but also indicates that the practice is still evolving as needs emerge and new technologies are adopted. CVTs were split by their purposes, to explain known information or allow users to explore climate change data. The analysis identified issues in existing CVTs, and suggested methods which others had used to address them, organized as design recommendations for future CVT development.

Chapter 4 presented the results of an interview study of 22 tool creators to understand the practice of CVT development. The study examined the backgrounds of CVT designers, the intentions behind CVT development, metrics of success, and recurrent challenges of using CVT to meet climate-related objectives. I distinguished five broad intentions, which included: increasing the use and influence of climate data, supporting community participation, improving climate change literacy, increasing the visibility of climate change issues, and making climate data more meaningful. Designers used a wide range of metrics and measurements to gauge success, ranging from controlled experiments to informal observations. The results highlighted the wide variety of approaches to the challenging task of evaluating the impact of CVTs in their real-world use. They also revealed significant divergences from metrics described in the research literature, with the frequent use of practical measures of success such as the number of active users, user observations, and informal feedback.

By using overlapping samples of CVTs across both empirical studies it was possible to test speculative results about the intents of their creators from the content analysis by asking about the reasoning behind design decisions. Many CVTs contained social media share buttons and options to export data and graphics, suggesting an increasing emphasis on the use of CVTs to appeal to news and social media to increase the visibility of climate issues. This intent was substantiated in the interview study, where increasing the visibility of climate issues was described as a key intent by designers.

Taken together, the findings suggest a prolific, heterogeneous, and evolving landscape of CVTs. This landscape has come to involve a growing number of disciplines and actors, as noted in recent research (Hewitson et al., 2017; Neset et al., 2016). Yet critical evaluations suggest that CVTs have yet to meet their full potential (Xexakis & Trutnevyte, 2019). I argue that this potential could be further realised by integrating dispersed insights from multiple disciplines into current research and practice.

This thesis also revealed significant challenges in CVT development, such creating web applications that have lasting stability and relevancy, obtaining the resources needed to create and maintain them, and overcoming the difficulties of simplifying complex climate change information to meet the capabilities of non-scientist audiences (Roth et al., 2015). Many of these challenges are currently faced independently by different research and development teams. Many such teams have created innovative and resourceful solutions that could benefit the field of climate change visualization as a whole. I hope that the coded repository of 41 existing CVTs (included in Appendix A) and the results of the interview study can help to spread such knowledge.

Lastly, extant typologies of interactivity, user inputs, and outputs were found to be insufficient in describing the diversity of features in interactive web tools applications. Web tools aimed at non-expert audiences had a distinct set of output functionalities from data visualizations common in the Infovis literature, which are often focused on data analysis applications. This thesis has provided analytical tools for future research, including empirically derived typologies to understand the characteristics, intentions, and success of CVTs and interactive visualization web tools in other domains.

A significant limitation of the assessment of CVTs in this research was that it did not evaluate them in their capacity to meet their intended objectives with real users (Lam et al., 2012). Instead, our approach examined their characteristics and self-reported success from developers themselves. I hope that further discussions can be stimulated on the use of interactive visualization to develop ever-more effective tools to serve the growing challenges presented by climate change.

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Appendices

Appendix A. Coded dataset from Chapter 3

The coded dataset from the content analysis in Chapter 3 can be accessed at: https://github.com/smlum/climate-vis.

Appendix B. Developer survey questions from Chapter 4

1. Tell me about how you got into your current line of work
2. Tell me about your job responsibilities as they relate to the [PROJECT]?
3. Were any other people or organisations involved in the project? If so, how?
4. Thinking back to the initial stages of the project, tell me about the original intent behind the tool. What problems did it address? How did you envision people using it?
5. Did you have any particular goals for the tool? What were your metrics for success?
6. From the initial stage to launch, give an overview of the development process. How long was the process in total? Did development continue?
7. Did you receive any feedback on the tools during their development? If so, what kind? Was it useful? Please give examples.
8. Thinking back to its release, how did you go about judging the success of the tool?
9. Did you collect data or feedback on: Who the users were? How easy it was to navigate the interface? How the tool benefited end users? Any other aspects of the tools' impact? If yes to any of the previous questions, how did you measure it? What were the results?
10. Did these match your expectations for how you thought the tools would be used? How did they compare to your initial goals? Were there any surprises?
11. Thinking broadly, what do you think are the key advantages of using interactive web tools to communicate climate information?
12. What do you see as the key limitations of interactive web tools?
13. Finally, do you think there's anything about the topic of climate change that makes interactive tools more or less useful?