Integrating Geospatial Web 2.0 and Global Climate Models for Communicating Climate Change

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Abstract

This study investigates the use of Geospatial Web 2.0 and Global Climate Models for climate change communication. The aim of this research has been to integrate the data, models, and tools of climate science with Geoweb to advance climate change communication. Several Geoweb applications have been developed to demonstrate the solutions for this integration and to fulfil two research objectives: (1) develop a method to employ Geoweb technologies for communicating climate change, (2) improve the accessibility of Global Climate Model by providing tools to engage people in the practice of climate science as well as the fundamental procedures involved in global climate modeling.

My research method is to extend Geoweb functionality to existing climate science tools, with the goal of easing the interface and increasing the interactivity of those tools to elaborate the scientific process of climate modeling. Geoweb has the power to manipulate climate change datasets from diverse sources for creating interactive climate change visualization. This power can be further enhanced if we integrate Geoweb with scientific climate data analysis and visualization systems. Nonetheless, Geoweb technologies that provide 2D visualization are more stable, faster, and popularly used than the 3D visualization. It is more robust to use Geoweb for climate model output. Instead, employing Geoweb for other aspects of global climate model requires close cooperation between climate modeling scientists and Geoweb technology experts due to its complexity. It is crucial to balance an easy-to-use user interface and the complexity of information transferred. Following this study, it is hoped that much more efforts from global climate modeling groups and Geoweb science researchers can be drawn together to facilitate climate change communication.

Sommaire

Cette étude porte sur l'utilisation de Géospatiales Web 2.0 et Modèle Climatique Global pour le communication du changement climatique. Le but de cette recherche a été d'intégrer les données, les modèles et les outils de la science du climat avec Geoweb pour faire progresser la communication du changement climatique. Plusieurs applications de GeoWeb ont été développés pour démontrer les solutions de cette intégration et de remplir deux objectifs de recherche: (1) développer une méthode d' utiliser les technologies GeoWeb pour communiquer du changement climatique, (2) améliorer l'accessibilité de Modèle Climatique Global en fournissant des outils pour engager personnes dans la pratique de la science du climat, ainsi que les procédures fondamentales liées à la modélisation du climat mondial.

Ma méthode de recherche est d'étendre les fonctionnalités de Geoweb à des outils existants des sciences du climat, dans le but d'alléger l'interface et en augmentant l'interactivité de ces outils pour élaborer le processus scientifique de la modélisation du climat. Geoweb a le pouvoir de manipuler des ensembles de données du changement climatique provenant de diverses sources pour créer une visualisation interactive du changement climatique. Ce pouvoir peut être encore améliorée si l'on intègre Geoweb avec analyse scientifique des données climatiques et des systèmes de visualisation. Néanmoins, les technologies GeoWeb qui fournissent une visualisation 2D sont plus stables, plus rapide et couramment utilisée que la visualisation 3D. Il est plus robuste à utiliser Geoweb pour la sortie des modèles climatiques. Au lieu de cela, en utilisant Geoweb pour d'autres aspects du modèle climatique global nécessite des coopérations étroites entre les scientifiques de modélisation du climat et des experts en technologie de GeoWeb en raison de sa complexité. Il est essentiel d'équilibrer un outil facile à utiliser l'interface utilisateur et la complexité des informations transférées. Suite à cette étude, il est à espérer que beaucoup plus d'efforts de groupes mondiaux de modélisation du climat et des chercheurs en sciences GeoWeb peuvent être réunis pour faciliter la communication pour le changement climatique.

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Contributions of Authors for Chapter Three and Chapter Four

Chapter Three and Chapter Four of this thesis are manuscripts that we plan to submit for publication. This section details the contributions of co-authors to each manuscript.

Chapter Three Employing the Geoweb for Climate Change Communication (co-authors: Renee Sieber, Mark Chandler, and Eric Galbraith)

I designed and developed all the applications presented in this chapter with ideas and feedback from all the co-authors. I wrote drafts and addressed comments from all co-authors. Dr. Eric Gailbraith reviewed an early draft of this chapter and provided comments. Dr. Sieber proposed the coupling matrix to reconstruct the paper and contributed significant edits. Dr. Chandler reviewed a recent draft of this chapter and provided valuable refinement.

Chapter Four Communicating Climate Change Findings through Climate Modeling and Web 2.0 (co-authors: Renee Sieber and Mark Chandler)

I developed and implemented the project and provided lead authorship. Mark Chandler provided specific advice regarding project design and climate modeling expertise. Renee Sieber contributed overall project design and counsel on geoweb integration, as well as significant contributions to initial sections of the paper. All authors iteratively edited drafts of this paper.

Chapter One Introduction

1.1 Research context

There is broad scientific consensus that climate change is an urgent concern for society (Oreskes 2004). However, considerable scientific literacy is required to understand the complexity of climate change scientifically. Although there is evidence to the contrary (Kahan et al 2012, Lindzen 2009), it is still hoped that understanding (if not action) will increase if the subject of climate change is better communicated. Numerous reasons have been identified in the literature – also mentioned in the literature review chapter of this thesis - to explain why it is difficult to communicate climate change (Pidgeon et al. 2011, Dilling et al. 2007, Moser 2010). Among these is that phenomena occur at a global scale and possess long-term and gradual effects and acceptation of climate change faces cultural and ideological divides (Roser-Renouf et al. 2010, Zia et al. 2010). These factors lead to the public's low understanding of climate change, including its causes, consequences, and mitigation strategies (Moser 2010, Zia et al. 2010). Thus, it is why we may need innovative ways to communicate scientific results to the general public.

The Geospatial Web 2.0 (Geoweb, for short) may be a promising way to communicate scientific results. The Geoweb is defined as spatially enabled next generation web (Web 2.0) (ESRI 2006). Geoweb can be considered as a collection of web applications, technologies, and services with geospatial awareness (Goodchild 2007, Maguire et al. 2008). A subset of Geoweb technologies is the Digital Earth (also called Earth Browser), for example, Google Maps and OpenLayers. Digital Earth was named by former U.S. vice president Al Gore in 1998 to describe a multi-resolution, three-dimensional (3D), virtual representation of the Earth (Craglia et al. 2008). It is so widely used by the general public and professionals that Digital Earth is considered to be revolutionizing the way scientists conduct research and how the general public perceives science (Blower et al. 2007, Chen et al. 2009). Indeed, there are several climate-related applications already built on Digital Earth platforms (Climate hot map 2011, weAdapt 2012), as well as others built more generally with the Geoweb. Thus, it is important to research how existing applications use Geoweb to visualize climate data both in space and time and relate it to other geographically referenced datasets that have social significance. Moreover, it is important to explore the possibility of using Geoweb to engage and promote collaborations between stakeholders such as scientists, general public, and policy makers.

The climate data used in these Geoweb applications are primarily generated by computational global climate models. These models are simplifications of the real world for the purpose of simulating climate change projections (McGuffie et al., 1996). They are now the primary tools used today in climate change research. They have been little more than a "black box" to most people, predominantly because they demand many years of undergraduate and postgraduate training to be understood and used. This unfamiliarity often engenders the public's distrust of scientific findings based on climate models (Chandler et al. 2005, Pidgeon et al. 2011, Sohl et al. 2010, Allen 1999). Engaging people in the day-to-day practice of climate science and explicating the scientific climate modeling methods can offer new avenues for communicating climate change (Pidgeon et al. 2011, Nerlich et al. 2010, Sterman 2011). Research gaps have been found in the integration of climate models with the Geoweb, with the majority of efforts merely dealing with model output. The integration presented in this thesis emphasizes the scientific process and advocates a critical thinking environment in which interested members of the public are encouraged to make up their own minds about climate change by having them experience climate modeling research from beginning to end.

1.2 Research questions and objectives

Accordingly, two research questions have been identified for my research. The first is how to employ Geoweb technologies, especially a Digital Earth approach, for climate change communication. Regarding the definition and scale of climate change communication, we comply with the main efforts that focus on communication between climate scientists and the general public. Moreover we expand it and look at the communication between generations of climate change research scientists from different institutions and working on different fields and aspects of climate science (e.g., climate impacts and adaptation). Several research objectives follow from this question. We need to find out and evaluate the current efforts on the analysis and visualization of climate change data for the purpose of climate change communication. Then we will present the methods and several Geoweb applications to demonstrate how Geoweb can be used to facilitate climate change communications between and within different audiences.

The second research question is how can we improve the accessibility of global climate models for climate change science communication? It is important to note that research question one (as well as almost all existing climate change communication applications) focuses on the manipulations of climate change data outputted from climate models. (Those applications are evaluated in the matrix in Section 2.10.) Thus, questions that are parallel to research question two include: what is the reason for visualizing climate model output data only? What about climate model input and can we visualize it as well? Is it possible to employ a Digital Earth approach for communicating climate model input? Meanwhile, Digital Earth has been used to facilitate public outreach by connecting scientists with general public, but how can Digital Earth be used to improve climate change communication within the scientific community? My second research question looks at a closer integration between Digital Earth and global climate models.

I define improved accessibility as engaging people in the practice of climate science as well as the fundamental procedures involved in global climate modeling. My research looks into not only the approach to analyze and visualize climate model output, but also the possibility to use the Geoweb to elaborate the scientific process for using climate models, and to communicate climate change science via having the user involved in climate modeling. By taking advantage of Digital Earth, I aim to bridge climate scientists' complex work within the understanding of the general public. This initiative addresses the possibility of providing a closer integration between Digital Earth and climate model input. The objective of this closer integration is to facilitate public participate and engagement in climate modeling. Matched with the second research question, it is necessary to identify which climate model I should use and try to improve its accessibility. For a chosen climate model, my research also looks into the graphical user interface (GUI) design for explicating climate model scientific process in an understandable way and forming a critical thinking environment in which great emphasis has been placed on motivating and empowering the general public to make up their own minds about climate change.

This thesis is composed by five chapters. Chapter One has provided context and identified two research questions and objectives for this study. Chapter Two reviews related literature such as climate change communication, global climate models, and Geoweb. In Chapter Three, I address research question one and explore how Geoweb can be employed to communicate climate change. Research question two is answered in Chapter Four, where I improve the accessibility of GCM by elaborating the scientific process for climate modeling. In Chapter Five, I conclude my research and offer opportunities and advices for future research.

Chapter Two Literature Review

To help answer these research questions, I need to explore several bodies of literature. First I will explore the literature of climate change communication with a focus on identifying the gaps remaining between climate change scientific community and the general public. I point out the reasons and obstacles that lead to these gaps, the pitfalls that must be avoided, and the effective strategies for communicating climate change facts, impacts, and science.

The scientific tool used to study climate change is climate model. Thus, following climate change communication, it is necessary to look into definitions and usage of climate model. I will use a pyramid to help define, categorize, and compare various climate models. Then I will present some basic usage of climate models in the scientific community. This usage includes communicating the scientific process, as well as needing to understand the required skills and computer resources, to assess climate models. I argue that we can communicate climate change science by allowing more of the public to access climate models in the same way as climate scientists. Thus I also point out the obstacles to improve climate model accessibility. I investigated several available climate models for my research. A comprehensive review of climate model is crucial for addressing the second research question.

To answer the first question (how do we employ Geoweb technologies, especially employing a Digital Earth, for climate change communication), I will explore Geoweb related concepts and technologies. The Geoweb is the intersection of geospatial awareness and Web 2.0 (Goodchild 2007, Sieber et al. 2010: 1). As part of the literature of Geoweb, I will present a popularly used Geoweb technology for climate change communication called Digital Earth. I present the advantages provided by Digital Earth applications and argue that it is time for us to harness the power of Geoweb for climate change communication. I also will cover concepts such as neogeography and volunteered geographic information

(VGI), both of which came in part out of Geographic Information Systems (GIS) and are technically supported by Geoweb technologies.

My second research question (how can we improve the accessibility of global climate models for climate change science communication) relies heavily on the literature of GCMs, the Geoweb, and Digital Earth.

As a summary for the literature review, I present a matrix to analyze the current efforts that use the Geoweb for communicating climate change. I determined the list of sample applications considered in the matrix. The attributes chosen to characterize the applications were driven by the literature review, which relates the literature of climate change communication to new technologies and phenomena that are developed out of the Geoweb.

2.1 Communicating Climate change

In 1988, James Hansen said in a U.S. Senate committee meeting that human activities were already warming the climate (Hansen et al. 1988). In 1990, the Intergovernmental Panel on Climate Change (IPCC) concluded that climate change was human-induced (Houghton et al. 1990). In 1992 the World Scientists' Warning to Humanity, signed by over 1500 scientists from 69 nations, emphasized that "human activities inflict harsh and often irreversible damage on the environment and on critical resources" (Kendall et al. 1992 online). Actions, policies and protocols (e.g., UNFCCC, short for United Nations Framework Convention on Climate Change) are implemented among countries and industries to address climate change (UNFCCC Convention 1992, Dilling et al. 2007). In spite of this, the emissions of heat-trapping Greenhouse Gases (GHGs) continue to increase and accumulate in the atmosphere (Pachauri et al. 2007). The earth's environment, accordingly, has further degenerated in the last two decades.

It has been well recognized by the majority of scientists that climate change is an urgent concern for the society. However, the same consensus is not shared by stakeholders outside the scientific community. Dilling and Moser (2007) raised eight points to explain why climate change is not perceived as urgent and therefore complicates communication. First, there is a "lack of immediacy" since GHGs appear to have no direct negative health impacts on humans and their impacts on the environment cannot be detected immediately. Second, a "remoteness of impacts" (e.g., sea-level rise affecting distant tropical islands in the Pacific or temperature rises in the extreme north) means that climate change may not be able to compete with personal concerns. Third, "time lags" of the climatic system may cause scientists to feel the urgency of acting on global warming but these lags can work against making the problem urgent in the eyes of the general public. Scientists are calling for actions immediately but because of the time lags, it is difficult for the public to see how their actions are making a difference in the short term. Fourth, "solution skepticism" makes it difficult for individuals to see how their small actions can make any discernible difference to a global problem. Fifth, "threats to values and self-interests" makes climate change a highly contested political issue since climate change has become aligned with political ideologies. Sixth, "imperfect markets" and insufficient internalization of negative externalities prevent the capital market from adequately accounting for damages to environment. Seventh, climate change is an instance of the "tragedy of the commons" because the whole world shares one atmosphere, whether or not individual countries are responsible for the majority of the emissions. Eighth, "political economy and injustice" refers to regions' differential levels of exposure and vulnerability to the risks, and differential ability to cope and adapt. Others add that the general public perceives a very low risk that they will be impacted by climate change (Kahan et al. 2012, Leiserowitz 2007). Non-experts may experience the effects of global warming (e.g., with rises in global mean temperature and increased frequency of extreme weather events); still they are not acting as a society to combat the problem.

Whereas the majority of scientists say climate change is urgent, why are scientific results still unable to convince a large portion of the general public of its urgency? Is it the problem for scientists when they communicate their results? Or is it because of the way the general public perceives the risks of climate change?

Furthermore, what are the strategies for communicating climate change effectively? In this section, I explore the literature of climate change communication to try to answer these questions.

Gaps have been found between climate scientists and society at large's awareness of climate change and between what people are aware of and when they actually act (Leiserowitz 2007, Bingham 2007). These gaps are partially caused by the conventional way that climate change is communicated, which employs a one-way (top-down) broadcast from scientists to the general public and which focuses on the presentation of scientific facts and impacts (Nerlich et al. 2010, Dillings et al. 2007). Scientists are often criticized for not communicating information of climate change effectively. Because they function within the norms of their profession, they are responsible for communicating what they know, demonstrating how they do it and what the implications are (Hassol 2008). They present out of their narrow knowledge domains and are inclined to use scientific jargon when giving a presentation (Parsons 2001). These factors lead to public's low understanding of climate change that includes its causes, consequences, and mitigation strategies (Lorenzoni et al. 2007).

In the climate change communication literature, it is hoped that public acceptance will increase if the subject is better communicated in an easily understandable way. Five common pitfalls for communicators have been succinctly categorized by Dilling et al. (2007) and supported by numerous others (Roser-Renouf et al. 2010, Kahan 2010, Kahan et al. 2011 and 2012, Fischhoff 2007). First, communicators underestimate the problem in conveying uncertainty. As a result, uncertainty can be used as a "political battlefield" and fall into long-standing debates over the reality, causes, and solutions of global warming that can confuse the media consumers and erode trust in science. Second, communicators are often found in traditional media, where current "media practices and trends" always attempt to offer two opposing viewpoints whether there are legitimate opposing scientific viewpoints or not. This is coupled with the declining number of newspapers and science sections in newspapers. Third, people gain new knowledge through pre-existing frames of reference; "inappropriate frames and mental models" affect people's understanding, perceptions, and reactions to climate change information. Fourth, "cultural barriers" can make it difficult to relate climate change to any current cultural icons and values. Unlike economic crisis, climate change is normally not the subject of daily conversations. Last, climate change can be reported in an "alarmist" way to attempt "to create urgency". The authors above have found this to be unreliable in prompting the public's behaviour change. Successful communication should recognize as many of these pitfalls as possible and manage to circumvent or avoid them in practice.

Conversely, what are the effective strategies for communicating climate change facts and impacts? Answers can be drawn from Kahan and his colleagues' Cultural Cognition Project (Kahan et al. 2010). Scientists can act as better communicators if they make the abstract climate change concrete (Cho 2010), for example showing georeferenced photographs of houses falling into the ocean due to coastal erosion and linking that erosion to climate change. Although we cannot connect climate change to a specific extreme weather event, we can say that, with climate change, we may experience an increasing number of similar events. To get people's attention, scientists should try their best to connect scientific results with the public's immediate experiences. Individuals are more inclined to accept climate change if it is presented along with solutions (Kahan 2010, Cho 2010). To engage the general public rather than to threaten them, acceptable solutions are expected after informing climate crisis. Similarly, the public may engage in climate change issues if the influences of their daily actions on the environment are explained to them.

Pidgeon et al. (2011) argue that this communication cannot shy away from conveying the science of climate change. Accompanying the salience of climate change topic in mass media and related journals like *Nature*, climate change communication efforts shift from climate change debate, for example to persuade people about climate risks, and move towards empower people to advocate for science and adopt practical measures (Nerlich et al. 2010, Ki-moon 2009). These approaches are advanced by federal agencies such as NASA, NOAA, and National Science Foundation who call for proposals to increase the public's literacy of climate change science (Cooper 2011).

Since 1992, the UNFCCC has called for countries to promote the national and international "(i) development and implementation of educational and public awareness programs on climate change and its effects; (ii) public access to information on climate change and its effects; (iii) public participation in addressing climate change and its effects and developing adequate responses; and (iv) training of scientific, technical and managerial personnel" (UNFCCC Convention 1992, article 6, page 10). Similar worldwide campaigns to educate climate change scientific knowledge have been initiated by other international organizations. Here the question arises: why is climate change scientific knowledge so critical for the public?

Scientific knowledge is critical for persuading people of climate change. Scientific knowledge is critical for lay audiences to distinguish legitimate skepticism from radical skepticism (Pidgeon et al. 2011). Without basic scientific knowledge, it is easy to sow confusion by amplifying the uncertainties and virtual risks of climate change (*ibid.*).

As a specific group of non-experts, scientific knowledge is necessary for political leaders to evaluate climate-related proposals and budgets, and also desired by policy-makers to advocate climate policies that require broad public support (Pidgeon et al. 2011). April 2011 saw cuts of $1.6 billion from the United States Environmental Protection Agency's (EPA) fiscal year 2011 budget. These cuts hurt climate change, ecosystems, and our ability to adapt (Schnoor 2011). Politically, public sympathy for climate protection boosts, in part, the emergence of stronger climate polices (Compston et al. 2008).

Scientific knowledge also is crucial for emerging two-way climate change communication efforts like that afforded by the Geoweb (see below). By two-way communication I refer to both parties listening and learning from each other

(Fischoff 2007). This research does not evaluate the types or extents of this communication but it is important to acknowledge that exchanges can vary enormously from lengthy back-and-forth in person dialogue or, in the case of the Geoweb, a click on a site to indicate a preference (a "like"). Researchers in climate change communication urge communicators to move from top-down, one-way (scientists, government sponsored media - general public) exchange to both a two-way exchange of information and knowledge that is more bottom up (Nerlich et al. 2010, Dilling et al. 2007, Moser 2010). Bottom up means dialogue and topics emanating from non-experts. The emerging importance of bottom-up communication requires that people possess knowledge of how climate change works and where it occurs. Indeed, bottom up initiatives like those out of nonprofit organizations and on popular climate change applications can create new discourses and concepts for climate change which, as a result, can popularize climate change scientific knowledge (Nerlich et al. 2010).

The phenomenon of two-way communication where it concerns scientific knowledge is a form of citizen science (CAISE 2011). At its most basic, citizen science can be considered to be citizens voluntarily participating in scientific activities (Silvertown 2009, Haklay 2012). These activities generally concern data collection, analysis, visualization and communication of scientific research (Cohn 2008; Silvertown 2009). Citizen science also can be employed as a form of informal science education and outreach to promote public understanding of and engagement in science (Brossard et al. 2005, Baron 2003). It contributes to the awareness and understanding of scientific concepts and the development of scientific skills (CAISE 2011).

Citizen engagement, which extends past a one-way top-down transfer of information, can be problematic for climate science. Should complex science like this be left to the scientists? Haklay (2012) says not necessarily. Even complex science can be aided by participation of non-experts. He points to the citizen science project in which scientists collaborated with non-experts to finally solve long-standing protein folding problems (Khatib et al. 2011). It appears there are possibilities for citizens to engage in climate issues via the GCM.

2.2 Global Climate Models

The primary instruments of climate science are climate models and, specifically, GCMs. What is a GCM? The acronym "GCM" was originally coined to refer to General Circulation Models, because these models were numerical representations, primarily, of the general circulation of the atmosphere and oceans. During the past 30 years many components of the Earth's climate system have been incorporated into general circulation models through parameterizations of the land surface, vegetation, the cryosphere, aerosols, clouds, and even the carbon cycle. These parameterizations make the models something more than mere general circulation models and the acronym GCM is often now used to refer to "Global Climate Models". More recently the term Earth System Models (or ESM) has emerged, and may eventually replace GCM. The literature is not consistent on this issue right now but I use the acronym "GCM" throughout this thesis to refer to Global Climate Models. They have been identified by IPCC as "suitable tools to provide useful projections of future climates" (McAvaney et al. 2001).

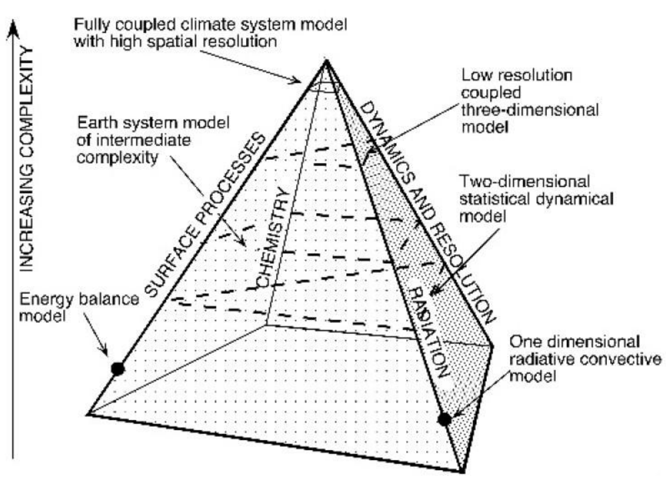


Figure 1. The climate modeling pyramid. (Source: McGuffie et al. 2005)

Figure 1 shows the pyramid to hierarchically arrange the varying types of climate models. Important components for analyzing climate models' complexity are radiation, dynamics and resolution, chemistry, and surface processes. As one moves up the pyramid, one sees more complex climate models that contain greater interactions between these four components (McGuffie et al. 2005). Almost all the climate models used for IPCC reports are at the top of the pyramid. These are considered to be fully coupled climate system models (e.g., models that join atmosphere and ocean models at intermediate time periods) with high spatial resolution. Like any simulation, these models are limited by our knowledge of the climate system and available computer resources, but the largest amount of processes are simulated in these models. This is not to suggest that there is 100 percent agreement about how to model these processes. Some complex real world processes, for example, cloud formation and dissipation, are understood differently by various experts and therefore simulated differently in various models. This is the main reason for the differences between models even at the top of the pyramid.

One thing in common among various climate models, however, is the rigorous scientific process that must be followed for accessing GCMs. The scientific process includes designing GCM inputs for setting up model simulations, running climate simulations, analyzing and visualizing GCM output. Scenarios of GHG emission serve as one of the inputs for GCM.

Climate models are only increasing in complexity, due to a deeper understanding of the Earth's physical system but also an expansion of high performance computing (HPC). Arguably, GCMs are driven to become ever more complex to match the speeds of the currently available computing resources. This may allow us to better simulate the climate system but it can cause an almost total lack of non- or less-expert access to GCMs. This has the effect of rendering GCMs as little more than a "black box" to most people who also may be simultaneously skeptical about the value of these GCMs (Sohl 2010, Yearley 1999). Unfortunately, current climate change communication efforts are essentially urging lay audiences to trust results (i.e., model output) from these models that they fail to understand nor accept, and to behave and response to information disseminated from the black box.

Can GCMs be made less of a black box? Thanks to various open-source projects, there exist a range of GCMs that do not require HPC. The coupled atmosphere-ocean model (AOM) developed at NASA Goddard Institute for Space Studies (GISS) is an example. The model runs on UNIX workstations and is programmed using Fortran-90 and Open-MP parallelization statements. The Fortran source code and input files for the 2004 version of the AOM are downloadable from their website (NASA/GISS 2007). However, a high level of computer skills, scientific (climate) knowledge, and computer resources are expected to use the model in a "scientific manner", for example knowing the appropriate file formats and understanding the acceptable ranges/limits of input variables. In other words, there is no error correction. Another example is the PRECIS Regional Climate Modeling System (Met Office 2012). It was developed at the UK Met Office Hadley Centre to help climate change study primarily in UNFCCC classes Annex I nations. It has been ported to run on a Linux-based personal computer like a laptop; however, it takes 4.5 months to complete a 30-year simulation for a typical experiment run on a 2.8 GHz machine (ibid.).

Another GCM that deserves consideration is different model from NASA. This is the NASA/GISS Model II whose source can also be downloaded from NASA/GISS website. Model II servers as a classic GCM based on which state-of-art GCM (such as the NASA/GISS AOM) are built. Model II is still in use and maintained by scientists from NASA/GISS. Model II was originally compiled in the 1980s to run on IBM mainframes. In those days, it required approximately six months to complete a 100-year simulation using the IBM supercomputer, one of the fastest machines in the world. Nowadays, the same simulation can be completed within two days on a 2.7GHz desktop personal computer. It has a relative simplicity and raw resolution, but it is a fully functional GCM that appears excellent for testing the possibility of improving GCM accessibility to a less-expert audience.

2.3 Web 2.0

We move from discussing climate change and its simulation models to computer systems that may better "wrap" climate models and their data to better communicate the science of climate change to a non-expert public.

On November 7, 2008, at the Web 2.0 Summit hold in San Francisco, former U.S. Vice President Al Gore called for a new vision of the World Wide Web to enable society to combat climate change. Gore mentioned that "the enormous climate crisis should be understood and acknowledged [by the whole world] as a group so that we can respond to it in a unified way" (Gore cited in Fehrenbacher 2008, online).

Gore was referring to climate change but also to the evolution of the web. The web has evolved from a static, producer-centric, and publishing media (Web 1.0) to a dynamic, user-centric, and collaborative environment (Web 2.0) (O'Reilly 2005, Cormode et al. 2008, Fensel et al. 2011). The expression Web 2.0 suggests a vision of the web that is crowdsourced: interactively produced by countless individuals around the world (Howe 2008; Alexander et al. 2008). It refers to a blurring of web developers and end users use the web, that they both contribute and consume content (Bruns 2008).

It also refers to a fundamentally different method of developing applications. O'Reilly's (2005) central proposition about Web 2.0 is that the web is becoming more interactive, more integrated and consequently more useful. The real significance is that applications are not built "from scratch" but are "mashed up" or made interoperable. Applications are developed by integrating many smaller application services to create sophisticated and useful mainstream solutions to a range of business problems at both personal and enterprise levels. The evolution from Web 1.0 to Web 2.0 is a movement from 'one for all' (i.e., one website for all users) applications to ‘all for all’ (i.e., all users for the other all users) applications (Maguire 2008).

Web 2.0 applications facilitate information sharing and also incorporate the value added by end user information (Constantinides et al. 2008). Example platforms include Wikipedia, Twitter, and Facebook. These platforms all allow users to interact with each other, for example to comment on (e.g., “like”, retweet) each other’s content and export that content to other applications. Value comes from users who contribute to the contents on the platform. Platforms like Twitter also offer Application Programming Interfaces (APIs) so user-developers can create applications by, for example, embedding a Twitter feed on their webpage.

This interaction is most striking because the users described in Web 2.0 applications like Wikipedia are not experts creating content; they are non-experts (Sui 2008). There is, of course, great concern over inaccuracy of content and general non-expert interaction with sophisticated technologies (Bertot et al. 2012, Flanagin et al. 2008), although many solutions are proposed to improve this accuracy, for example by increasing the number of people contributing to the application (Raymond 1999). For an issue like climate change Web 2.0 offers new potential to communicate climate change knowledge and leverage expertise by connecting the climate change expert with the non-expert public. The hope is that Web 2.0 has the potential to engage a broad audience to look at and even possibly solve common social problems like climate change that concerns everyone’s life (Gruber 2007).

2.4 Geospatial Web 2.0

The Geospatial Web 2.0 (Geoweb) is considered to open up new and innovative applications to use geospatial data (Goodchild 2007, Maguire 2008). Several initiatives have spurred the growth of the Geospatial web. For example, in 2005 Google released free web mapping applications and free APIs to allow users to geocode and map their own data. The increase in use of the Geoweb is consistent with the shift in geospatial data creation and use (Elwood 2009). It is not surprising that there is a relationship between the amount of people who use Google Maps and the amount of information uploaded by Google Maps' users.

Maguire (2008) suggests that Geoweb represents the next generation of geographic information publishing, access, and use. The Geoweb allows information to be searched for and retrieved on the Web using geography as a parameter (e.g., allowing latitude and longitude to be a linking factor in querying and showing Web search results) (Rouse et al. 2007). Thus, Maguire (2008) referred to the Geoweb as a system of systems bound together by a common interest in, and reliance upon, geography.

It should be noted that there is a critique about the Geoweb, most of it concerns the data produced through the Geoweb. Leszczynski (2012) argues that government is "rolling back" its responsibilities regarding the production and maintenance of geographic information, that information for which it has been the traditional custodian. Its activities are beginning to blur with those of large corporations, which have very different motives for existence. With citizen science projects like Foldit (Khatib et al. 2011), the worry is that science is similarly ceding its responsibility for data collection and analysis to citizens. Crampton (2009) warns us that the Geoweb could lead to a diminishing role for and deprofessionalization of experts. There are numerous privacy, confidentiality, and surveillance issues regarding putting user generated content on the geoweb (e.g., Elwood and Leszczynski 2010). Even though it is promoted as a suite of technologies amenable to climate change, we must remember that these are technologies owned by the private sector. Its business is to make money off our content, which relies on data mining of personal information, whether that is climate change or relationship status. Violations of our privacy and surveillance of our online activities are not its problem.

Developments in the Geoweb are tied to the general, fast-paced advancement of the Web itself. Most academic research into the Geoweb focuses on the technical aspects of spatially enabling the Internet and on the infrastructure as opposed to only the data. This can be seen in the first academic definition of the Geoweb, which was the “integrative, discoverable collection of geographically related web services and data that span multiple jurisdictions and geographic regions” (Lake and Farley 2007, page 15). There is an emphasis on the technical developer-side of this.

Jurca (2011) offers a good example of positing the Geoweb as a technical research challenge. The following instances of his work illustrate this technical turn. For example, he discussed the problems in generating underlying datasets from multiple data sources and the need for persistent parallelized computing to do this. Researchers also must determine how the infrastructure can perform geoweb tasks in parallel (e.g., loading tiles while computing inferences on what users want to search). He reported on the computation challenges in needing to manipulate Street View images to obscure people’s faces to protect personal privacy and processes to control geographic “spam” on Google Maps (e.g., the"Locksmith" problems of overreporting one’s business locations to obtain more sales). It is clear that these technical issues often focus on computer science to the exclusion of geography. For instance, Jurca (ibid.) uses the term 'geocoding' for the challenges in searching/indexing the geoweb and the use of n-grams/named graphs to resolve these challenges. Geography equals retrieval of spatial information, searching for places as opposed to interpolation of geometry, the latter being the realm of geography or at least computational geography. He discussed the importance of standardization of geographic data because more data introduces greater ambiguity (e.g., he finds a strong bias towards irrelevance and non-standardizability when localities submit their datasets on restaurants).

For climate science, a main value of Geoweb lies in its ability to solve real-life problems in geographic context. According to the Surging Seas web site (2012), if the sea level rises 0.5 meter in this century due to global warming, by using the Geoweb we should be able to answer questions like which areas of the world will be affected and how many residents have to move.

2.5 Non-expert, volunteer engagement in the Geoweb

The Geoweb has opened up new and innovative ways to use geography in the new areas of mainstream Web use, with terms like mashups (discussed above), Neogeography, and VGI (Maguire 2008).

Echoing the concepts considered in Web 2.0, the usage of geographical techniques and tools by non-expert group of users is termed as Neogeography (Turner 2006, Haklay et al. 2008). The set of geographical techniques and tools is combined from cartography and GIS, and should, where possible, be placed within the reach of non-expert group of users (ibid.). According to Turner (2006, page 3), "Neogeography is about people using and creating their own maps, on their own terms and by combining elements of an existing toolset". In other words, non experts produce content (Goodchild 2009, Hudson-Smith et al. 2009). Neogeography consists of a set of techniques and tools that fall outside the realm of traditional GIS tools. For example, a Neogeographers uses Google Maps API rather than professional ArcGIS to manipulate maps, to geotag his or her photos in Flickr to share them with friends and watch the world (Turner 2006).

The concept of VGI is in a similar vein as Neogeography. VGI is defined as the "widespread engagement of large numbers of private citizens, often with little formal qualifications in the creation of geographic information" (Goodchild 2007, page 212). Important concepts in the VGI are local knowledge, data access, and the representation of multiple realities (Rouse et al. 2007, Haklay et al. 2008). Examples of VGI can be drawn from the flourish of spatial information available in Digital Earth platforms such as Google MyMaps and OpenStreetMap. VGI draws on public participation GIS (PPGIS) with attempts to broaden access to online projects and increase public participation in the decision-making process (Kingston 2007, Sieber 2006). Perhaps the most obvious aspects of PPGIS that is coming to fruition via the Geoweb and VGI are that of community empowerment through collaborative web mapping (ibid.). For example, individuals and groups can potentially gather online and add data to a central web mapping platform like

OpenStreetMap. VGI shares social-theoretical critiques of PPGIS (also termed as GIS 2.0) including the potential for knowledge distortion and differential access to spatial data and geospatial technologies (Rouse et al. 2007, Elwood 2010, Warren 2011).

Similar to Web 2.0, the most significant concerns that come together with the rise of VGI are the motivation of contributors and the accuracy of user contributed information (Flanagin et al. 2008, Coleman et al. 2009). Contributors may be motivated by professional status or altruism or pride of place (Coleman et al. 2009). They may attain a stronger sense of achievement if the contents they contributed turn out to be helpful and searchable by the others. Conversely, sites like surfacestation.org, a climate denial application, demonstrate that individuals are not necessarily motivated by ends like the promotion of science. Regarding the accuracy and quality of VGI, VGI has been defined as a blurring of the distinction between spatial information created by the authorities and the assertions of the Neogeographers/non-experts (Goodchild 2009). If we begin to rely on non-expert data, for example for baseline map data then we have to be assured of its accuracy. Goodchild (ibid.) argued that the geographic context of spatial information safeguards VGI's accuracy while the traditional mapping guarantees bounds on inaccuracy. Crowdsourcing is one way to ensure that entries created by a large number of people (e.g., a big participant population in the same spot) are likely to be more accurate (Howe 2008). Moreover, the concept of human as sensors implicates that humans are equipped with five senses and with the intelligence to interpret what they sense. From Goodchild's perspective, having human as sensors will tremendously improve the accuracy of spatial information and bring down the needs for post-processing when comparing with spatial information collected by hardware sensor equipment.

There are also some critiques and social concerns for VGI. Taking human as sensors for example again, using human as sensors also means that the same objective information will be sensed subjectively thus be interpreted differently by different people (or even the same people at different time and age). Thus, when I argue about the Citizen Science and participant populations, it is farfetched to take citizen as a whole. What is more, one important issue in VGI is the protection of privacy (Elwood 2009); this could that can work against contributors' motivation for VGI. As mentioned by Goodchild (2007), a lot of VGI becomes available to all while it was thought to be shared only with friends and authorized personnel.

2.6 Digital Earth and Climate Change

Digital Earth is the best-known example of the Geoweb. It represents comprehensive geographic computing systems that organize information at a global scale with a georeferenced grid (Grossner et al. 2008). Digital Earth applications provide interactive (e.g., zoom and pan) interfaces to visualize multi-resolution tiles of data. The data may or may not bundle with Digital Earth. They may be 2D (e.g., OpenLayers) or 3D (e.g., Google Earth, Layerscape) and may offer time series data in 4D. Former Vice President Al Gore presented an initial vision of Digital Earth, which he defined as "a multi-resolution, three-dimensional representation of the planet, into which we can embed vast quantities of geo-referenced data" (Gore 1999, page 528). In 2009, the Beijing Declaration on Digital Earth was approved at the International Symposium on Digital Earth to promote better understanding of the impacts of Digital Earth (Foresman 2008, Guo 2012). Digital Earth is well established and adopted because of development in fields like computational science, telecommunications and mobile devices, GIS, and multi-source, -resolution, -temporal global earth observing systems as well as Global Positioning Systems (Gore 1999, Goodchild 2008).

A next-generation Digital Earth, together with priority supporting research areas, has been proposed in various scientific forums with participation by the public and private sectors and by universities (Guo 2012, Craglia et al. 2008, Craglia et al. 2012). The 2008 Vespucci Initiative for the Advancement of Geographic Information Science (GIScience) framed the next generation Digital Earth to be more audience and problem oriented with the hope that it would be more engaging, open, participative, and interactive. The 2011 International Society for Digital Earth's Working Group Meeting on Digital Earth and Goodchild (2012) considered Digital Earths to be composed of a set of visualization applications and services, including a 'a geoportal', 'an organizing metaphor', and 'a strategic infrastructure' (Guo 2012, Craglia et al. 2012, Goodchild 2012).

Here I focus on the advantages provided by current Digital Earth to support climate change communication. Actually, as soon as the Digital Earth concept was articulated by Gore, its potential application in predicting climate change was identified (Gore 1999). Recent years have seen increasing numbers of climate scientists adopt Digital Earth to share and visualize climate change data (e.g., IPCC DDC Data Visualization Tools and Climate Hot Map by Union of Concerned Scientists). Indeed Blower et al. (2007) and Chen et al. (2009) believe Digital Earth has the potential to revolutionize the way scientists conduct research and the general public perceives climate change related information.

A Digital Earth allows for the indexing and presentation of climate change data at a wide range of spatial scales (Blower et al. 2007). Climate change occurs at a global scale thus it is natural to use Digital Earth as a platform to display global climate change data. A global view can provide the overview; whereas local details can be resolved by zooming in. The use of Digital Earth enables more sharing of data beyond 2D static images (ibid.). Experiential elements (e.g., local details of the photo-realistic imagery, addition of multimedia, ability to zoom in or out, and availability of 3D bird's eye views) are said to be critical for successful visual communication (Nicholson-Cole 2005). By taking advantage of the interactivity of Digital Earth for climate change communication, it should be easy to support experiential elements by, for example, enabling users to zoom in or out and pan around the earth.

Digital Earth is designed to maximize user-friendly interfaces; they are designed for a non-expert general public as opposed to an expert scientist community. Because one can easily input new data into a Digital Earth, users are provided the means to visualize climate change data from many different sources (Blower et al. 2007, Chen et al. 2009). Many Digital Earth platforms, especially Google Earth, support the time dimension in the form of animations and allow images to be placed on the Earth's surface (Blower et al. 2007). The hope is that employing Digital Earth to communicate climate change is promising and can improve the dialog and interaction between scientists and the general public because Digital Earth is widely accepted by the public.

Adding and sharing geo-referenced information on Digital Earth are well supported by an Open Geospatial Consortium (OGC) standard data format for Digital Earth called KML (Keyhole Markup Language), It is the use of this markup language that allows scientists to publish and consume climate change data without the need for technical assistance (ibid.). With the emergence of Web 2.0, increasing numbers of research applications are being transferred from local machine-based environments to online web-based platforms (Chen et al. 2009), thus making them potentially available to a much larger audience. The release of Digital Earth APIs enables their functions to be available to mashup in other sites.

It is well reasoned to employ a Digital Earth approach for displaying, demonstrating, and communicating climate change mechanism and its spatial-temporal impacts (ibid.). Related literature has been calling for a closer cooperation between Digital Earth and global change research (ibid.). Although these Digital Earth platforms do not have any powerful analytic functions since they are not designed to replace professional GIS software (e.g., ArcGIS Explore), they have been referred as the democratization of GIS (Butler 2006, Hudson-Smith et al. 2009).

Digital Earth enables geovisual exploration of climate change, which has an inherent complexity and interdisciplinary nature. Geovisualization has the potential to provide windows into this complexity since it can integrate approaches from multiple disciplines (e.g. information visualization, interface design, and cognition) for visual exploring, analyzing, and synthesizing of climate change. It goes well beyond climate change representation to support exploration and ultimately to facilitate the generation of knowledge about climate change (MacEachren et al. 2001).

2.7 Current efforts to model climate change in Digital Earth

Accompanying the development of Geoweb technologies and the emergent of new approaches like Digital Earth, recent years have seen increasing numbers of web and mobile applications for sharing, analyzing, and visualizing climate change. The World Environmental Organization (WEO) has collected and updated the 100 top climate change sites (WEO 2012). The organizations that release and maintain these sites range from international institutes, national government agencies, numerous universities, and climate change research groups to local communities and nonprofit organizations. To varying degrees, these sites have incorporated elements of the Geoweb, social networking, and GIS. Instead of comparing each site and monitoring each new application, I present a matrix to represent and summarize major climate change applications. This can be found in Table 1.

I chose the list of sample applications based on several criteria. First, I tried to cover applications done by developers and agencies of all scales and sectors (from international organizations like IPCC to nonprofit organizations like Climate Central). It is hoped that, for organizations that plan to launch similar applications, this matrix can be useful for those of the same type and level of organizational resources. Second, the contents of these applications cover key aspects of climate change that include climate change science, impacts, adaptation, and mitigation. Third, the organizations/applications communicate climate change effects in the various geographic scales: global, national, provincial, and local. Fourth, the organizations and individuals that get engaged with these applications include all stakeholders of climate change (Midttun 2009). I found that it is climate scientists who primarily lead and direct these applications, whereas government agencies provide data and funding supports.

Engagement is varied. Most of these applications present information to citizens in a one-way top-down manner, whereas some have volunteer citizens who participate and contribute to the contents of these sites.

Table 1. Matrix for summarizing major climate change applications and efforts

Application Name	Link	Developer/Agency	Purpose	Groups involved /contributors	Content, Scale	Features					
						Public participation	Knowledge Sharing, integration, and collaboration	Relate to daily life/experience	Interactive graphics and animations	Multimedia	
										Dimensionality	Video/Audio
IPCC DDC data visualization tools	http://www.ipcc-data.org/maps/	IPCC DDC	Data visualization for the purpose of data distribution and sharing	Various climate change research groups	Climat change data, Global	N	N	N	Y	2D	N
Climateprediction.net	http://climateprediction.net/	Climateprediction.net	Produce scientific predictions of the Earth's climate and test the accuracy of climate models	Climate scientists, climate modeller, and volunteer citizens	Climate change science and modelling, Global	Y	Y	N	N	2D	N
Environmental Atlas of Europe	http://discomap.eea.europa.eu/map/environmentalatlas/	European Environment Agency	Project showcasing communities responding to environmental change across Europe	Government Agencies	Climate change facts and impacts, Global to local	N	Y	Y	Y	2D	Y
SEC Climate Portal	http://climatechange.sg/html/?link=1&routine=1	Singapore Environment Council (SEC)	Provide information, education material, tools, and solutions for global and national climate change	Government Agency	Climate change facts and impacts, National to local	Y	Y	Y	Y	2D	N
Cal-Adapt	http://cal-adapt.org/	California Energy Commission	Provide access to data, information, and tools that show climate change effects in California	Government Agencies and universities	Climate change facts, impacts, and adapation, State to local	Y	Y	Y	Y	2D	N
Climate hot map	http://www.climatehotmap.org/	Union of Concerned Scientists	Show evidence of climate change and teach local consequences of global warming	Scientists and citizens	Climate change facts and impacts, Global to local	Y	Y	Y	Y	2D	N
weAdapt	http://weadapt.org/	weadapt.org	A knowledge platform for collaborating on climate adaptation	Scientists, government agencies, and citizens	Climate change facts and impacts, Global to local	Y	Y	Y	Y	2D, 3D	Y
Surging Seas	http://sealevel.climatecentral.org/	Nonprofit Organization Climate Central	Communicate the science and effects of climate change	Universities, organizations	Climate change impacts, National to local	Y	Y	Y	Y	2D	N
Climate Mobile	http://itunes.apple.com/ca/app/climate-mobile/id388928572?mt=8	GeoOptics Inc.	Provide climate information and personal climate analyzer at fingertips	Company	Climate information, Global	Y	Y	Y	N	2D	N

I categorized the features of these applications based on the needs identified by climate change communication literature and the technical possibilities provided by the Geoweb. A main obstacles to communicate climate change concerns its high level of abstraction, in scale (e.g., global scale, remoteness of impacts, differential geographic impacts and GHG contributions), time (e.g., lag, lack of immediacy) and effects/perceptions (low risk of impacts, inability to understand uncertainty, reacting negatively to alarmist presentations, lack of concrete examples and explanations of science). Consequently, I added features such as "relate to daily life/experience", "public participation", and "knowledge sharing, integration, and collaboration" to the matrix in Table 1. Related to the Geoweb, I added usage of interactivity and addition of multimedia.

"Relate to daily life/experience" means that the information (e.g., impacts and scale of climate change) needs to be related to public's daily life, and also the approaches (e.g., expansion of education beyond science centers to television, and movie entertainment) for how this information is communicated (Cooper 2011). I consider "relate to daily life/experience" to be an important feature because of its potential to make climate change vivid and an immediate concern or common topic in people's daily life and acts.

I define "public participation" as the applications' ability to allow climate change stakeholders (e.g., nonprofit organizations, general public, and policy makers) to interact with and contribute contents to the applications. Having the general public participate, as well as reading about how other individuals or communities get involved, in climate change can potentially make it easier for the public to connect their daily actions to global impacts and solutions.

The column "knowledge sharing, integration, and collaboration" speaks to improving stakeholders' knowledge and understanding of climate change that includes its causes, consequences, and mitigation strategies. Examples I looked for included the creation of live and virtual forums that facilitate discourse for mutual learning has been identified as a strategy to improve public acceptance of climate change science (ibid.). Being able to "like" (send to Facebook) or "tweet" (send to Twitter) is another instance of knowledge sharing. The hope is that these features facilitate the collaboration between and within climate scientists, the general public, and policy makers.

Several features that are possible because of the advance in Geoweb technologies also have been added to the matrix as evaluation factors. "Interactive geo-graphics and animations" refers to the standards of Digital Earth such as panning and zooming. With climate data overlays, this links a global view of climate with local effects as well as the ability to compare impacts and activities at multiple locations. "Multimedia" refers to whether or not a Geoweb application shows diversity of content like text, audio, and video. It also refers to whether the application offers 3D visualization. Applications with these features offer multiple ways to connect with audiences.

Chapter Three Employing the Geoweb for Climate Change Communication

(Note: This chapter aims to answer research question one, which is how Geoweb can be employed for climate change communication. It is a manuscript ready to be submitted. It is authored by Jian Zhou, Renee Sieber, Mark Chandler, and Eric Galbraith.)

3.1 Abstract

In this paper, we explore how Geoweb, and more specifically, Digital Earth, can be better integrated with the digital tools of climate science for climate change communication. We firstly address the literature and characteristics of the Geoweb, Global Climate Models, and digital tools. Then we introduce a matrix of two related concepts: the use of general purpose versus special purpose climate systems and the degree to which climate related systems can be coupled. This matrix is built and elaborated to help us understand how the Geoweb can be better integrated with the data and tools of climate science. Following the matrix we present five Geoweb climate applications we developed to assess the two concepts and to demonstrate four distinct solutions for the integration. We conclude with a more general discussion about the pros and cons of each solution.

3.2 Introduction

Recent years have seen tremendous adoption in the climate science community of the geospatial web 2.0 (Geoweb), which is defined as the geospatially enabled next generation web (Web 2.0) (Goodchild 2007, Maguire et al. 2008). Geoweb applications tend to focus on expert to non-expert communication from climate change research scientists to the general public; efforts also are desired to facilitate and expand communication between generations of climate change research scientists from different institutions and between climate change research scientists and climate change adaptation scientists who may not have access to climate change scientific research tools (Weingart et al. 2000, Fischhoff 2007, Nisbet et al. 2009, Reser et al. 2011, Pearce et al. 2009, Shaw et al. 2009).

The Geoweb has the potential to provide opportunities for that networked, multi-group, horizontal and vertical communication. As a collection of web applications, technologies, and web services (Lake et al. 2007), the Geoweb can integrate approaches from multiple domains for visual exploration, analysis, and synthesis of information such as climate change (Goodchild 2007, Maguire 2008, Craglia et al. 2008, Haklay et al. 2008). In this paper we explore how the Geoweb and, more specifically, Digital Earth (e.g., Google Earth, Bing Maps, and OpenLayers) can be better integrated with the digital tools of climate science according to a matrix of two related concepts: the use of general purpose versus special purpose climate systems and the degree to which climate related systems can be coupled together.

These two concepts essentially represent a closer integration of disciplines and systems. Geoweb applications built for the non-expert public represent an important advance in communicating climate impacts but the types currently being produced are unlikely to meet the specific requirements of climate science and related disciplines like climate adaptation or oceanography. We will examine both non-expert and expert related applications in this article.

The Geoweb and changes in climate modeling each offer a different way of thinking about interoperability of technological systems, one that we may forget with the seeming ubiquity of the former and the sheer complexity of the latter. As will be discussed, the Geoweb is designed for easy interoperability. The concept of coupling aligns with interoperability. The field of climate modeling is heading increasingly towards integrating atmospheric, terrain and oceanic and other models. Models are coupled when the developer does not or cannot build them "from scratch", because of the expense and complexity of systems. We will discuss characteristics of the Geoweb and climate models, then the two concepts of general/special purpose systems and loose/tight coupling of those systems. Then we will discuss five Geoweb climate applications we developed to assess the two concepts.

3.3 Methodological Approaches for Integrating the Geoweb and Climate Change Research

The Geoweb has opened up new and innovative approaches to visualize climate change data. Numerous Geoweb applications have been developed. Among the most popular are Climate Hot Map (http://www.climatehotmap.org/), Cal-Adapt (http://cal-adapt.org/), weAdapt (http://weadapt.org/), The European Union's Environmental Atlas (http://discomap.eea.europa.eu/map/environmentalatlas/), the SEC Climate Portal (http://climatechange.sg/), Surging Seas (http://sealevel.climatecentral.org/) and Climateprediction.net (http://climateprediction.net/). With the exception of climateprediction.net, a Web 1.0 application which distributes analysis across unused personal computing resources, those applications predominantly take advantage of Geoweb platforms for the visual exploration of climate change data in space and time and relate it to other geographically referenced datasets that have civil, demographic, social or even industrial significance.

For various reasons, researchers working in climate change communication and visualization accord to the Geoweb and Digital Earth technologies the potential to revolutionize the way scientists conduct research on and the general public perceives climate change related information (Blower et al. 2007, Chen et al. 2009). Much of the focus is on this end user experience, whether expert scientist or non-expert public. Indeed, the Geoweb has blurred distinctions between expert and non-expert (Goodchild 2007), which concern some of the climate scientists with which we have worked. Communication is aided with increased levels of user friendliness of computing and individuals have evinced comfort with Geoweb and Digital Earth platforms (Elwood 2011). It helps that many of these sites also are free-of-cost to the end user. The Geoweb by design, furthers shareability of information among users, for example via plug-ins that allow users to broadcast content on social media sites like Twitter and Facebook. Adding and sharing geo-referenced information on Digital Earth are supported through a customized XML schema called KML (Keyhole Markup Language), an Open

Geospatial Consortium (OGC) standard data format for geospatial data. Use of this markup language allows scientists to publish and consume climate change data within their technical capabilities without the need for technical assistance (Blower et al. 2007).

Blower et al. (ibid,) point to the geovisualization potential for climate communication. He emphasizes the range of scales afforded by Digital Earth, which are built on a georeferenced grid indexing system. Climate change happens at a global scale thus it makes sense to use a Digital Earth to display global climate change data. That global view can provide an overview; local details, because of the relatively high resolution data bundled with most Digital Earth platforms, can be revealed by zooming in. Nicholson-Cole (2005) has argued that experiential elements (e.g., local details of the photo-realistic imagery, ability to zoom in or out, and 3D bird's eye views) are critical for communication that affects constructive changes in a non-expert public's perceptions of climate change. Digital Earth platforms provide a means to visualize multi-dimensionality, 2D, 3D as well as time-dependent climate change data (Guo et al. 2010, Wrobel et al. 2009), the latter of which appears predominantly in the form of animations. These Digital Earth platforms do not have powerful analytic functions since they are not designed to replace professional Geographic Information Systems (GIS) software (e.g., ArcGIS). However, the Geoweb has been referred as the democratization of GIS (Butler 2006, Hudson-Smith et al. 2009) because its geovisualization ability and ease of use.

The Geoweb has also transformed the developer experience. A major advantage provided by Geoweb lies in its mashability of code components, where full functionality of a service is frequently available with a single line of code. This interoperability is a hallmark of the Web 2.0 and the Geoweb (Batty et al. 2010, Haklay et al. 2008, and Roche et al. 2011). Geoweb associated components such as APIs (Application Programming Interfaces – e.g., Google Maps API, Twitter API, and Facebook social plugins) are now sufficiently mature to facilitate the use of Geoweb in web applications for collaboration and communication purposes

(Goodchild 2012, Roche et al. 2011). Geoweb use is further enhanced by its platform-independence, for example the same code allowing it to run in a web browser and a mobile device (O'Reilly 2005, Roche et al. 2011). These advances both ease development and greatly reduce the time to deployment.

The application URLs above show that the Geoweb, especially Digital Earth, has been used in public outreach to connect scientists with general public. Is it possible to employ a Geoweb approach for closer integration with Global Climate Models (GCMs)?[1] Can the Geoweb be used to facilitate climate change communication within the scientific community? This requires a closer look at GCMs.

GCMs are the primary tools used by climate scientists for climate change research. They are simplifications of the real world that simulate various climate change projections (McGuffie et al. 1996). A lengthy scientific process must be followed to utilize GCMs, which includes designing GCM input files for use with model simulations, running climate simulations, and analyzing and visualizing GCM output (Hansen et al. 1987, Taylor et al. 2012). For example, scientific predictions for future climate change resulting from increasing emissions of greenhouse gases (GHGs) caused by the extensive use of fossil fuels, are based on GCM experiments with GHG emission scenarios as one of the inputs for GCM (Parry et al. 2007).

The spread of inexpensive computing and the increase in computing power that makes the Geoweb accessible also generates increasingly complex models. Combined with a deeper understanding of the Earth's physical system, research drives GCMs to become ever more complex to exploit the speeds of the fastest available computing resources (ibid.). This causes an almost total lack of non-expert (meaning non-climate scientist) access to GCMs, rendering GCMs little more than a "black box" to individuals who express skepticism about the contents of these GCMs (Chandler 2005, Yearley 1999).

[1] GCMs also may stand for General Circulation Models. An emergent term for GCMs is Earth System Models.

A number of GCMs are publicly accessible, such as the NASA/GISS GCM Model II and the NOAA Community Earth System Model. Individual GCMs handle climate system processes differently (Reichler et al. 2008, Masson et al. 2011). Some complex processes, such as cloud formation and dissipation, are not fully understood and thus separate model development groups will have chosen unique parameterizations to implement cloud processes in their models. These unique parameterizations may be coded quite differently, even utilizing different computer languages. One great challenge then is the lack of transferability or interoperability among the models. Modifying the computer components of one does not mean one can transfer this knowledge to modify another GCM, even though most GCMs will generally have modules that deal with all the major components of the climate system (Masson et al. 2011).

Various computer-based tools have been developed inside and outside the climate research community for communicating climate models and the output data of those models (McKendry et al. 2009). Nocke et al. (2008) subdivided these tools into two major approaches, general purpose systems and special purpose systems (Table 2). First, visualization specialists have developed general purpose systems (e.g., IDL, Microsoft Layerscape). We argue that the benefits of general purpose systems lie in their support of heterogeneous data formats and provision of a variety of visualization methods (e.g., 4D animations and multimedia in information windows). The systems are not necessarily free nor open source/access, the latter of which is important for customization and also coupling. Many general purpose systems are developed in information technology companies. Nocke et al. (ibid.) argue that it is difficult for them to meet climate scientists' specific requirements. General purpose systems can be expensive to purchase and to maintain a valid license. The widely used visualization package, IDL, requires the purchase of a license to distribute the application. Despite powerful features, some general purpose systems are only marginally used in climate change research and communication.

Table 2. Comparison of current climate change data visualization approaches (modified from Nocke et al. 2008)

Approaches	Examples	Developers	Strengths	Weaknesses
General purpose systems	IDL, Microsoft Layerscape	Information technology companies	Support heterogeneous data, provide various visualization methods (e.g., 2D maps, 3D globes, multimedia)	Hard to meet climate scientists' specific requirements
Special purpose systems	Ferret, GrADS	Computer programmers working closely with climate scientists	Widely used by specific field of scientists, provide spatial or temporal visualization of individual variables.	Traditional visualization (e.g., static 2D maps), loss of overview

Special purpose systems are those specifically designed for the climate research, like Ferret and GrADS. Nocke et al. (ibid.) focus on visualization tools; the most domain-specific special purpose system of climate science is the GCM itself. Compared to general purpose systems, special purpose systems primarily use traditional visualization methods (e.g., static 2D maps suitable for publication) and emphasize the spatial or temporal visualization of individual variables. Specific components of a large data set are analyzed thus often lead to a loss of overview and hamper insights into larger geographic patterns in the climate change data set.

Research efforts are desired to take advantages of the strengths provided by the broadly available technologies employed in general purpose systems and the applied special purpose systems used by scientists and combine these strengths together for the purpose of climate change communication. To do this we need "models that are sufficiently simple and robust to allow automatic application and interactive interrogation by end users with little [domain] expertise." (Al-Sabhan et al. 2003, page 10). This allows us to do more than integrate the Geoweb with climate data output but also integrate the Geoweb with climate model input. Then we will combine the general purpose and special purpose systems with the coupling in a matrix to understand how the Geoweb can be better integrated with the data and tools of climate science.

We borrow the concept of coupling from GCMs and environmental models. There is no strict definition of coupling, for instance, in GCMs. Coupling generally means integration at the data or software level of diverse types of model components (e.g., differences in domains like atmospheric and terrain or differences in scale like regional and global). The goal is to increase the complexity and comprehensiveness and extend functionality of that model (Soden and Held 2006). Coupling primarily responds to legacy, complexity and resources problems in modeling. One couples models because legacy models like GCMs are complex and were expensive to produce so one does not want to/cannot rewrite from scratch, even if the source code is available (Brandmeyer and Karimi 2001, Charnock et al. 1996). Legacy models can have large user communities that have developed trust in results and skill sets in using them; they become "industry standards" (Karimi and Houston 1996). We may wish to increase functionality through full model integration; coupling offers an effective near-term solution.

It has been particularly difficult to couple GCMs and global environmental models with geospatial technologies like GIS (Steyaert and Goodchild 1994). Any differences in geographic scale or resolution or differences in data structures must be addressed; new user interfaces must be created to interact with expanded functionality of the coupled system (Brandmeyer and Karimi 2001). GCMs generate time-series data as intermediate and end products, which GIS may not be able to store. There are fundamental differences in modeling structures. GCMs are process models. Even the most dynamic GIS is static in comparison because GCMs do not fix data at specific geographic coordinates during model runs. Karimi and Houston (1996) identified prospects for loose coupling as data exchanged between the model and the GIS. There also have been calls for a tighter coupling between geographic technologies and environmental models, whether at the pre- and post-processing levels or within the model itself (Steyaert and Goodchild 1994, Thorpe and Karimi 1998). Through web services and APIs, the inherent modularity of the Geoweb may be able to surmount a number of the problems experienced in GIS, of its complexity, user-unfriendliness of the interface, lack of customization (e.g., of said interface or to satisfy highly specific domain needs), and platform dependency (Al-Sabhan et al. 2003). We argue that the Geoweb can effect a tighter coupling of geospatial technologies with GCMs.

Our goal is to develop applications that demonstrate loose and tight coupling with the Geoweb. Existing efforts mentioned in the above URLs are considered to be loose coupling, in which the data from a GCM is automatically transferred from one model to another (Brandmeyer and Karimi 2001). That is, the Geoweb is coupled after GCM simulations have been finished and is used for communicating model output. Just as GCMs have grown to encompass other models of global scale earth systems, we seek a tighter coupling with Digital Earth. A tighter coupling also aims to provide insights into the working of GCMs. We argue that non-experts can gain better insights into the inner workings of climate modeling if we explicate the progression of GCM simulation runs. As suggested above (Steyaert and Goodchild 1994, Thorpe and Karimi 1998), the tighter coupling occurs at the parameterization level of and within a GCM.

We combine the two concepts of general/special purpose and coupling in the matrix in Table 3. Loose coupling general purpose refers to integration between a broadly accessible climate tool and the Geoweb via a data exchange. Loose coupling special purpose is integration between a domain specific climate tool and the Geoweb via customization of the former and a data exchange with that latter. Our applications differ from prior applications like Surging Seas in that the user selects which climate output to be displayed. Our aim was to create both loose and tight couplings of the Geoweb to climate models (see Table 3). Loose coupling is focused on the display of model output. A tighter coupling in the most general sense would allow people to work directly with a GCM and requires the integration of an API into the model. Tighter coupling at the specialized level would make it possible to integrate a GCM with a Digital Earth and even allow considerable code modification.

Table 3. Matrix of Geoweb coupling typology and visualization approaches

	General Purpose System	**Special Purpose System**
Loose Coupling	Multiple Digital Earth platforms to visualize climate data output	Customized Ferret scripts for 3D static and animated geographic and animation via Digital Earth
Tighter Coupling	Application of climate variables charts API for a GCM	Vegetation boundary conditions of the GCM

3.4 Applications

We created several applications to fill the four cells in the matrix of Table 3. The goal was to create a loosely coupled general purpose system by using two Digital Earth platforms (OpenLayers and Google Earth) and Open Geospatial Consortium's (OGC's) standard Geoweb XML (i.e., .KML and .KMZ) to display climate model output. That .kml was generated by customized scripts that extended a system extensively used in climate related science called Ferret; this represents our loosely coupled special purpose application. Our tighter coupled general purpose application is a charting application that plots and displays the progression of climate variables during GCM runs. While not a Geoweb application, it serves to illustrate the attributes that are mapped in post-processing. The possibility of a tighter coupled special purpose application is demonstrated by an OpenLayers application for customizing GCM input files. This user interface collects and then converts vegetation input and is built into the GCM.

3.4.1 Loose Coupling with General Purpose Systems

OpenLayers API was used for the dynamic display (i.e., the ability to pan and zoom) of two dimensional (2D) climate maps. OpenLayers is an open source JavaScript library for building web-based applications similar to Google Maps (OpenLayers 2012). As shown in Figure 2, we allow users to create multiple instances of OpenLayers rendered in one web page so that interested parties can compare datasets. The source and dimensions of climate data offered to users are outlined at the top of the figure.

Considerable effort was placed on user control of scales and styles for colorbars, with the possibility to view the data values behind the map in a spreadsheet format if preferred (Figure 2). The scale bar can be customized by first clicking on the scale bar. A pop-up window appears that allows the user to change the scale extent and choose a colorbar style. It fully interacts with the main window thus any settings in the popup window will cause instant changes to the maps in the main window. Seen from the users' perspective, this loosely coupled general purpose application provides an interactive interface for visualizing GCM output data but also meets scientist's requirements regarding scientific information provided in an accurate manner according to scientific norms (as opposed to the more populist climate impacts applications mentioned above).

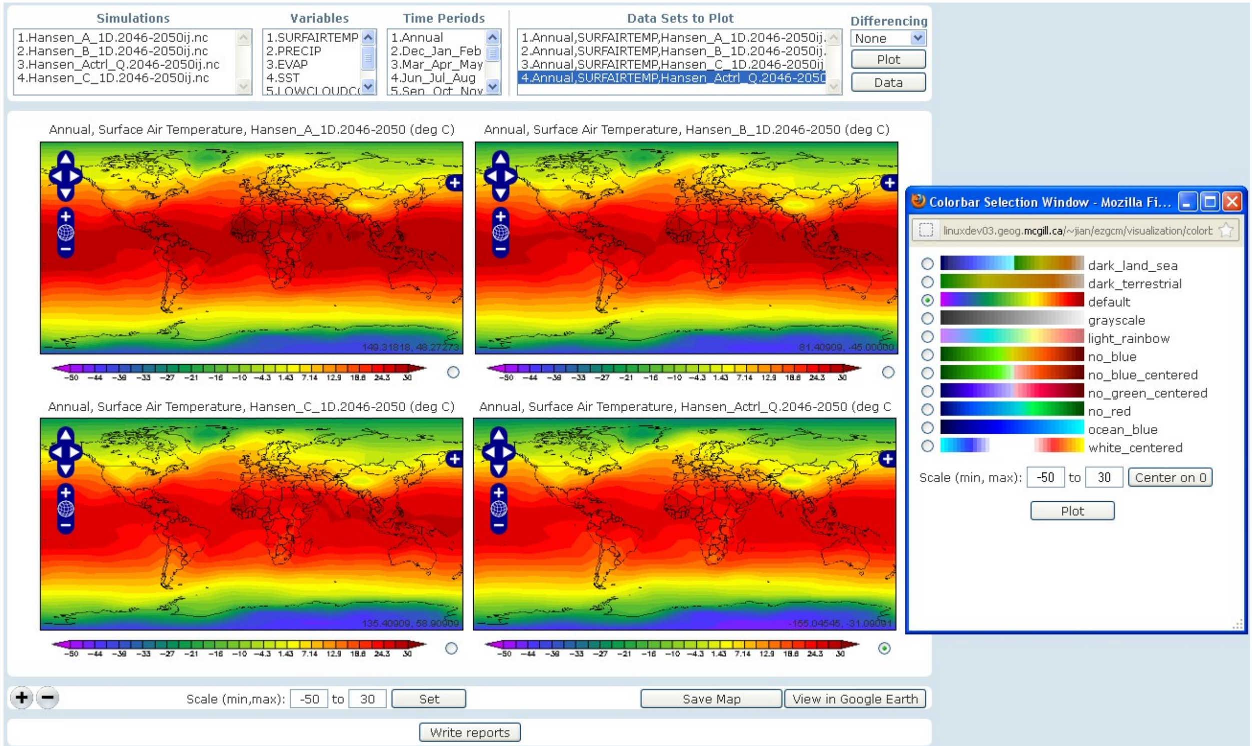


Figure 2. Loose coupling with OpenLayers. Through the interface, users can select datasets to plot global maps or anomalies, overlay continent outlines or masks, navigate the interactive maps, and customize map titles and colorbars. The interface also supports displaying one to six OpenLayers Maps at a time. "View in Google Earth" allows users to visualize selected datasets dynamically in three dimensional Google Earth.

We explored loose coupling with a general purpose system on two Digital Earth platforms. The second application provided a 3D view of climate impacts (we call it the Multiple Google Earth Platform). We produced two applications as a response to Craglia et al. (2008) who argued that we must stop thinking about a single Digital Earth solution but instead create multiple connected solutions that recognize different user needs. Whereas OpenLayers represents the earth in the most standard projection and dimensionality used by climate scientists; others may feel more comfortable with a 3D globe view.

Here we took advantage of the Google Earth plug-in and its JavaScript API. We developed an application that can simultaneously render up to nine earths. These multiple earths can be controlled asynchronously or synchronized. As shown in

Figure 3, each earth instance has its toolbar enabled in asynchronous mode. In the synchronized mode, however, only the earth in the top left contains toolbar that controls the behaviour of all earth instances.

We also utilized extensions to the OGC KML standard that contain features to display time through KML animations. To implement KML animations and have animations displayed in earth instances, the Ferret scripts running on the server side are customized to output KMZ archives (i.e., zipped KML files with supporting files such as images) that are KML tours. We will describe these customized Ferret scripts in the next section.

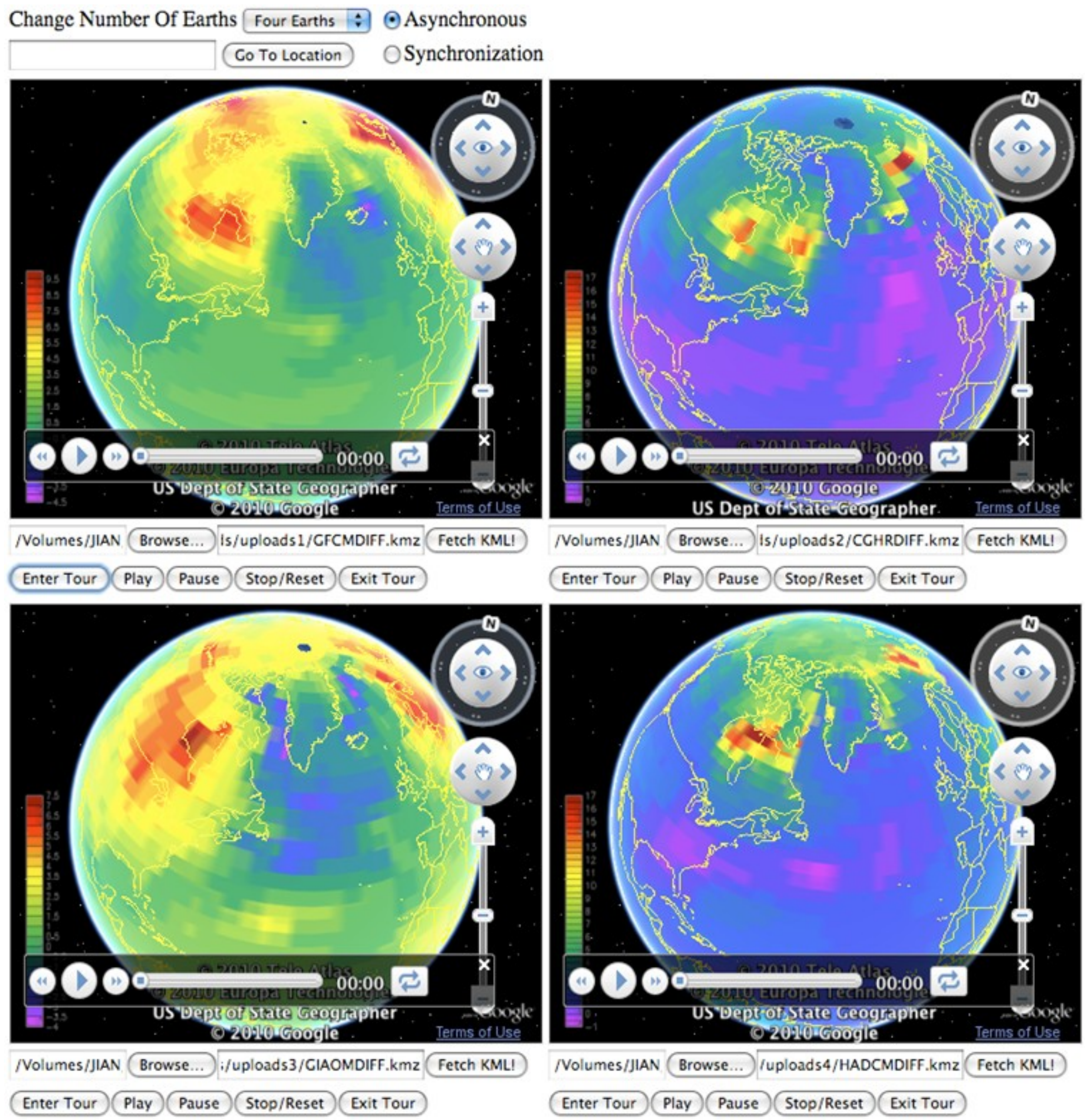


Figure 3. Loose coupling with Google Earth. From left to right, from top to down are animations exploring air temperature change predicted by GFCM2.1, CGCM3.1, GISS-AOM, and HADCM3 under IPCC scenario A1B.

Figure 3 shows a set of Google Earth instances in which the user selects a KMZ file for each earth. The platform then fetches and displays the KMZ file. Since these KMZ files are KML tours, the loaded animations show how climate variables change through time in a 3D geospatial environment. In synchronized mode, the platform can show four movies (tours) at the same time step, zooming into the same spatial scale. The ICA Commission on Visualization and Virtual Environments has indicated the priority to explicitly incorporate into geovisualization applications location and time components of data (MacEachren et al. 2001). Our multiple Google Earths platform represents spatially referenced climate change while using animations to display its time dimension.

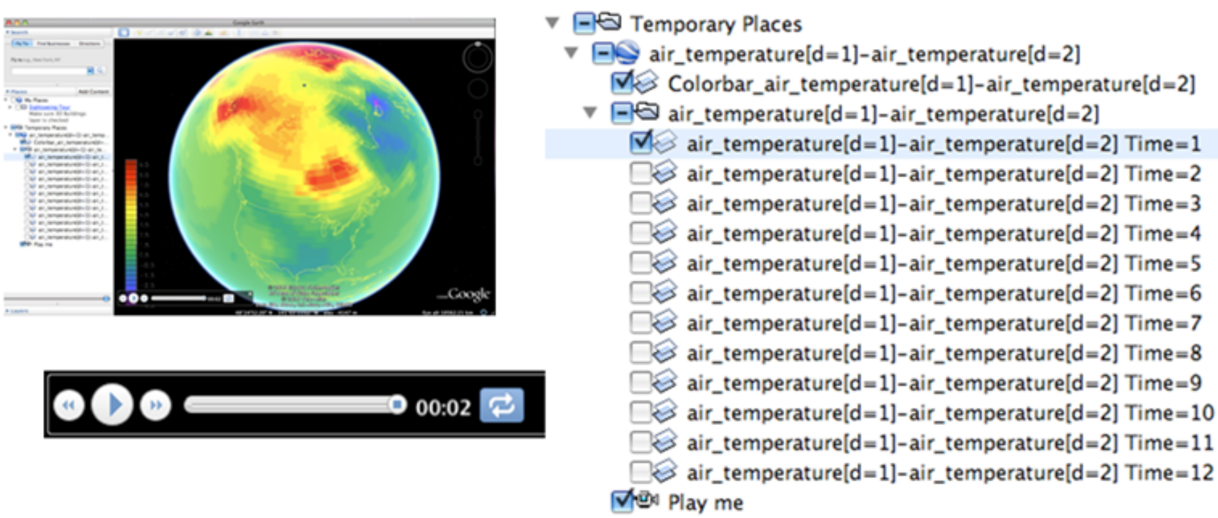
3.4.2 Loose Coupling with Special Purpose Systems

The special purpose system we used for analyzing and visualizing climate change data is Ferret (NOAA/Ferret 2012). Ferret is a popular scientific visualization and analysis package designed by NOAA/OAR/ Pacific Marine Environmental Laboratory (PMEL) for the purpose of analyzing gridded data. We used Ferret because 1) as a special purpose system used by climate scientists, it supports all features (e.g., customizable color bars in multiple styles, various projections, and mathematical process of climate datasets) requested by climate scientists for scientific analysis and visualization; 2) Ferret is free and open source software (FOSS, as opposed to IDL), which is therefore extensible and supported by a large user community; and 3) Ferret scripts can be run in the command line; thus it is easy to setup and run Ferret on the server side.

Figure 4 shows the input and output of scripts we wrote to allow Ferret to produce KMLs. These scripts are capable of generating multiple images (with a single legend for all) along either spatial or temporal dimensions from a NetCDF climate data set with the execution of one line of Ferret command (Figure 4a). NetCDF is a common data format used for creating, accessing, and sharing climate change data. In addition to KMLs, the scripts enable Ferret to support the KMZ output format (KMZ embeds a KML file with images and legend, Figure 4b). Our scripts have been incorporated into the Ferret release since Ferret V6.7.

```
yes? go create_kmz shade air_temperature[d=1]-air_temperature[d=2] k null l 1 12
     adding: Colorbar.gif (deflated 0%)
     adding: L1.gif (deflated 0%)
     adding: L2.gif (deflated 0%)
     adding: L3.gif (deflated 0%)
     adding: L4.gif (deflated 0%)
     adding: L5.gif (deflated 0%)
     adding: L6.gif (deflated 0%)
     adding: L7.gif (stored 0%)
     adding: L8.gif (deflated 0%)
     adding: L9.gif (deflated 0%)
     adding: L10.gif (deflated 0%)
     adding: L11.gif (deflated 0%)
     adding: L12.gif (deflated 0%)
     adding: doc.kml (deflated 95%)
   ! --- end of create_KMZ.jnl ---
   ! --- Visit http://rose.geog.mcgill.ca/~jian to Animate the KMZ ---
```

(a)



(b)

Figure 4. Loose coupling with Ferret. (a) Use of Ferret "go" command to run our customized script set named as create_kmz by setting proper parameters. The command line in (a) will output a KMZ archive that is composed of twelve anomaly maps and a consistent colorbar for all maps. (b) Table of contents of the output KMZ archive in Google Earth. (A zoomed in image of the table of contents to the left of the globe. We

also include a zoomed in image of the temporal tour bar.) This KMZ is an animation that is composed of twelve images where each image represents one month.

3.4.3 Tighter Coupling with General Purpose Systems

Our tighter coupling with a general purpose system is a charting application that plots and displays global climate variables whose values evolve throughout model runs. Although our application here is not strictly geographic, we wanted to illustrate the use of Web 2.0 APIs to more tightly couple models. We used the Highcharts charting library (http://www.highcharts.com/), a general purpose JavaScript API for creating online plots and charts. Highcharts is open source and is free for the nonprofit sector. Like Web 2.0 systems, it can run on mobile devices as well as on desktops. In this instance, the Highcharts Charting API is embedded and executed synchronously with the model runs. Changes in the values of climate variables are plotted dynamically. It is also possible to represent this tighter coupling even if the simulation has been finished since the values of these variables at each time step are saved as separate files.

Figure 5 shows a 100-year experiment that contains a set of four simulations in this case running James Hansen's classic climate model (Hansen et al. 1988). Each simulation is based on a slightly different set of predictions (i.e., differences in the trend of Carbon Dioxide from 1950-2050) and is represented by one color of a line. Each chart has been designed to show values for climate variables such as surface air temperature and precipitation as they change dynamically throughout the simulation. The user – this is part of a larger application that has been designed for high school students – can start and stop the run and hovering over any point in the lines will show the values at that point in the line.

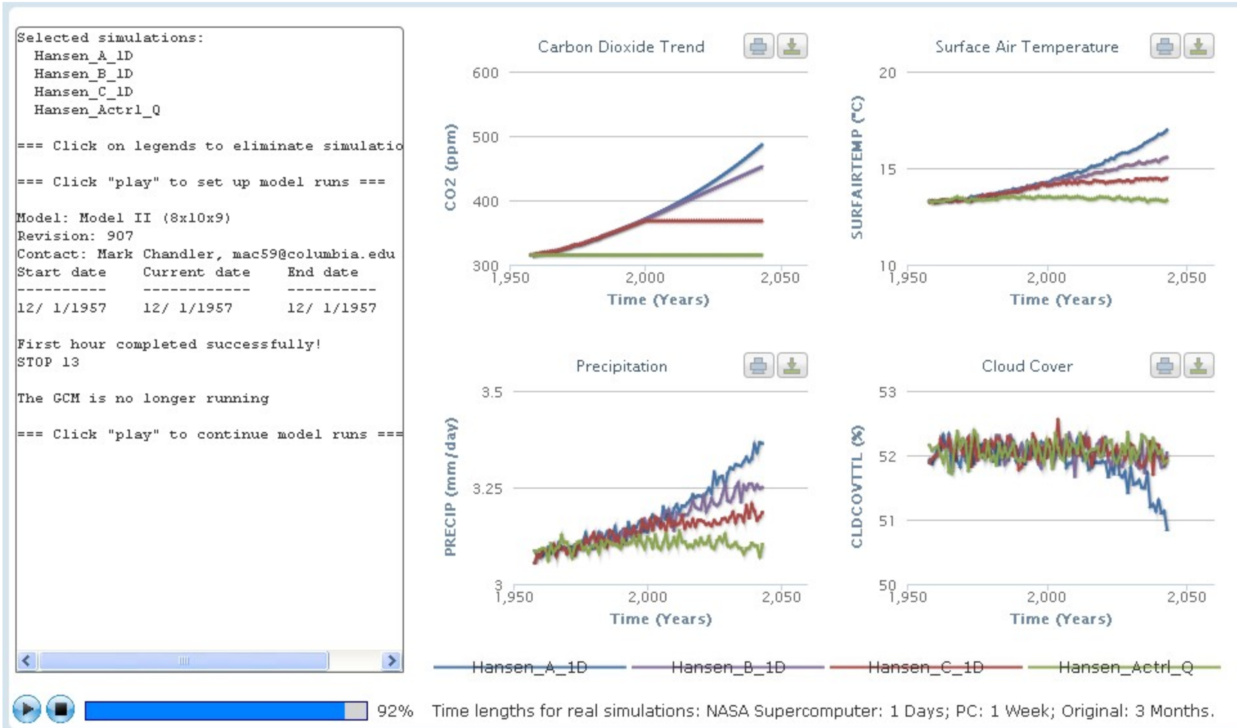


Figure 5. Tighter coupling with a general purpose system. While the simulation runs dynamic charts make it easy to visibly compare trending climate variables from different simulations (e.g., Hansen _A_1D, Hansen_Actrl_Q).

The tighter coupling general purpose application shows the possibility of transferring abundant scientific information through a simple interactive interface. We show the progression of the GCM in text in the window on the left side of the screen. The interactive plots are shown simultaneously on the right side. Not shown in the image is the ability for users to share this content, via Twitter and Facebook.

3.4.4 Tighter Coupling with Special Purpose Systems

The examples thus far have explored the integration of Geoweb with output and during the running of the GCM simulation. We looked to integrate it further into the actual preparation of model boundary condition file as well. This integration is possible since GCM input – most input is not a set of single values but a series of files – such as earth topography and vegetation coverage, contains gridded georeferenced information. Our tighter coupling with special purpose systems integrates a Digital Earth and a GCM.

We chose to work with the NASA/GISS GCM Model II for this tighter coupling. First we have a close cooperation with scientists and programmers from NASA/GISS who provide scientific reference to couple other systems with Model II. Second, Model II, while an older version, is a classic GCM on which state-of-art GCMs are built. Third, Model II is still in use, open source, and maintained (updates and bug fixes) by scientists from NASA/GISS, which allowed us access, as opposed to other models we investigated. Fourth, Model II has a relative simplicity and a course grained latitude by longitude resolution (8° X 10°), but it is a fully functional GCM that is excellent for testing the possibility to integrate Digital Earth and GCM input. Last, NASA/GISS Model II has sufficient 'hooks' to fuse geographically referenced content into the system.

The model pre-processing function that we integrated deals with the vegetation coverage and its relationship to the climate system through albedo, soil moisture, and evapotranspiration. A vegetation file assigns terrestrial vegetation characteristics (and land surface also) and serves as one of the boundary conditions (i.e., limits) for Model II. Vegetation tends to be modeled fairly simplistically in many GCMs. Vegetation types (e.g., desert, tundra, and grass), distributions, and their properties, such as visual albedo, field capacity, and roughness length, are all used and are supplied by the vegetation file. Chemistry is not simulated in Model II, nor in any of the production NASA GCMs, though a physiologic approach to creating dynamic vegetation distributions in climate model has been explored in several cutting-edge GCMs.

We developed an OpenLayers application to allow users to create and modify vegetation files (Figure 6). Prior to the development of this application, creation of a vegetation boundary condition file required the use of Fortran executables. Error checking was also done at this time, but corrections had to be made either by modifying the text files or, often, through coded conditional statements. Our application supports a global extent and enables various ways for the visual selection of multiple cells, for example by grouping/averaging modifications (bounding box in Figure 6). We show a chart of the values in the selected area, whether it is a single grid cell or a grouping of cells.

We realized the relatively high threshold for working with the vegetation file. We provide users with a default vegetation file to 'import' based on which users can do modifications and 'reset' to original sample vegetation file. Unlike the prior modification system, in which mistyping percentages would most likely crash climate model runs, stringent rules were implemented in the application logic to ensure that vegetation file output by the application would not cause fatal errors. The implementation of this logic and its error checking reduces the threshold to working with the vegetation file and makes the application useful for training young professionals as well as making it easier for scientists who are not familiar with the specific input formats for the NASA global climate model.

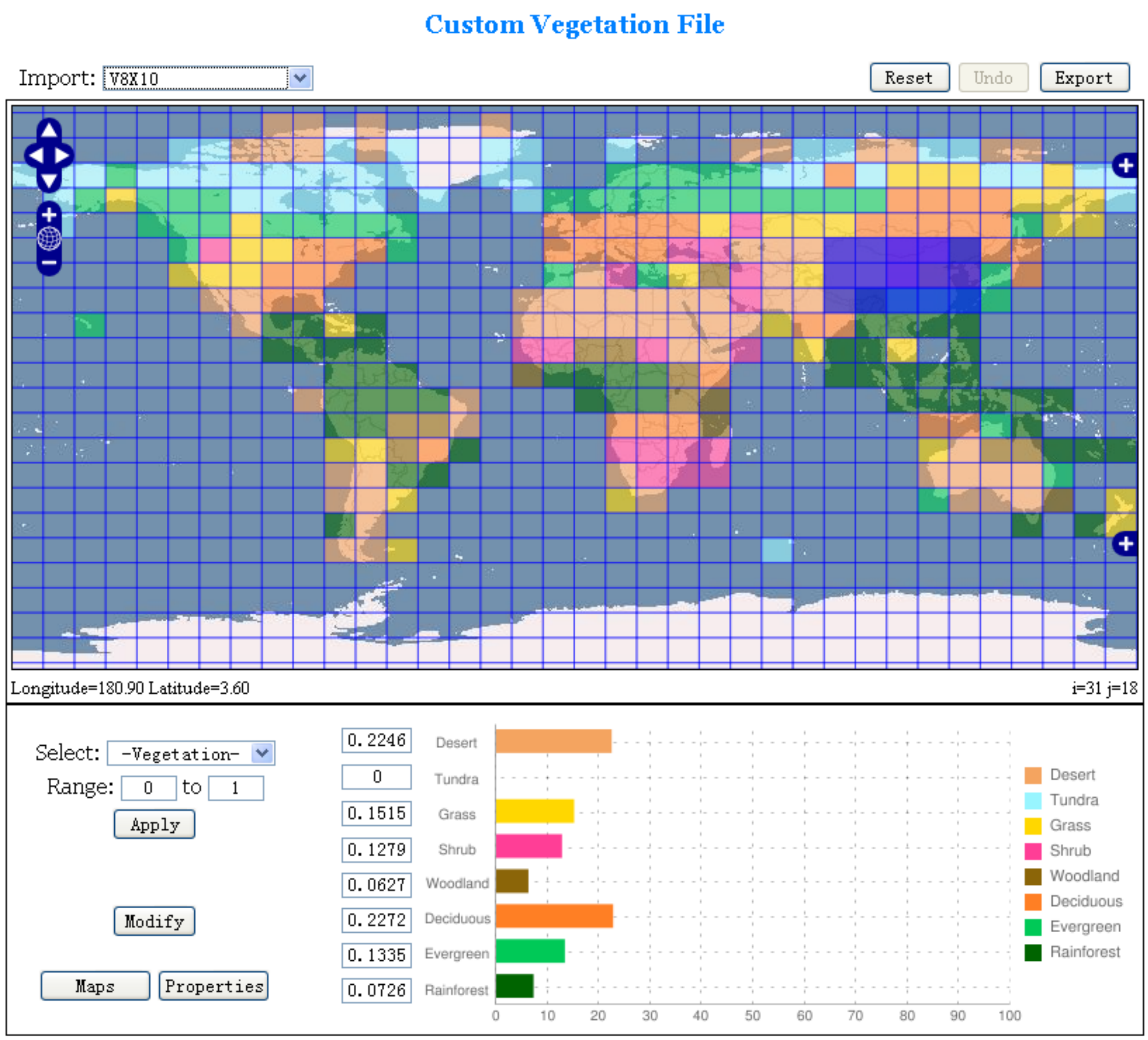


Figure 6. Tighter coupling with Scientific Fortran programs and OpenLayers.

We define the OpenLayers application as tighter coupling with special purpose systems rather than general purpose systems because of the Fortran programs, part of the GCM, that were modified to read in and output vegetation coverage. Although we use a front end Digital Earth interface, these special purpose components run in the back end and respond to user's requests in the interface.

3.5 Discussion and Conclusion

Our matrix offered four distinct solutions to integration, depending on audience and access to models, and responded, given the flexibility of the Geoweb, to changing needs. This section offers a more general discussion about the pros and cons of applications for each cell of the matrix.

As demonstrated by the first OpenLayers application and the Multiple Google Earths platform, applications in the category of loose coupling with general purpose systems have the potential to allow large gridded datasets from diverse sources to be displayed on one screen. This responds to Nicholson-Cole's (2005) argument that effective climate communication brings together many aspects of climate data for an engaging computer-generated visualization. Our applications allow variables and images to be compared, and provide simultaneous visualization of climate data from different sources (residing in the same or different physical locations).

Loose and tighter coupling with special purpose systems make it possible to build a Digital Earth "interface" for special purpose systems, essentially wrapping those systems to increase accessibility for a broader audience. The user need not know Ferret script or commands to make maps and animations for the analysis and visualization of model output. In the case of the OpenLayers vegetation application, end users employ the OpenLayers interface where indirectly they actually are manipulating Fortran programs for vegetation files.

The integration between Digital Earth and special purpose systems also can benefit our understanding for Digital Earth platforms. A Digital Earth need not replace more sophisticated systems for the purpose of performing data analysis tasks. In the integration, special purpose systems run in the back end to perform data analysis through Web Services. From front end users' perspective, the special purpose systems are hidden and Digital Earth can perform these necessary analyses. The coupling with special purpose systems enhance Digital Earth's ability to access and visualize GCM output; whereas the tighter coupling with special purpose systems make it even possible for Digital Earth to preprocess and generate compatible GCM input.

Chen et al. (2009) argued that integration of Digital Earth with special purpose systems could free scientists from their respective domain-induced boundaries and their current “conventional” scientific research tools. Compared to the existing interface, our OpenLayers vegetation utility provides a relatively easy interface for the design, creation, and modification of model input. Simplifying the user interface comes with a cost. The more special purpose the system, the more likely the interface will not be simple. One may gain increased flexibility and platform-independence because the application exists in the cloud. Access can be increased without ease-of-use for some participants. We developed a complete web parameterization interface for Model II, of which vegetation boundary condition pre-processing was a component. Change in user attitudes is not easy; anecdotal evidence of use of the application reveals that atmospheric scientists can react with hostility to the simplistic visual look and feel. Digital Earth interfaces can make GCM use looks ‘too easy’. There is generally a balance between the ease of use and the complexity of information to be transferred; attempts to increase user friendliness can obscure complexity.

We found numerous technical development issues. Compared with OpenLayers and Google Maps, Google Earth can display 4D climate data. Achieving this feature requires that the Google Earth Plug-in must be installed in the client machine. Our experience of developing Google Earth applications demonstrates some of the fragility of these couplings: Google Earth can be quite slow and crash frequently. Even though the Google Earth Plug-in is touted as Web 2.0 compliant it remains operating system dependent and is currently not available for Linux machines. GCMs vary enormously in format and architecture representing different approaches to climate modeling. Extensive investigation and interrogation among team members was required to select a GCM that could be modified with a geospatial technology; indeed the team shifted with the model selection. Tying our applications to a specific GCM means that our code is not transferrable to other GCMs. This is the unavoidable overhead of working with a complex legacy system.

A close cooperation between climate scientists and other scientists is critical for climate change communication (Weart 2012, Goodchild et al. 1996). Extensive cooperation among researchers in climate science, GIScience, and computer engineering was essential to develop our special purpose couplings. One unanticipated challenge for integrating a GCM with a Digital Earth came in the bundled data sets of the latter. Our vegetation utility also can be used with topography. The global topography (e.g., size, shape, and position for global continents) bundled with most Digital Earth is based on modern topography. Paleoclimatologists, however, study climate changes that occurred on Earth from thousands to millions of years ago. This is a necessity since future climate change is of a magnitude that scientists must look to the distant past to find analogous changes on Earth. At times in geologic history when large ice sheets were present on Earth, or if we are examining past periods when continental drift becomes a factor, topography may have been dramatically different. It would be ineffective to visualize GCM input and output from paleoclimatology research on a modern topographic earth. Where we lacked flexibility in the legacy system, we had the flexibility to switch Digital Earth in response to this identified need.

We demonstrated the ability to categorize and exemplify climate change communication efforts by the matrix in Table 3. They are designed to cover all aspects of climate modeling (e.g., input, process, and output). These applications demonstrate the potential of Geoweb technologies, which can not only be used for conventional communication of climate model output, but also employed throughout the climate modeling process. It is hoped that Geoweb integration of the data and tools of climate science can increase understanding of critical climate change scientific findings, but also encourage active dialog and interaction between scientists and the general public that is facilitated by greater access to these scientific tools.

3.6 Acknowledgements

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Chapter Four Communicating Climate Change Findings through Climate Modeling and Web 2.0

(Note: This chapter aims to answer research question two, which is how to improve the accessibility of GCM by elaborating the scientific process of climate modelling. It is a manuscript ready to be submitted. It is authored by Jian Zhou, Renee Sieber, and Mark Chandler.)

4.1 Introductory paragraph

Engaging people in the fundamental practices and procedures involved in global climate modeling offers a unique avenue for communicating climate change. It is increasingly possible to offer realistic, participatory research experiences by delivering climate modeling through Web 2.0 applications. These are the same type of applications that have become so popular for communicating all forms of information online and the approach makes it possible for teachers, students and the general public to view the scientific method through the lens of the climate scientist. Our project, EzGCM, emphasizes the significance of each step in the scientific process and alleviates the necessity for participants to possess high-level programming skills or to have access to vast computing resources. Our objective is to advocate a critical thinking environment in which interested members of the public can reproduce for themselves how scientists obtain climate change projections. We find that this method can be used to demystify climate modeling in both formal and informal educational settings, and may be crucial for communicating climate change findings in a way that inspires trust.

4.2 Communicating the Scientific Method of Climate Change

The last two decades have seen the proliferation of efforts to communicate climate science to the general public, including communication of future climate change projections and the scientific reasoning behind them (Nerlich et al. 2010, Dilling et al. 2007, Pidgeon et al. 2011). Understanding the complexity of the climate system requires a significant amount of interdisciplinary scientific knowledge, and understanding climate *change* requires additional knowledge of the scientific process, including a basic understanding of climate modeling (Moser 2010). In addition, the depth to which we need to communicate this information is greater than it might be than for many topics because the public is faced with distinguishing legitimate skepticism from messages that aim to obscure scientific findings (Pidgeon et al. 2011). Building a base of knowledge about both climate science and the scientific process also lays a stronger groundwork from which public officials can evaluate climate-related proposals and it is also necessary for political leaders and their staff so they can advocate, knowledgably, for policies that require broad public support (Pidgeon et al. 2011, Schnoor et al. 2011, Compston et al. 2008).

Despite the demonstrable need for communicating the science of climate change, scientists have been criticized for ineffectively communicating scientific knowledge to a non-scientific public or even to specialists in other scientific fields (McBean et al. 2000, Fischhoff et al. 2007). Using idiosyncratic jargon in papers or during presentations only partially explains the problem. More fundamentally, climate scientists often work in environments (e.g., research universities and national labs) that reward advanced, highly technical research and specialized publications, not the communication of basic results and procedures. Research suggests that one-way dissemination from experts to non-experts, via information from scientific reports and news media cannot impart to the general public how climate change works (Nerlich et al. 2010, Sterman 2011). At the same time, researchers are encouraging both students and the general public to become more engaged with climate change science (Pidgeon et al. 2011, Sterman et al. 2011, Allen 1999).

Engaging the public in the actual practices of climate change science was once viewed as a foregone conclusion. In the mid-1990s prominent climate scientists were predicting that schools and politicians would "soon" be running Global Climate Models (GCMs) on their laptops (Randall 1996). This did not occur largely because labs had greater imperatives to create ever-more complex GCMs or, as some are now called, Earth System Models (McGuffie et al. 1996, IPCC Climate Change 2007, Trenberth 2010). But, this renders a prime instrument of climate scientists, GCMs, as little more than a "black box" to most people, including many scientists, who may then become skeptical about the results and perhaps even the value of critical models (Sohl et al. 2010, Yearley 1999).

In more than a decade of working with teachers, students and the general public through the Educational Global Climate Modeling (EdGCM) project at Columbia University and NASA we have found that people greatly value the ability to participate in even the most complex aspects of climate research, but we've also discovered that our standard practices take longer than most formal and informal settings can afford. In this paper, we present a means for teaching climate modeling through a Web 2.0 methodology that remains comprehensive, but streamlines the procedure involved in the scientific method employed in climate modeling studies.

4.3 Current Use of Web 2.0 to Communicate Climate Science

An emergent method of communicating climate change is via applications that take advantage of Web 2.0 technologies, particularly Earth browsers like Google Earth and OpenLayers (Nocke et al. 2007, Yzer et al. 2008, O'Neill et al. 2009). The concepts underlying Web 2.0 are mashability, that is interoperability among modularized components called application programming interfaces (APIs), platform-independence since applications can run, for example, in a web browser or a mobile phone, user-centered design and end user interactivity, and shareability of content produced both by application developer and the end user

(O'Reilly 2005). As suggested, this suite of technologies is useful not only from a developer point of view but from also an end-user point of view.

It is not insignificant that Web 2.0 implementation transcends technical details and embeds societal concepts, for example of egalitarianism and empowerment of non-experts and emancipation of data and process by which the data are created (O'Reilly 2005). However, the empowerment of non-experts afforded by Web 2.0 activities can also extend to a disdain for expertise (Turner 2006), which poses problems for science, particularly in the charged political atmosphere of climate science (Gauchat 2011). We look to several positive examples of Web 2.0 usage to reveal the practice of the climate model and scientific method to a non-expert general public.

Numerous government agencies and climate change scientific research groups now develop Web 2.0 applications for sharing and visualizing climate change data. One example is Cal-Adapt, a product funded and overseen by the California Energy Commission (2011). Cal-Adapt is a set of climate change data access and visualization tools to show climate change impacts at the local level. The Union of Concerned Scientists (2011) launched a similar application called “Climate Hot Map” to visualize the local consequences of climate change effects around the world. New applications emerge regularly and forthcoming applications of this type have the potential to shift how the general public perceives climate change related information (Blower et al. 2007, Chen et al. 2009).

Though manifest in different styles, these Web 2.0 applications publicize climate change data through Earth browsers so that the public can visualize the data both in space and time and relate it to other geographically referenced datasets that have civil, demographic, social or even industrial significance (California Energy Commission 2011, Union of Concerned Scientists 2011, Climate Central 2012). Although interactive, we argue that this still represents somewhat passive transmission of climate change information by scientists. The applications show the outcome of science rather than illuminate the process by which the outcome is generated. Web 2.0 technologies are used but most of these applications do not provide the full interactive potential of Web 2.0 for engagement and collaboration of interested members of the general public learning about climate science.

Climateprediction.net (2012) is an example of a computing activity to engage people in the activity of climate modeling[28]. It is a slightly older Web 1.0 distributed computing model and uses volunteers' computer time to complete a large climate forecasting experiment (Climateprediction.net 2012). Citizen science volunteers, without specific scientific training, are able to contribute to the climate change science research. However, climatepredication.net does not have as a primary goal the opening of the "black box" of the climate modeling process and participants are not asked to design experiments nor analyze model results.

4.4 Use of Web 2.0 to Communicate the Methodology of Climate Science

We explored the potential to guide non-experts through the same scientific method a climate scientist would use by employing a Web 2.0 tool we call EzGCM (pronounced "Easy GCM"). The project is a joint venture of NASA/GISS, Columbia University, and McGill University. It builds on the EdGCM Project (Chandler et al. 2005), which has provided a robust technological and instructional platform for students (primarily college and advanced high school students) to operate a full GCM. Similar to EdGCM, the EzGCM project emphasizes teaching steps involved in the climate modeling process; EzGCM focuses less, however, on the myriad details of model setup and operation and emphasizes instead the step-by-step process and basic analysis of results.

In EzGCM, we attempt to mirror the scientific method/process, as viewed through the lens of a climate modeler. We should note that there is debate about the universality of this scientific method, the discreteness of steps, and indeed at which step to begin (Millar 1994, Bybee 2004, National Research Council 1996). In conversations with climate modeler developers at NASA/GISS and based on our experience with running experiments for the Intergovernmental Panel on Climate Change (IPCC) assessments we decided to emphasize four basic steps:

1. Hypothesis development and designing experiments
2. Running the requisite simulations (a single experiment may require multiple simulations)
3. Analyzing results
    a. Post-process the raw output of those simulations (for modelers, this is a form of filtering or data mining)
    b. Explore output via data visualization
4. Communicating the results of those analyses

EzGCM provides a series of hypotheses through the introductory webpage called “Rediscovery Experiments” (Figure 7). We chose the set of experiments, which deal with a range of climate topics, from increasing atmospheric CO_2 to examining Ice Age climates because they are highly cited in the scientific literature and can be used to examine fundamental climate issues. The goal of the application is to provide an open-ended collection to which other climate modeling groups could suggest and then add new experiments. Figure 7 introduces NASA’s first global warming simulations. Choosing this experiment allows users to reproduce and analyze for themselves a famous scientific study that many point to as ushering in the era of global warming politics (presenting both business-as-usual and mitigation scenarios). EzGCM users are expected to employ the same model and analyze nearly identical data to that which was published, and to compare their own results to those of Hansen’s NASA research team (Hansen et al. 1988).

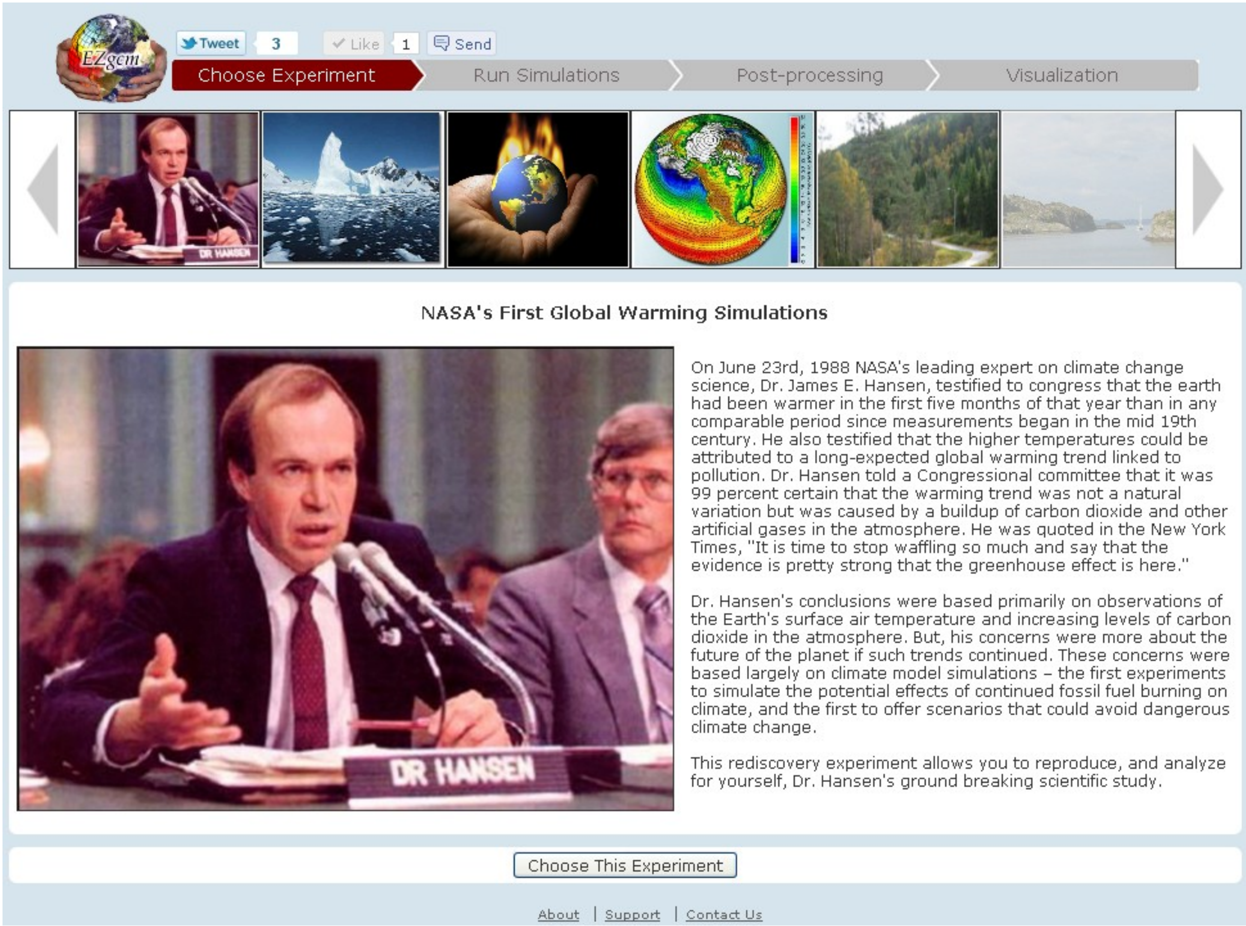

Figure 7. EzGCM "Rediscovery Experiments" interface. The image slider at the top contains icons for different experiments. The user can click on icons to view the description for each experiment and then run ("choose") the experiment.

An experiment may be composed of several related climate modeling simulations and the simulations for EzGCM have all been pre-computed to avoid the days to weeks that would otherwise be required. However, as EzGCM simulates that actual process of running the climate model the interface indicates the actual length of time required to complete simulations were they run using any of a variety of different computing facilities (Figure 8, bottom of screenshot). Users are still asked to walk through a simplified process of setting up and running the simulations and, while the model runs, the interface (left side of Figure 8) offers the user model feedback. In addition, as the simulations proceed plots convey the progression of climate change drivers, such as trending CO2, as well as diagnostic climate variables like surface air temperature and cloud cover. Charting APIs that provide optional displays of climate drivers and variables along with the ability to simultaneously compare climate change experiments to control experiments, imbue this EzGCM component with features that are distinctly Web 2.0.

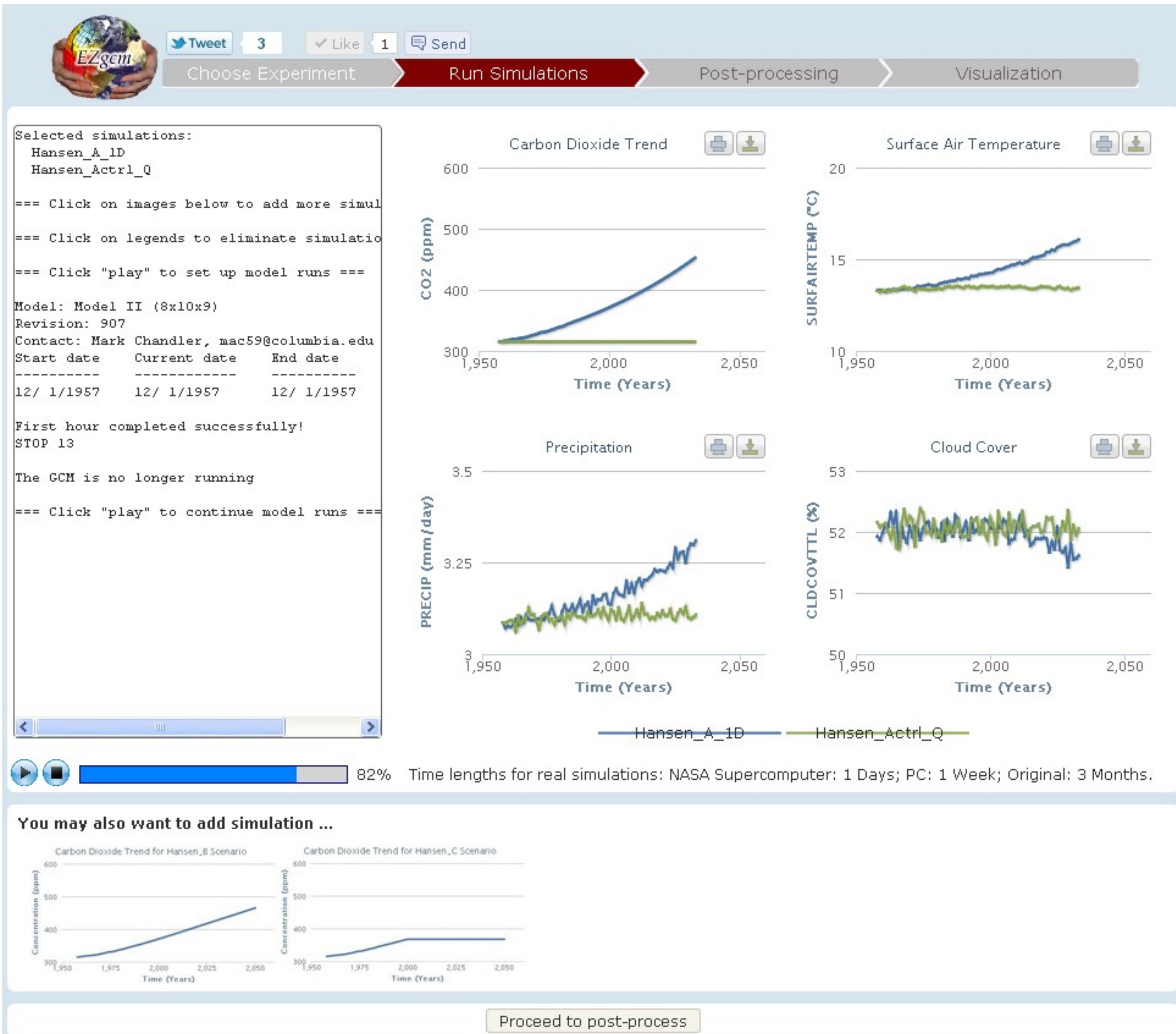

Figure 8. Raw data from pre-computed simulations make it possible to complete this step in minutes rather than days. We still emphasize the full scientific process and the information field on the left guides and responds to users' actions as well as offering feedback from the climate model. While the simulation runs dynamic charts make it easy to visibly compare trending climate variables from different simulations (e.g., Hansen _A_1D, Hansen_Actrl_Q).

The preparation of climate model raw output for analysis is referred to as post-processing. Post-processing involves several steps as indicated in Figure 9. Post-processing tasks are commonly performed by skilled programmers. EzGCM automates a number of these oft-used post-processing steps, such as averaging across temporal and spatial domains and extracting individual variables from large binary data files. This post-processing method runs in real time rather than provide pre-computed data for three reasons: (1) unlike GCM runs, post-processing can be computationally executed in a matter of seconds rather than hours or days; (2) processing the data, interactively and in real time empowers users to understand that raw climate model output demands a degree of "analysis" prior to visualization; and (3) requiring an interactive step involving post-processing allows users to recognize the importance of making analytical choices prior to analysis of individual variables. All of this conveys to users the significance of decisions that are made throughout the scientific process and that the initial output is not "map-ready". It is necessary because few people who have grown up using video game consoles, smartphones, and now tablet computers realize that there are crucial steps between a complex computer operation and the visual display of information. In the EzGCM interface, users advance through required post-processing steps while a log instantaneously provides feedback on input decisions, processing status, and output results (Figure 9).

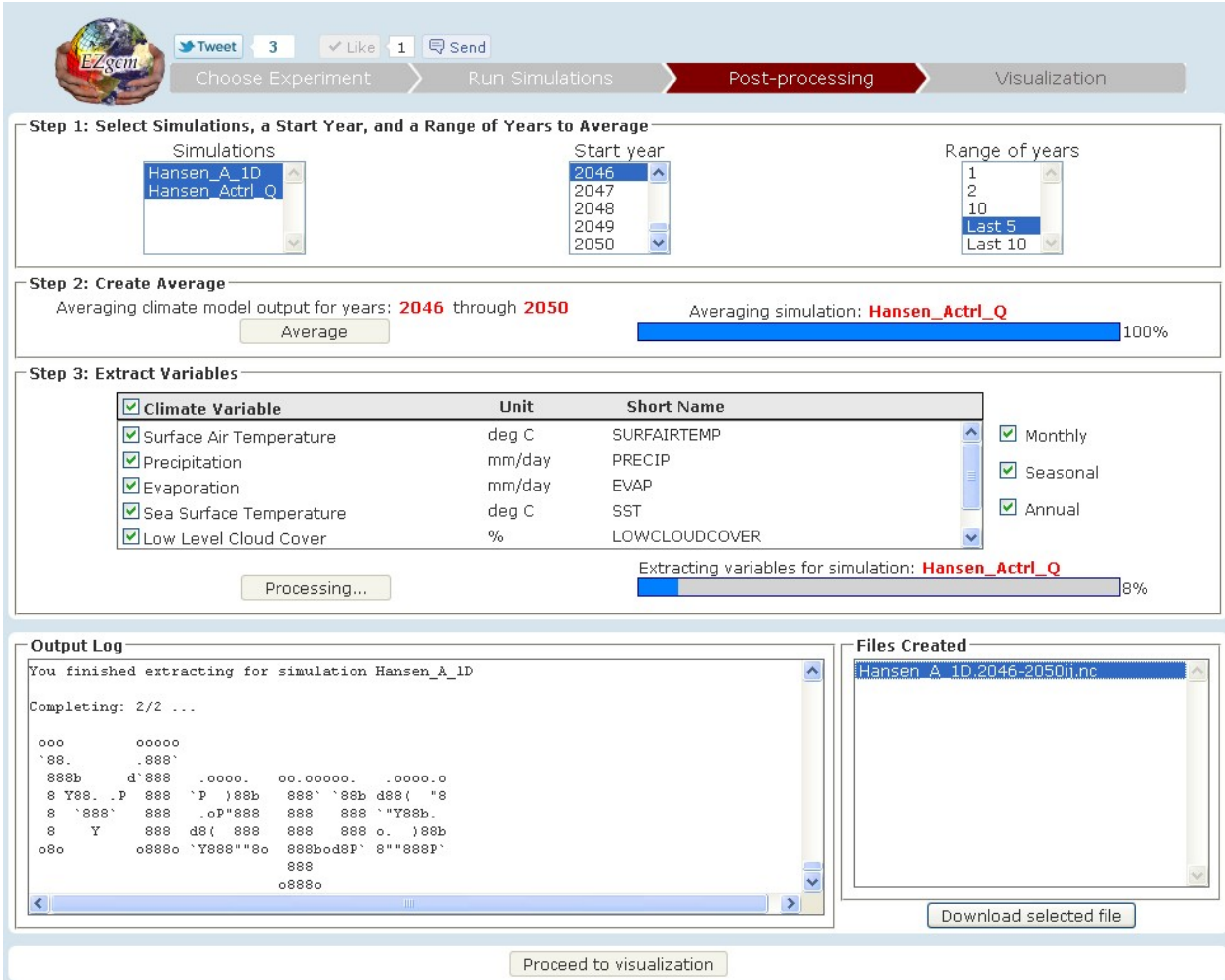

Figure 9. In the EzGCM post-processing step raw climate model output must first be averaged over meaningful time intervals (step 1 and step 2). And then climate variables of interest must be extracted from the large binary files, scaled to standard meteorological units (e.g., degrees Celsius), and converted to formats (e.g., NetCDF format) that are popularly used by climate scientists (step 3).

After post-processing steps are complete, EzGCM utilizes image representation available in geospatial Web 2.0 technologies (geoweb - Figure 10) to visualize and further analyze the climate model output. Innovations in the geoweb, like image representation and map-based APIs have the capability to condense complex information and rapidly convey messages, making it easier to relay abstract climate change concepts (Robins 1996, Nicholson-Cole 2005, Sieber et al. 2010, Special Eurobarometer Report 300 2008). The EzGCM visualization and analysis method uses the geoweb to render multiple maps simultaneously to compare variables for various time periods and regions, something that many researchers labor to do using scripting and programming.

Finally, EzGCM allows for the dissemination of results and analyses through compact electronic media outlets, such as blogs, social networking sites, earth browsers, and Twitter (see example in Figure 11). The integration of the geoweb and related social media tools enables users to conveniently collaborate and share their GCM research projects and results (Chen et al. 2009). Research and surveys have shown that young people who are more aware of climate change become promoters of change, from the family household to advocacy on science and policy developments (Nerlich et al. 2010, Special Eurobarometer Report 300 2008). Thus, changing the method of communication to take advantage of electronic media outlets that are popular among young people might prove to be a significant strategy for acting on the very real problem of climate change.

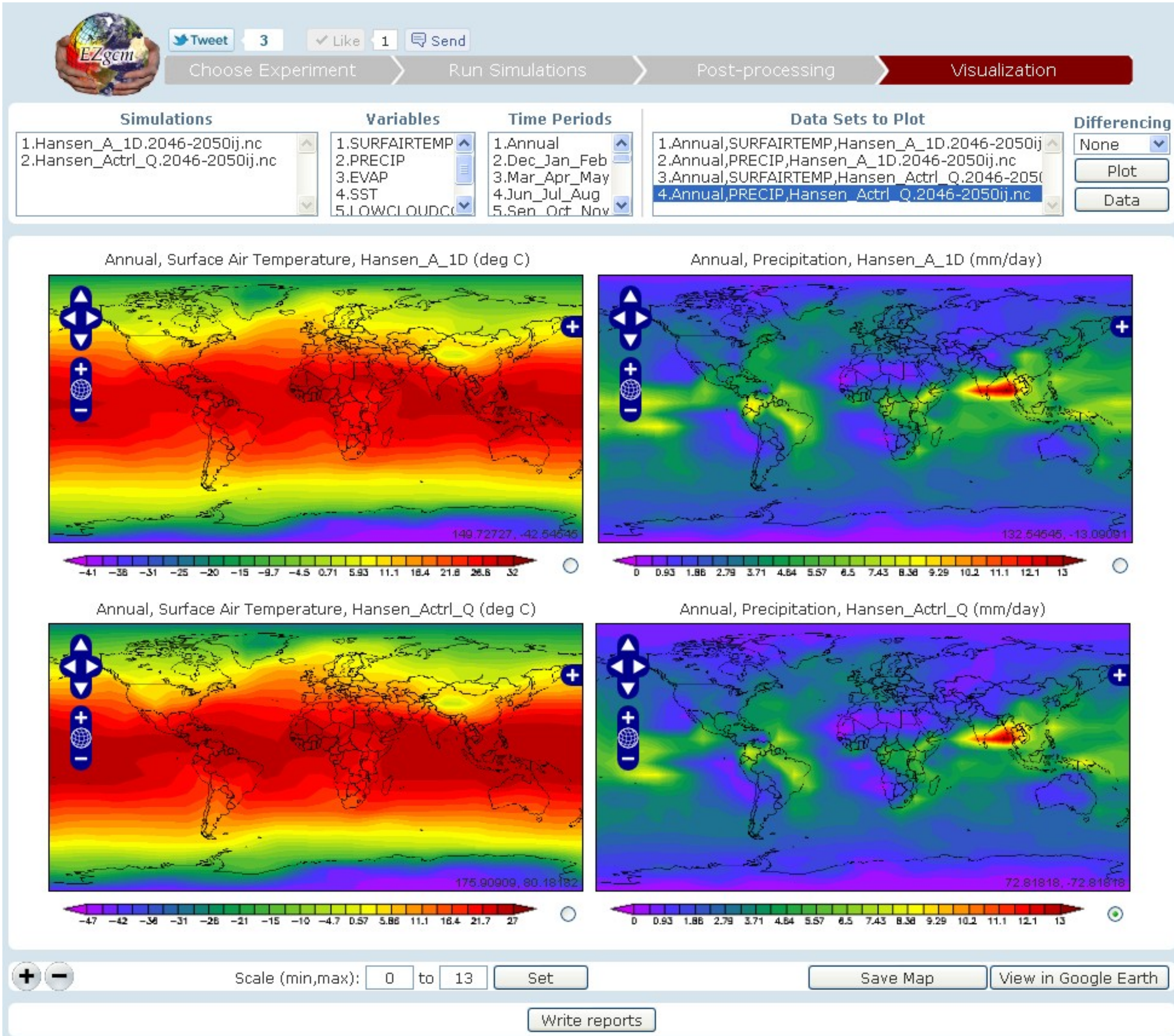

Figure 5. EzGCM visualization interface for analyzing and interpreting climate change output. Through the interface, users can select datasets to plot global maps or anomalies, overlay continent outlines or masks, navigate the interactive maps, and customize map titles and colorbars. The interface also supports displaying one to six OpenLayers Maps at a time. “View in Google Earth” allows users to visualize selected datasets dynamically in three dimensional Google Earth.

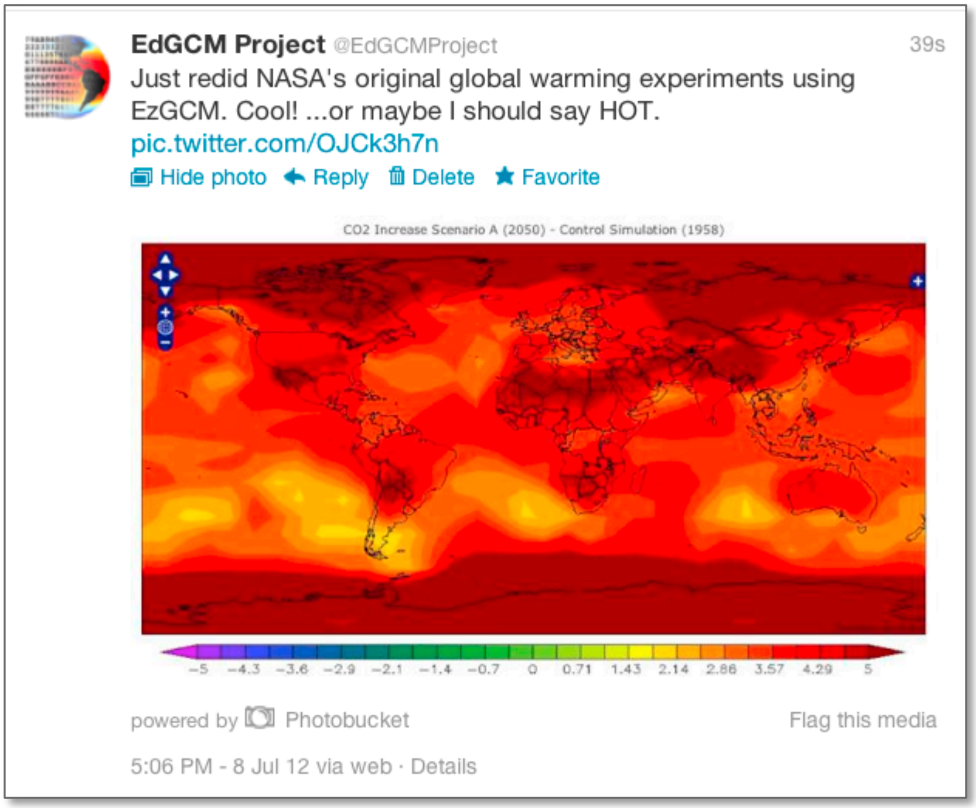

Figure 6. A tweet posted from EzGCM after following NASA's first global warming experiment.

Overall, the EzGCM project emphasizes the role Web 2.0 can play in climate change communication and education as well as the need to enhance our usage of Web 2.0 capabilities to bring climate change and climate modeling to the masses. It focuses attention on the fundamental steps involved in climate science research that involve the use of computer models for climate simulation. It reduces the focus on the myriad details involved in model setup, operation and post-processing without ignoring the importance of these critical steps for the scientist. EzGCM walks users through the full scientific process with the objective of revealing more than in traditional communications and in current Web 2.0 climate applications about how science research is conducted. It communicates the key role that process plays in assessing climate change and is in stark contrast to what the public learns from the current politicized debate over climate change.

4.5 Concluding Remarks About Non-experts "Practicing" Climate Change Science

EzGCM does not seek to enforce preconceived notions about climate change – rather, the Web 2.0 methodology encourages users to do for themselves and make up their own minds. It empowers interested members of the public, including teachers and students, to take the initiative in following the scientific process, just as climate modelers do in the study of past or future climate change. EzGCM allows people to select from a list of prominent climate modeling experiments, which we term rediscovery experiments. These are pre-computed for use in places like schools, which often have limited computing resources as well as limited time to cover climate change in an earth science curriculum. The user has significant freedom to pursue many levels of analysis of the data and is given access to powerful visualize capability that can be used to explore GCM output in a manner similar to climate scientists and the similarity of EzGCM's web tools to those of EdGCM would make more advanced studies much easier to pursue.

Although EzGCM provides an easy-to-use graphical user interface (GUI), which we see as essential for opening the process up to the general public (particularly younger students), users perform fairly complex operations that are similar to those conducted by climate scientists and scientific programmers. We realize that creating a GUI to control complex tasks retains aspects of the proverbial black box so our Web 2.0 tools make every attempt to ensure that the user must conduct all key steps in the process. EzGCM is not a tool where one pushes a button and colorful visualizations are immediately displayed. Our intent is to portray accurately, if somewhat simplified, the comprehensive procedure involved in climate model experimentation and analysis, while reducing the necessity for significant programming skills and vast computing resources.

We take advantage of Web 2.0 technologies to promote engagement and interaction and we use rediscovery experiments to reduce complexity. We also provide significant information about these experiments so that, in addition to what they gain through their own inquiry, students and general users would also have a more traditional learning path. Users of EzGCM can compare their own results and analyses with others as well as with trusted sources from organizations such as NASA and NOAA and from major refereed scientific journals.

Our goal is to provide a critical thinking environment in which learners control many aspects of a climate simulation, particularly aspects about which people have expressed doubts (i.e., GCMs and their results). Through this mechanism we hope to foster a learning environment that will bridge the gap between the citizens and scientists. EzGCM challenges people to think critically, carry on experiments, and analyze results like scientists. They can even publish results, with evidence and analyses, to express their own viewpoints on the subject. Ultimately, the objective is to advocate critical thinking on this important subject leading to a better-evinced form of peer review in the social networking world than currently exists in the often unsupported-by-evidence blogosphere.

4.6 Methods

The EzGCM project applies web-based platforms and languages to guide the general public through the scientific process of climate modeling. This included plug-ins, APIs and code libraries to build more dynamic and interactive applications. The image slider in Figure 7 is implemented based on open source code Dynamic Drive – Image Galleries and Viewers. The Highcharts charting library written in JavaScript was used to produce charts in Figure 8. We utilized OpenLayers, an open source geographic mapping platform, for viewing global climate change maps in 2D (Figure 10). The Google Earth Plug-in and its JavaScript API was used for the 3D visualization. Social media plug-ins from Facebook developers and plug-ins from Twitter are included in all the web pages.

We used Object-Oriented JavaScript, HTML, and CSS to implement the web-based graphic user interfaces for EzGCM. The server side scripting language, PHP, was used to respond to users' requests. Communication between web pages and the web server was handled with AJAX (asynchronous JavaScript and XML methods). For example, clicking on "Average" button in the post-processing interface will send users' selections (e.g., simulations and year range) to the server (Figure 9). On the server side, a PHP script is executed to run post-processing programs. The outputs of these programs are retrieved and displayed in the "Output Log" window without the need to refresh the page.

EzGCM also uses specific technologies that have been developed for climate science. We used programs written in Fortran for post-processing raw climate model outputs (Figure 9, step 2). A Fortran 90 interface to the NetCDF library has been applied to create NetCDF datasets (Figure 9, step 3). The interactive data visualization and analysis tool, Ferret, which has been developed collaboratively by the climate science community, was modified to plot global maps and anomalies from the NetCDF datasets (Figure 9). With AJAX and PHP scripting it was possible to execute domain-specific programs like Fortran programs on the server. We believe that the close integration of all these technologies made EzGCM a rich web-based application for the purpose of climate change science communication.

4.7 Acknowledgements

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Chapter Five Conclusion

The aim of this study has been to integrate the data and models of global climate change within the Geoweb to advance climate change communication. I looked into this integration by addressing two research objectives and building several applications. These include a customization of the data visualization system Ferret with two Digital Earth tools to display climate data, a web-based vegetation utility for creating the vegetation boundary condition of an existing NASA/GISS GCM (GISS Model II, which is used in EdGCM), and the complete site for EzGCM using numerous APIs.

The first research objective was to develop a method to employ Geoweb technologies, especially Digital Earth, to improve climate change communication. This research method is to extend Geoweb functionality to existing climate science tools, with the goal of easing the interface and increasing the interactivity of those tools. The purpose of my study was to expand the definition and scale of climate change communication by facilitating a scientific dialog, not only between climate modelers and the general public, but also within the research community. During the study several applications were developed and prototyped to demonstrate how Geoweb can be used to hopefully facilitate climate change communication.

The second research objective was to improve the accessibility of a GCM. I defined improved accessibility as providing tools to engage people in the practice of climate science as well as the fundamental procedures involved in global climate modeling. Collaboration with NASA/GISS helped me to develop a more user-friendly approach to setup, run, analyze, and visualize the output of a GCM via Geoweb. I also applied the Geoweb to elaborate the scientific process that is employed when climate scientists conduct research using GCMs. Finally, I prepared a specific Geoweb approach – EzGCM – that allows users to become directly involved in climate modeling through a sequence of applications that guide the learner from set up of an experiment, through the operation of a climate model and post-processing, and finally into scientific visualization and data analysis.

5.1 Findings

I reached several specific conclusions about research question one on the role that Geoweb can play in climate change communication: (1) Geoweb technologies have the power to manipulate large gridded climate change datasets from diverse sources for creating interactive climate change visualizations for data analysis. (2) The mashability of Geoweb and the release of Digital Earth APIs make it possible to perform relatively sophisticated data analysis on top of the original lightweight GIS system, Digital Earth. If integrated with special purpose scientific climate data analysis and visualization systems, we can further enhance the power of these Geoweb applications. (3) Geoweb technologies help us build easier-to-use scientific tools that have the potential to free scientists from some of their most inefficient research methods. I created a visual, zoomable interface that is different from the old terminal based interface. (4) Digital Earth APIs that provide 2D visualization (e.g., Google Maps API, OpenLayers) are more stable and popularly used than the 3D Google Earth API, which is relatively slow, beset with crash-level issues, and not available for key scientific platforms, such as Linux. (5) It is more technologically robust to use Geoweb for climate model output if that output is provided in a standard format (NetCDF format). Output has standard format that is used commonly in various modeling groups. (6) To employ Digital Earth for other aspects of the global climate modeling research process (e.g., input, simulation start-up and monitoring), a close cooperation between climate modeling and Digital Earth modeling groups is necessary.

On research question two, I decided to communicate climate change via explicating the scientific process of climate modeling. After gaining experience in the use of the Geoweb to convey the scientific process of climate modeling I conclude that: (1) This methodology has the potential to encourage users to "practice" climate change science for themselves. Freeing them to repeat key scientific experiments and allowing them to come to their own, more educated conclusions about climate change; (2) Technologically, relative to the other aspects of Geoweb development, it is easy to implement a web-based front end graphic user interface for information presentation. Using server side scripting to modify and execute scientific programs in real time can be more complex. Besides, the communication between front end interface and web server to respond to users' request is also challenging. To implement a project like EzGCM, the programmer not only needs to be familiar with web technologies, but also is challenged to master necessary climate modeling knowledge and build scientific processing applications in program language like Fortran; (3) One needs to balance an easy-to-use GUI and the complexity of information transferred. The more complex and specialized the information, the more likely the GUI will not be simple. The sheer amount of information that must be input to parameterize a GCM makes the GUI difficult to comprehend. It is crucial to decide upon the most important aspects of climate research that we are trying to transfer, while keeping the GUI easy-to-use. I believe that Web 2.0 technologies provide promising capabilities that will engage people's interest in the source of climate change information and foster a learning environment in which it is possible to challenge people to think critically, carry on experiments, and create their own analyses of the data.

5.2 Future Research

Having developed a suite of Geoweb applications for this study, further research efforts should be aimed at evaluating the effectiveness with which they can be applied in real-world settings to improve climate change communication.

I have taken preliminary steps by developing an integrated subset of the Geoweb applications (called "EzGCM") together with NASA's Educational Global Climate Modeling project in professional development training workshops and in conference presentations. Through continuing interaction with NASA's climate modeling development group and the NASA Innovations in Climate Education

(NICE) program I anticipate that EzGCM can become a popular tool for middle to high school classrooms – particularly those in which NASA's own EdGCM climate modeling curriculum does not fit the time constraints of the course. To follow up on my research, a student could conduct research into educational metrics, for example to evaluate how well people can learn through a hands-on connection to global climate modeling. It will be important to work closely with teachers and curriculum development specialists in the future to prepare companion materials that can help teachers deploy EzGCM in the classroom or within distance learning environments.

Early feedback from educators regarding the EzGCM Geoweb application has suggested that it could serve an additional role as a training tool for the more complex (and less structured) EdGCM software that NASA distributes. That software, which runs on local machines, has been used in many colleges around the world, as well as for the American Museum of Natural History's distance learning courses. To make EzGCM an effective EdGCM precursor and training tool the interface components of EzGCM would need to be modified so that they more closely mimic the look-and-feel of EdGCM interfaces.

Finally, I appreciate that the ultimate goal may be to provide a hybrid capability between NASA's Educational Global Climate Modeling software and our EzGCM Geoweb approach. EzGCM provides real-time processing of raw model output as well as real-time data imaging and scientific visualization. However, it uses pre-calculated climate model simulations to avoid delays between steps in the scientific method that would be problematic for typical classroom periods or lab settings. The real GCM, which EdGCM software deploys, can take days to run, thus it cannot be implemented unless teachers modify lesson plans to accommodate running simulations over nights or weekends on dedicated computers. Can we develop a combination EdGCM/EzGCM that takes advantage of the Geoweb but also runs NASA's actual computer GCMs? I anticipate that this will require future model development to allow greater interoperability with APIs, as well as the interoperability between components. To assist in this, future research could be conducted on mobile application that supplied students, teachers, and even scientists with real-time control and response of the global climate modeling process.

5.3 Recommendations

I conclude by summarizing the skill sets that would be preferable for those who want to integrate climate science and climate modeling with Web technologies for climate change communication. This may help others pursue a path that has enormous growth potential and which could be of great value to society in the future, as climate change becomes a significant part of people's lives. My own bachelor's degree was in Software Engineering and I participated in various projects involving location-based services. I started my master project at McGill University by working with a Digital Earth API and the Ferret scientific data visualization package. I recommend that, to build an interactive Geoweb application, developers will need to be familiar themselves with Web technologies such as PHP, Javascript, JQuery APIs (e.g., Digital Earth APIs and Chart APIs), HTML, CSS, and HTTP Web Services.

During my Master's research I also needed to gain specific knowledge about GCMs because it was insufficient to focus only on the GCM output. Specifically, this meant learning about the NASA-GISS Global Climate Model. To do this, I needed to work closely with climate scientists from NASA's climate model development group. In those projects in which I worked directly with climate scientists I used Fortran, XML and XML-like languages, Shell Script, 4D SDK, SQL Database, IDL, and Realbasic to develop programs for Linux, Mac OS, and Windows platforms. The EzGCM product was made possible by facilitating close cooperation between climate modeling scientists, computer scientists, and GIS experts that focus on social concerns of Web technologies.

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