The Teaching of Anthropogenic Climate Change and Earth Science via Technology-Enabled Inquiry Education

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ABSTRACT

A gap has existed between the tools and processes of scientists working on anthropogenic global climate change (AGCC) and the technologies and curricula available to educators teaching the subject through student inquiry. Designing realistic scientific inquiry into AGCC poses a challenge because research on it relies on complex computer models, globally distributed data sets, and complex laboratory and data collection procedures. Here we examine efforts by the scientific community and educational researchers to design new curricula and technology that close this gap and impart robust AGCC and Earth Science understanding. We find technology-based teaching shows promise in promoting robust AGCC understandings if associated curricula address mitigating factors such as time constraints in incorporating technology and the need to support teachers implementing AGCC and Earth Science inquiry. We recommend the scientific community continue to collaborate with educational researchers to focus on developing those inquiry technologies and curricula that use realistic scientific processes from AGCC research and/or the methods for determining how human society should respond to global change.
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Key words: technology, anthropogenic climate change, Earth Science, inquiry

INTRODUCTION

Anthropogenic global climate change (AGCC) and Earth Science teaching in many classrooms looks similar to how science was taught in the 1960s. Teachers spend the majority of class time lecturing, and students passively receive information or take notes (Birk and Foster, 1993; Wyckoff, 2001; Gibson and Chase, 2002). The lecture approach persists, in large part, because strategies like inquiry-based teaching require considerable resources (e.g., time, planning, and teaching assistants) from faculty with already hectic schedules. Such pedagogy does not fit with cognitive research, which shows that individuals construct mental models of physical and conceptual aspects of the world (Kaplan and Kaplan, 1982; Kearney and Kaplan, 1997) "based on experience" that is "maintained unless it is modified or contradicted" (Kearney, 1994, 423). Students may have difficultly experiencing the issue of AGCC in lecture because it involves global average temperature, change happening on a huge scale, and abstract, intangible scientific concepts (Kearney, 1994). Students in North America also are exposed to a public discourse where understandings are based on cultural or political identity (Leiserowitz et al., 2009; Kahan, 2010; Kahan et al., 2011, 2012) and scientific information is viewed skeptically (McCright and Dunlap, 2011).

Inquiry courses adopt the tools of scientists to build experiences that generate understanding of AGCC. Inquiry is a central component of the 1996 National Science Education Standards (NRC, 1996) and the 2013 Next Generation Science Standards (NGSS Lead States, 2013). It is defined by teaching that asks students to pose questions, evaluate and formulate answers using evidence, examine alternate explanations, and communicate findings rather than learn "a collection of facts" that "can be found in their textbook" (Rakow, 1986, 14). In the decades surrounding the standards, student inquiry into AGCC has included semester-long policy summits where role-playing leads to negotiations over improvements to the Kyoto Protocol (Gautier and Rebich, 2005), work as meteorologists who observe local temperatures (Pruneau et al., 2003), and projects using participatory planning processes to learn the social implications of climate change (Godfrey, 2015). Challenges have included finding time throughout a course to record and report data (Butler and Macgregor, 2003), making observations consistent with scientific concepts (Oh, 2010, 2011), incorporating tangible learning about impacted places (Gold et al., 2015), and developing access to global data and evidence (Chambers et al., 2008; Ledley et al., 2011). Educational researchers have also devoted time to solving a mismatch between the needs of educators and the information, tools, or data made available by scientists (Slater et al., 2009; Ledley et al., 2011).

Findings from research over the past decade indicate technology-enabled inquiry strategies can engage students (Swarat et al., 2012), result in deeper understanding and higher achievement (Songer et al., 2002; Butler and MacGregor, 2003; Bodzin, 2014), and improve attitudes about science (Pea et al., 1994; Baker and White, 2003; Jafer, 2003; Harwood and McMahon, 2013). The caveat is that teachers must carefully design curricula, use and explain the related technologies, and provide strong guidance and

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feedback all while relating student learning to personal experience. In this paper, we examine the refereed educational literature on inquiry AGCC and Earth Science teaching to identify how further collaboration and study could help develop more effective tools and curricula. We first identify a gap that has heretofore existed between educational technologies available to educators and those used by climate scientists. We next review the strengths and weaknesses of a wide variety of AGCC and Earth Science technologies and curricula. We then conclude with a summary of what instructional designers must take into account when designing AGCC learning materials and identify collaborations that could speed the development of new technologies.

CLOSING THE GAP: DESIGNING EDUCATIONAL TECHNOLOGY TO BENEFIT STUDENT LEARNING

In this section, we consider how technological design influences student learning and the constraints educational researchers face in designing technology-enabled AGCC and Earth Science inquiry. We also consider different approaches to computer modeling, their strengths and weaknesses, and how they impact student learning. Many educational technologies and computer models did not exist less than two decades ago, and, consequently, a gap existed between the ways in which scientists conducted their research into AGCC and the ways student inquiry on the subject took place. The appearance of such technologies illustrates that the gap between scientific and educational AGCC and Earth Science tools has narrowed. The computer models described in this paper vary widely from simple programs simulating charging of electric capacitors to global climate models (GCMs) and video games, but we define all as representational models like those that play a central role in science (Frigg and Hartmann, 2012). In places, we also consider communications, audio/visual, and visualization technologies used to teach AGCC. The development of these tools makes it important to consider the benefits and drawbacks of curricula incorporating diverse technologies in the hope of instilling robust AGCC understandings.

Studies on student reactions to technology-enabled inquiry learning are largely positive. A recent survey of 533 middle school students in the Midwest United States asked about 100 different possible instructional episodes. It noted that students were most interested in hands-on activities "that involved the use of scientific instruments or technology" (Swarat et al., 2012, 530). Given such strong favoritism, we examine how hands-on use of technology can aid learning. Some explanations include that tools help students to plan investigations that use processes like calculating, acquiring, sorting, or visualizing data, and retrieving and saving information, or that students control the pace of their learning with computers by utilizing information and hints, either within a program's interface or its Web-based help (Bell et al., 2010). Furthermore, computer tools often provide prompting or activities for students to reflect on learning (Pilkington and Parker-Jones, 1996; White and Frederiksen, 1998) and cues for when to interpret data more carefully (Reid et al., 2003).

These advantages do not come without drawbacks. An inquiry course with 203 Dutch high school students employed a research design that varied the level of expertise (and age) of students taking part in model-based learning about how a capacitor charges over time. Students were given a 50 min introduction to this simple model and 100 min in which to undertake experiments. They found novices needed preexisting simulations just to learn about the model and background concepts but, in practice, ran fewer simulations than their more knowledgeable counterparts (Mulder et al., 2015). Such behavior indicates that less experienced students construct and modify models poorly without seeking to adequately understand the program or the scientific concepts. In contrast, courses that provide support and guidance in teaching students progressively how to use a model often show better learning outcomes (Mulder et al., 2015).

An examination of how teachers utilize computer modeling in their classrooms is revealing. Most usages fall into two categories, first defined by Joan Bliss as explorative modeling and expressive modeling (Bliss, 1994). Learners engaged in explorative learning use a model representing someone else's ideas by either exploring its workings or running simulations that vary slightly from the original. In contrast, expressive modeling engages learners in constructing their own computer model to explore a given idea. While many simpler programs and video games often only ask students to undertake explorative tasks, expressive modeling better represents scientific inquiry.

More recently, educational researchers have made accessible computer models for many topics in science that can be both explorative and expressive (Löhner et al., 2005). New interactive models like the Columbia University–National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies (GISS) Educational Global Climate Model (EdGCM) allow students to run simulations that can be changed, rerun, and discarded in favor of student-designed experiments. Several studies have shown that learning in this manner more accurately recreates actual scientific work by enhancing learning of science content and process skills (Eysink et al., 2009; Scalise et al., 2011). This method of using models to teach better reflects modern science's own routine employment of model building, testing, and revising when undertaking experimentation (Giere, 1988; Longino, 1990; Darden, 1991; Kitcher, 1993; Nersessian, 2005; Duschl and Grandy, 2008).

This research indicates that although students strongly favor learning that includes hands-on experiences with technology, curriculum designers must consider the practical constraints on classroom time, the infrastructure required by overly complex tools, and appropriate amounts of instructor guidance (Edelson et al., 1999). A review based on "four generations of software and curriculum" (Edelson et al., 1999, 392) developed during research at Northwestern University has shown technology can help students achieve integrated understandings. Obstacles included the accessibility of programs, motivation for students to adopt them, practical constraints on teachers implementing slow or costly programs, and limitations caused by the amount of background knowledge students needed. This review indicates that special AGCC curricula will require time for students to gain fluency with new technology during teacher demonstrations and strong guidance when students work on their own. Technologies that make both explorative and expressive practices possible also more closely resemble scientific processes and generate unique AGCC experiences.

Initial research on scientifically realistic models indicates support for their educational value if instructors scaffold and guide their use to overcome the high levels of technological proficiency they require (Fraedrich et al., 2005; Gautier and Solomon, 2005; Clark, 2015). Models that allow such functionality but instead focus on how society should respond to AGCC also show promise (Hubble, 2009; Lahti, 2013; Sterman et al., 2014). Further research is still needed to assess many of these technologies. In the next section, we review the educational research on AGCC and Earth Science technology and curricula. In our conclusion, we discuss how further research can help determine which technologies and curricula might benefit from wider dissemination, further technological refinement, or more study.

TECHNOLOGY, INQUIRY, AND DEVELOPMENT OF STUDENT CRITICAL THINKING

In this section, we review cases where technology has helped students to adopt the mindset of science while learning key reasoning skills, important practices, central AGCC concepts, and the functioning of computer tools. We have selected more than 29 tools that impart experiences that lead to more complete mental models of AGCC. Because many technologies and curricula can be utilized by both secondary schools and university courses, our review is inclusive of studies involving K–12 and university students to focus on the range of technologies and how they shape student learning. These technologies are reflective of work that has brought climate scientists, educational researchers, and affiliated colleagues together, and they demonstrate the capacity of educational researchers to design effective AGCC inquiry teaching strategies.

In the following subsections, we review GCMs, visualization tools, games, and collaborative software. Not all of these tools and curricula have associated empirical educational studies of their effectiveness in the classroom, in part due to their recent development and a continued need for refinement. Some do not mirror scientific research processes or technologies, while others include much detail and complexity because of this resemblance. Each shows promise in helping students understand AGCC. Many also come directly from the scientific community and reflect how the gap between research and educational technologies has narrowed.

We organize the following subsections by whether they help students replicate scientific processes, develop expert-level critical thinking, contextualize reasoning to evaluate consistency with observations of natural places, or simplify difficult concepts using visualization tools, toy models, and games. In our conclusion, we discuss a need for the scientific community to collaborate with educational researchers to refine the most effective curricula and tools, reduce time lags between developing cutting edge models and making them available to nonexperts, and provide support to instructors who might wish to use such products.

Replicating Scientific Methods with Inquiry-Based Technology

In this section, we review eight educational curricula and technological tools that show promise in helping students gain integrated understandings of modern scientific processes. Inquiry science can help cement AGCC and Earth Science learning through student investigations that resemble scientific processes or through the use of scientific methods to explore how society might respond to this issue. To replicate the practices of scientists, students must learn to pose questions, evaluate and formulate answers using evidence, examine alternate explanations, and communicate findings (NRC, 2000). These processes mirror methods in AGCC science that include testing ideas using simulations, exploring systems, analyzing outcomes with models, and devising collection procedures using available scientific instruments.

Using tools that scientists use to better understand global spatial relationships and explore change helps to accurately replicate the scientific process and aid student learning of AGCC. Tutorials incorporated in three different semester-long geography classes at California State University, Northridge, using Environmental Systems Research Institute's (ESRI) ArcGIS (http://www.arcgis.com/features/) and Earth Resources Data Analysis System (ERDAS) Imagine (http://www.hexagongeospatial.com/products/remote-sensing/erdas-imagine/overview) demonstrated results after 74 students worked to analyze satellite data and draw conclusions about AGCC (Cox et al., 2014). Thanks to a grant from NASA, students were able to use remote-sensing technologies to analyze data from the agency's satellites and to map topics such as snow cover changes in Yosemite National Park, deforestation in Brazil, and global CO_2 levels. Pre- and postcourse surveys have shown that work with such tools improved student understandings of core AGCC concepts, remote-sensing technology, and the processes scientists use to study the climate using this technology (Cox et al., 2014). While such work brought students in contact with processes involving global data, strong instructor guidance was needed to help students design research projects at appropriate scales, identify the right data sets, and actually find the needed data.

The GLOBE network (https://www.globe.gov/) has improved student learning of sampling and measurement processes employed by the scientific community (Butler and Macgregor, 2003) by asking actual scientists to design protocols for data collection for schools across the planet and then mentoring students on their climate science investigations using communications technology (Charlevoix et al., 2011; Tessendorf et al., 2012). We discuss this project in more detail in the next section.

Curricula that incorporate scientific processes related to geographic information systems (GIS) and virtual globes have resulted in learning regardless of the age or implied experience of instructors. That was one finding in a study where 13 eighth-grade Earth and space science middle school teachers in the Northeast United States taught 1,177 students an 8 week curriculum that included 14 d of geospatial learning activities culminating in a week-long GIS project (Bodzin et al., 2014). Activities focused on exploration of energy consumption practices, laboratory work, demonstrations, and content readings. Work in five interrelated topic areas (energy and its everyday uses, sustainable energy sources, United States energy production and consumption, nonrenewable resources, and energy efficiency and conservation) promoted geospatial thinking and reasoning (GTR) skills using georeferenced data. Increases from pre- to post-test scores indicated students significantly increased both their energy resources content knowledge and their GTR skills related to energy resources. As in other research (Geier et al., 2008; Settlage et al., 2008), teachers reported being pressed for time, and many did not enact the curriculum as designed (Bodzin et al., 2014). Based out of the Environmental Literacy and Inquiry project at Lehigh University (http://www.ei.lehigh.edu/eli/), other curriculums in the program teach middle school students essential climate literacy principles, and land-use change related to energy consumption (Bodzin and Anastasio, 2006; Bodzin et al., 2013, 2014).

Simulations can improve student understanding of climate research processes in much the same way scientists use such tools. Teaching using a radiative transfer model, a tool scientists use to study the movement of solar radiation through the atmosphere, required considerable time introducing the model, SBDART-EDU (http://www.ncgia.ucsb.edu/projects/metadata/stard/uses/sbdart.htm), during a 10 week geography course on the science of global change. The course solicited scientific questions from students on weekly topics used in group experiments and final papers. Sixty-five percent of a class of 37 average (mean grade point average = 2.91) students at University of California, Santa Barbara, met educator's expectations when their learning was tightly scaffolded with background concepts (Gautier and Solomon, 2005). Instructors provided guidance to students on specific experiments into radiative processes that had established hypotheses and testing procedures. No student was given the opportunity for "more open-ended" model exploration until the final project (Gautier and Solomon, 2005, 442).

GCMs require students to grasp complicated process knowledge because they couple oceanic and atmospheric models and require extensive parameterization and post-processing of data. There are few empirical studies on their educational impact, but clear trends do exist. For example, Columbia University–NASA GISS EdGCM (http://edgcm.columbia.edu/) made its debut in January 2005, and over 150 institutions now use the software to model current, projected, and paleoclimates during short laboratory exercises and longer projects (Chandler et al., 2005, 2011; Sohl, 2012; Sohl et al., 2013). The advantage of EdGCM is that students are running an actual, albeit two-generations-old, GCM. K–12 instructors taking part in EdGCM trainings felt teaching with the model would definitely meet new education standards (NGSS Lead States, 2013). It also posed unique challenges, including class time constraints, a scarcity of curriculum materials, and inadequate classroom technology (Sohl et al., 2013). Not all research models are meant exclusively for educational purposes, and, consequently, do not contain interfaces like EdGCM. For example, the multimodel MAGIC/SCENGENN 5.3 (http://www.cgd.ucar.edu/cas/wigley/magicc/) software,[5] available for free, has not been studied in classrooms, although its code can be easily downloaded (see Fig. 1).

A model that focuses on how human actions influence predictions of change runs preprogrammed scenarios from Intergovernmental Panel on Climate Change (IPCC) reports. Its ability to teach students processes for understanding how humans might respond to AGCC underwent scrutiny during both an online course in the United Kingdom and at a university in the Upper Midwest United States. More than 270 students used the Belgium Université Catholique de Louvain's Java Climate Model (JCM; http://jcm.climatemodel.info/) during the course U316: The Environmental Web at the Open University in Buckinghamshire, UK. After examining 6,741 messages in six online tutor group forums during this semester-long course, researchers found the 278 students' capacity to use the software was impeded by their access to computers, the amount of time spent dealing with information technology issues, and the strong need for more guidance on how to cover the broad issues of AGCC (Hubble, 2009). In contrast, research by a Montana researcher included teaching a 4 week summer and 15 week fall intervention in four liberal-studies environmental science classes. His instruction helped 60 students progress through work with different types of models, including a (non-GCM) simple model of students' household water use, carbon footprint models, and, ultimately, the emulator, the JCM. Student responses to an assessment during pre- and postinterviews suggest that guided model usage followed by class activities where students reflect on learning increases knowledge of models and modeling. However, students' ability to create models as in expressive uses can depend "heavily on cognitive ability" (Lahti, 2013, iii).

The previous eight strategies for engaging students with scientific technology show strong possibilities for helping students learn AGCC and Earth Science process. Other factors also may inhibit learning with such tools. They include practical considerations in using the technology such as time constraints on educators using special curricula, the amounts of guidance planned for such strategies, and the costs of disseminating expensive technologies or needed infrastructure.

Using Global Data to Learn Expert Critical Thinking Skills

In this section, we review five technologies used in classroom curricula and teacher trainings that rely on global data and evidence to teach scientific norms and critical thinking skills. Teaching critical thinking, which is needed to interpret global Earth and AGCC concepts, presents a formidable challenge when students have been exposed to debate and misinformation about climate science. Definitions of critical thinking vary widely and have their origins in a view of it as the personality trait of reflective skepticism (Passmore, 1980; McPeck, 1981). In this section, we adopt a definition of critical thinking as an attitude that instructors can instill (Siegel, 1988) that leads students to re-examine their own concepts, attitudes, and identities (Yoram, 2010). Digital technology can help students think critically like scientists when they collaborate with peers to share data, learn new methodologies, and exchange ideas. These strategies track the norms in scientific thinking as required by science education standards (NRC, 2000; NGSS Lead

[5] It is important to note MAGIC represents an energy-balance simulator that carries through calculations at the global-mean level using the same upwelling-diffusion, energy-balance climate model employed by the Intergovernmental Panel on Climate Change (IPCC). In contrast, SCENGENN is an emulator that produces spatially detailed information on future changes in temperature, precipitation, and mean sea-level pressure using the IPCC's CMIP3/AR4 archive of GCMs. In computer science, emulations adhere to all the fixed rules of the system's behavior they are emulating, while simulations behave similar to a given system but may not obey all rules and may also be implemented in very different ways. Only research-grade GCMs like EdGCM simulate all of the interactions in between the atmosphere and ocean.

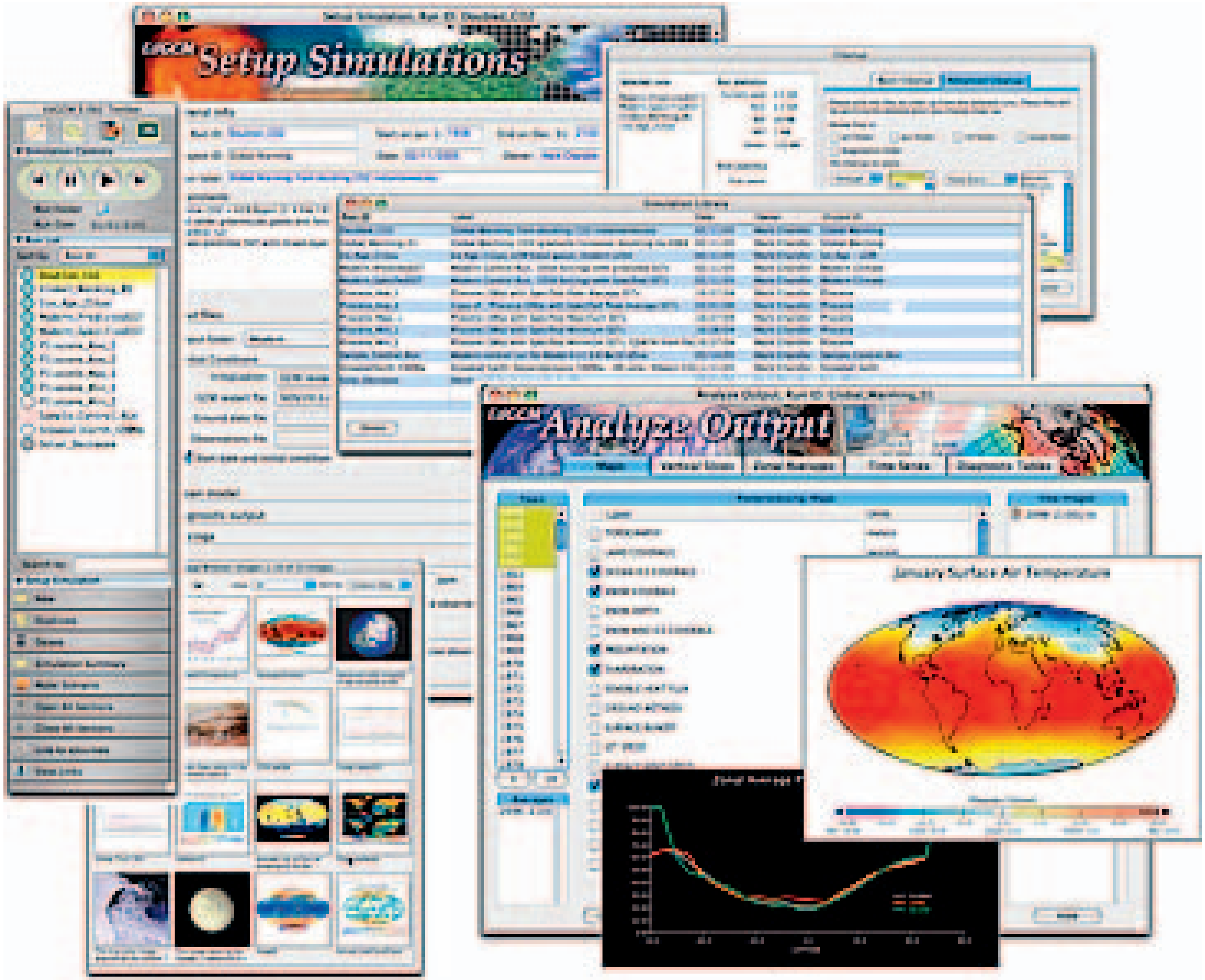

FIGURE 1: Screenshots of Columbia University's Educational Global Climate Model (EdGCM) showing the user interface wrapped around each of its functions, which include setting-up simulations, extracting and postprocessing data, visualizing data, and writing scientific reports. The code for the model itself, NASA's Goddard Institute for Space Studies research-grade Model II, runs in the background while students follow these steps of climate modeling practice to replicate their own and actual AGCC scenarios. (Image courtesy of The Educational Global Climate Modeling Project, Columbia University, NASA/GISS.)

States, 2013) and described by Robert K. Merton (1942): communalism (part of a science community), universalism (impersonal and objective), disinterestedness (acting for common scientific causes rather than personal gain), and skepticism (being exposed to scrutiny). It is important for students to understand, as they undertake science, that the values and processes of the larger scientific community are integral to understanding the scientific consensus on AGCC.

Collecting globally distributed Earth Science data requires students located in specific geographic regions to learn communalism and universalism to work together and develop critical thinking skills. In the GLOBE network, such skills derive from an emphasis on having researchers mentor teachers and students on sampling and measurement processes as they collaborate across schools on climate science investigations that take place throughout the year (Charlevoix et al., 2011; Tessendorf et al., 2012). GLOBE not only provides such a partnership, but it also allows students a means for contributing research-quality data. It makes use of collaborative technologies such as a Web site, database, and digital communication tools, and it also allows students to manipulate data using graphical and visualization tools. Now at 8,900 United States schools and 3,764 schools from 101 other countries, its students scored better than counterparts in non-GLOBE classes and possessed scientific abilities such as being able to interpret data and apply science concepts (Butler and Macgregor, 2003). Annual reviews conducted over 6 years have included visits to schools, discussions with teachers, students, and scientists, and selected assessment tests (Butler and Macgregor, 2003).

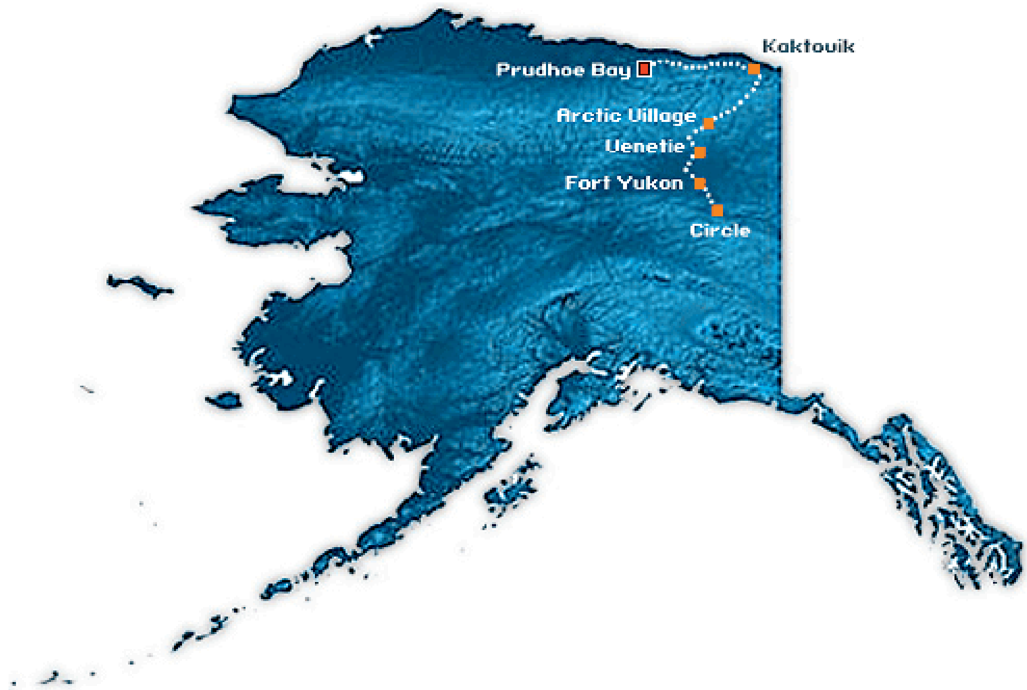

FIGURE 2: The route map taken by the GoNorth! Arctic National Wildlife Refuge (ANWR) expedition in 2006 helped students in 4,300 schools contextualize learning to a specific place. Students following along could track the expedition through ANWR as it examined oil exploration, Arctic climate change, and the value of traditional ecological knowledge with the Gwiich'n Inupiat Eskimo (Inuit) people. (Image courtesy of PolarHusky.com.)

Many teachers felt it offered "a new perspective on what it is to do science and to be part of a scientific investigation," but one challenge has been scheduling time throughout the year to continuously record and report data (Butler and Macgregor, 2003, 17).

Incorporating global CO_2 and temperature data into software called the Java-Digital Signal Processing/Earth Systems Edition (J-DSP/ESE, http://jdsp.engineering.asu.edu/jdsp_earth/index.html) has allowed students to practice critical thinking using time-series analyses such as those conducted by Earth Scientists. Created with support from the National Science Foundation, this online tool aims to teach Earth signals analysis, or the process of monitoring and reconstructing time-series data of Earth processes (Ramamurthy et al., 2014). J-DSP/ESE bundles together functionalities that include data preparation, spectrum estimation, time-frequency analysis, filtering, and coherency analysis into a user-interface where students create diagrams by dragging and dropping blocks, setting parameters in each block, and establishing connections among groups of blocks (Ramamurthy et al., 2014). Three tutorials developed as 3 h Earth climate signals laboratory sessions for undergraduate geoscience courses use this tool to examine the atmospheric CO_2 record (from Mauna Loa Observatory, Hawaii), global temperature records (from 3,000 surface stations), and paleoclimate ocean temperature proxy data (from calcitic shells of the foraminifer *Globigerina bulloides*). The tutorials were tested in workshops at the March 2010 Geological Society of America NE/SE section meeting with 10 participants, and at Arizona State University, Tempe, with 14 electrical engineering graduate students. Using conceptual and subjective assessments in the first workshop and pre- and postinstruction quizzes in the second, researchers have found that "attendees understood the presented concepts easily and gained a good working knowledge of the software" (Ramamurthy et al., 2014, 629). While tutorials with this model improved critical thinking about most major AGCC concepts, workshop participants still struggled with the counterintuitive slowing of global temperature rise in the past decade (Fig. 2).

Simple audio/visual technology can also be used to bring home the critical thinking scientists use in distant regions of the globe. For example, a researcher at Michigan Technological University traveled to the Azores (a Portuguese territory) to observe and participate in research being conducted by a team of scientists collecting aerosol particles that they then brought back to Michigan for analysis. During both phases, videos were filmed of various components of this research, including explanations of collection and analysis procedures and interviews of team members (Harkness, 2014). Uploaded to YouTube, the videos will serve as the basis for an inquiry course that teaches through "actual, ongoing scientific research on climate change" (Harkness, 2014, 21). Lessons that integrate meteorological concepts as they relate to the chemical properties of dust and gases culminate in questions about AGCC after students watch videos and examine real data collected in the field. The educational value here results from exposing students to actual research processes and scientific thinking to enable them to think critically about how to answer questions central to AGCC (Harkness, 2014).

My NASA Data (http://mynasadata.larc.nasa.gov/) makes the same global Earth Science data used by U.S. NASA scientists available to students and educators to promote critical thinking through classroom-based investigations. The project targets grade levels from elementary school to graduate school (Riebeek et al., 2009) and includes a Web site that contains larger data sets students can customize into smaller subsets, data that are already preconstructed into such microsets, lesson plans, and citizen science project ideas (Chambers et al., 2008). Using a Live Access Server (LAS), an open source software tool, the site integrates a visualization tool, Ferret, with access to georeferenced data. More educators than we could include here have used this database (Powers et al., 2011; Lee et al., 2012; Sneider et al., 2014) to, for example, teach 6th grade students in the Buffalo, New York, area about snow (Lange et al., 2012) or build three online data-based inquiry courses for masters of applied science students at the University of Nebraska, Lincoln (Gosselin, 2013). Pre- and postsurvey assessments of 51 K–8 and high school teachers who took part in either an 8 week or 16 week professional training using My NASA Data found indications of significant increases in content knowledge, confidence of teachers in teaching the science of the Earth system, and enjoyment of this teaching process (Gosselin et al., 2010). Further work will be needed to evaluate how teachers trained in this program improve student achievement test scores. Similar conclusions have been drawn from other professional trainings, with a program featuring 4 d high school teacher trainings in Alabama noting participants felt curricula including MY NASA Data should be part of classroom learning (Lee et al., 2012).

One more example serves to illustrate how computer-aided inquiry can improve professional development of teachers through trainings that make use of global materials. Researchers at the National Center for Atmospheric Research (NCAR) have long offered 2 week training workshops on climate and global change for middle and high school teachers, but, seeking to serve more educators from 2005 to 2007, the workshops were developed into online courses that utilized text and images, downloadable video clips, simulations, and both asynchronous and synchronous communication tools (Johnson et al., 2008). Researchers involved found these longer 6 or 7 week trainings helped support more than 200 educators who first wanted to develop their own expertise before teaching student AGCC critical thinking skills. The researchers felt such trainings became necessary because teachers feel ill prepared to teach a subject where knowledge keeps changing with new global research findings and evidence (Johnson et al., 2008).

These five examples suggest digital technology can provide teachers with support and help students learn many of Merton's (1942) scientific practices as they develop critical thinking skills based on global data. A key to each of these strategies is collaborations between the scientific community and educational researchers in designing curricula, mentoring students and teachers, and making real data available for student investigations or instructor professional development. Further empirical assessment would help in each of these programs to determine how experiences with global data and evidence actually shape student thinking about AGCC science.

Contextualizing Scientific Reasoning Skills with Local Changes and Scientific Observations

In this section, we review five technologies and curricula that help students contextualize their learning to develop robust understandings of AGCC and Earth Science. A particular area of struggle for educators has been finding ways to teach global reasoning or observations in ways that confirm personal experiences of local places or established scientific facts. This is particularly important to AGCC instruction because of the ways in which both the causes and impacts of AGCC are often distanced from personal experience at various geographic and temporal scales.

A study in geology notes that the temporal and spatial scales involved make direct observation of many "geological processes problematic" (Clark, 2015, 1). Hypothesizing that physical models allow the compression of these scales, researchers at Lawrence University asked students to use digital cameras and Microsoft Kinect (https://www.microsoft.com/en-us/kinectforwindows/) to monitor temporal and spatial changes in a scaled-down physical model of a fluvial setting. By making direct observations, visualizing processes, controlling inputs and boundaries, and even creating "what if" scenarios (Clark, 2015, 1), 26 students in three semester-long courses were better able to comprehend landform evolution in response to changing inputs and boundary conditions. Prior to implementation, the course needed to be reconfigured to include two laboratory sessions a week simply to incorporate work with models. The image processing activities in one class still took much longer than anticipated and prevented researchers from teaching other topics (Clark, 2015). Using computer tools often comes at the cost of time constraints on other class materials.

Geospatial Web tools help contextualize reasoning with local places by allowing students to visually examine places under study. One research project combined student work using Google Earth (https://www.google.com/earth/) and ArcExplorer 9 (http://www.esri.com/software/arcgis/explorer) with a hybrid distance education model called GoNorth! Arctic National Wildlife Refuge (GoNorth!, 2006). Two middle school classrooms in the Midwest and Northwest United States with a total of 65 students followed the travels by dogsled of Team GoNorth!'s scientists and educators through the U.S. Arctic National Wildlife Refuge (ANWR) from February to May 2006 (Doering and Veletsianos, 2008). Lessons such as "An Alaskan Transect," "Climate Maps," and "Sense of Place and GoNorth!" involved students in entering latitude and longitude data into ArcExplorer Java Education for Educators (AEJEE). Students were able to explore and interact with the data in activities where they acquired latitude and longitude coordinates sent from the trail, hot-linked digital photos and locale information along the route map, and developed snow cover maps that correlated snow depth with average temperature and elevation. Using focus group interviews after the conclusion of the course, researchers concluded that geospatial technologies helped educators contextualize global scales using data contributed both by scientists in Alaska and by students locally using global positioning system (GPS) units, photographs, and textual descriptions (Doering and Veletsianos, 2008).

A different approach using abductive scientific inquiry, or the generation of hypotheses by examining surprising facts, helped students contextualize their results against existing scientific knowledge. During a semester-long course in Seoul, Korea, an undergraduate classroom worked with computer models to better understand a typhoon named Wukong that advanced near the Korean Peninsula in August

2006 (Oh, 2010, 2011). Students conducted scientific investigations, designed Earth Science instructions, and performed microteachings. After writing narratives and reports based on work with computer models, the more than 40 students "considered the empirical consistency" of their explanations against observations of the natural world and established scientific facts (Oh, 2011, 423). Whereas many students struggled to design scientific research consistent with scientific norms (and testable hypotheses) because of a lack of background knowledge, an Earth Scientist asked to comment on results found improvement in how students considered their results in light of observations and established scientific ideas.

Finally, simple video tools can be harnessed to help students contextualize global topics with their own observation of local changes. In one case, students in Colorado spent 6 mo making videos about "locally relevant climate change topics" (Gold et al., 2015, 1), while in a separate research project, undergraduate and graduate students made public service announcements during a Climate Education in an Age of Media (CAM) Project (Rooney-Varga et al., 2014). In the first program, 64 students at eight middle and high schools in Colorado produced videos, were mentored by graduate and undergraduate students, and became convinced that "climate change is impacting their communities" (Gold et al., 2015, 8). Teachers implemented a program that asked students to plan, film, edit, and screen videos as part of environmental science classes or outside the formal school day. Many found it engaged students with AGCC's local impacts and the importance of mitigation (Gold et al., 2015). Similarly, 68 students enrolled in a 13 week upper-level university course showed gains in teamwork/interpersonal skills, understanding of AGCC, conceptual and analytical ability, and commitment to the issue from pre- to post-instruction on surveys after a semester that included the production of local school television announcements (Rooney-Varga et al., 2014). Incorporating student work on local environments not only contextualizes students' relationships with a complex subject, but it also gives them ownership over the issue in their own communities.

These five inquiry teaching strategies contextualize learning using specific places and simple audio/visual and geospatial technologies to make AGCC and Earth Science topics tangible. While time constraints again apply to any curricula designed with these technologies in mind, both courses that involve specific scientific practice and those that utilize video journalism or other methods show progress in developing robust AGCC learning. The use of complex scientific practices or tools must also be carefully supported during stages where students design experiments or write hypotheses.

Distilling Complex Ideas into Simpler Visual and Gamified Cues

The 11 tools and curricula we examine in this section are simplified by design to help students master basic scientific steps first. Teaching AGCC poses difficult challenges for educators located in classrooms who want to include interdisciplinary subjects and topics that require abstract and global reasoning. A plethora of software, toy models, and video games engages students with abstract global AGCC concepts through visualization and simulation. Much as GCMs may link to software that provides maps and graphs for students to examine, the power of this software lies in the fact that educators can choose what to visualize to impact student learning. Often quite simple, these technologies coincide with calls from educational researchers to: first, reduce visual complexity; second, scaffold the process of generating explanations; third, support student-initiated modeling of complex science; and, finally, use multiple linked representations (Kali and Linn, 2008). Many of these technologies accomplish two or three of these goals, although GCMs may be difficult for students to learn even with tight teacher scaffolding.

In some cases, simple tools still require careful planning. Researchers involved with the Learning for Collaborative Visualization Project (http://www.covis.northwestern.edu/) at Northwestern University determined their course would have benefited from more gradually taking students through data gathering, organization, and interpretation to give them confidence with difficult concepts and analogies (Gomez et al., 1995). Combining desktop videoconferencing, visualizers, distributed data sets, virtual field trips, and a collaborator notebook into one self-contained program helped these researchers connect students to scientific experts while demonstrably improving student AGCC knowledge (Pea et al., 1994; Pea, 2002). Assessments of high school students in the program began in 1993 and included evaluations of student attitudes toward school, science, and technology using surveys, quantitative and qualitative analysis of student projects, and interviews of teachers. Initially, even the vision of having students "learn science by doing science over the Internet" (Pea, 2002, 12) was considered improbable but, writing in 2002, the authors note it is now "integrated into the day-to-day learning activities of urban classrooms" (Pea, 2002, 12).

Video games simplify learning by allowing students to visually build each piece of a complex concept by interacting with user-friendly environments. Reviews of the benefit of educational video games support the use of games in learning language, history, and physical education, but not yet in science and math (Young et al., 2012). Researchers using a multi-user virtual environment (MUVE) called Quest Atlantis spent years refining AGCC video games and curricula and concluded that "gaming methods and technologies can be used in schools to focus on academic content in ways that are quite engaging to students" (Barab et al., 2006, 776). They drew this conclusion after two studies involving students attending varying lengths of teaching with K–12 grade students, where students were immersed in narratives about serious ecological problems using an avatar to interact with peers and interview virtual characters. The first study indicated significant gains on specific standardized test items, but researchers failed to obtain statistically significant learning gains (Barab et al., 2006). Just because gamified technologies are used to simplify concepts does not mean the software is itself simple. Those same researchers found existing technological infrastructures available in classrooms were an impediment to extending MUVE (Barab et al., 2006).

Other video games like Fate of the World (http://www.soothsayergames.com/), FutureCoast (http://futurecoast.org/), and EcoChains: Arctic Crisis (http://thepolarhub.org/project/ecochains-arctic-crisis) simplify abstract concepts and are "part of an entire genre of climate change games that offer powerful tools for education and engagement"

FIGURE 3: The user interface for the online game, Fate of the World, which helps simplify complex topics in the study of anthropogenic global climate change (AGCC) with a familiar game setting. This game features several scenarios based on scientific research where the user's goals range from improving living conditions in Africa to preventing catastrophic climate change. (Image used with permission ©Soothsayer Games Ltd., www.soothsayergames.com)

(Wu and Lee, 2015, 413). The proliferation of mobile technology has allowed the emergence of many new types of climate change games that utilize "ubiquitous internet connectivity and location-sensitive hardware" to "blend digital and physical mediums" (Wu and Lee, 2015, 414). They hold the potential to increase civic engagement with AGCC because game play can take advantage of networked technologies while also fostering trust and engendering empathy (Wu and Lee, 2015). However, no empirical assessments yet exist on how such games influence understanding of AGCC science (see Fig. 3).

The way in which new ideas are scaffolded can also help ensure technology's simplifying impact is not lost. In the Technical Education Research Centers' (TERC) EarthLabs (http://serc.carleton.edu/earthlabs) program, learners undertake six to nine rigorously sequenced and strongly guided laboratory activities that include examining satellite imagery, numerical data, computer visualizations, and data products (Ledley et al., 2012; Ellins et al., 2014). Taught in professional workshops in Texas and Mississippi, this highly structured form of inquiry led to 110 well-trained instructors who would later teach this material to their own students (Ellins et al., 2014). Further assessments included interviews with seven teachers and pre- and postcourse assessment data for 205 Texas high school students (with eye-tracking of 49 students to measure engagement) in courses such as chemistry, environmental science, and Earth and space science. Researchers found that EarthLabs significantly improved students' Earth systems understanding and that the online software adequately engages students (McNeal et al., 2014). The authors noted that researchers have an important role to play in evaluating the effectiveness of AGCC curricula because most educators inevitably run into limitations of time, personnel, and funding when asked to undertake a cycle of creating, testing, and revising individual curriculum.

Other strongly guided learning used a Web-based Inquiry Science Environment (WISE, https://wise.berkeley.edu/) unit called Global Warming to simplify instruction on albedo, carbon dioxide emissions, population, and pollution for 372 students (Svihla and Linn, 2012). Students that were enrolled in three semester-long sixth-grade courses taught by three different instructors in the United States discussed their ideas with partners and took turns controlling WISE computers. Teachers circulated through the classrooms helping students as needed. Outcomes from examinations of computer log files and pre- and postcourse multiple choice assessments indicate students gained the ability to make evidence-based decisions from this type of visual learning. Researchers also found students did not fully integrate the ideas of energy transformation or ideas about the types of activities that contribute greenhouse gases into the atmosphere into understandings of AGCC (Svihla and Linn, 2012). A community of several hundred teachers and over 100,000 students has used WISE's collection of curricula during 10 years of research funded by the U.S. National Science Foundation (Slotta and Linn, 2009).

So many tools now exist (some developed in specific university courses) to simplify specific AGCC or Earth Science concepts, it is difficult to mention them all. Links to educational games, simple tools, and visualizations can be found at organizations such as NASA and the National Geographic, personal blogs such as Michael Gorman's 21 CenturyEdTech (https://21centuryedtech.wordpress.com/) or Tim Osborn's Climate Models for Teaching (https://crudata.uea.ac.uk/~timo/teaching/model.htm), and in more comprehensive collections such as the one maintained by the University Corporation for Atmospheric Research (UCAR) Center for Science Education (https://scied.ucar.edu/interactives). Some simplified scientific tools include Earth System Models of Intermediate Complexity, sometimes known as toy models because of their ability to simply model complex systems (Claussen et al., 2002). Two educational modeling efforts illustrate the utility of simple models in understanding complex systems. NASA's Portable University Model of the Atmosphere (PUMA; http://gcmd.gsfc.nasa.gov/records/DKRZ_PUMA.html) is intended as a training tool for junior scientists; The Planet Simulator was developed for speed, easy handling, and portability (Fraedrich et al., 2005). Both respond to the need for simpler educational models that can simulate millennia and longer time spans in short amounts of real time (Fraedrich et al., 2005). These tools use inexpensive hardware with no need for time on mainframes, tend to be easily reconfigured for time periods that are far away from our present climate or for atmospheres of other planets or moons, make diagnosing simulations easier, and enhance conceptual understandings of key mechanisms in the atmosphere or climate.

Other educational models that have also been used in professional trainings use simple stock and flow simulations to teach the policy implications of AGCC solutions. Continuous time-compartment models such as the Climate Rapid Overview and Decision Support (C-ROADS; https://www.climateinteractive.org/tools/c-roads/) have been utilized in a World Climate negotiation exercise both in universities and professional trainings (https://www.climateinteractive.org/programs/world-climate/). It allows users to easily investigate impacts of differing mitigation policies on the carbon cycle, atmospheric stocks of other greenhouse gases, radiative forcing, global mean surface temperature, sea-level rise, and surface ocean pH (Sterman et al., 2012;, 2013). Research with this model developed by Climate Interactive began because of findings that highly educated people with training in science, technology, engineering, or mathematics (STEM) still struggle with complex systems such as the climate (Morecroft and Sterman, 1994; Sterman, 2000, 2011). Three evaluations assessed the effectiveness of the World Climate exercise with diverse audiences. These studies included 43 undergraduate/graduate students at the University of Massachusetts, Lowell, 100 master of business administration students at the Massachusetts Institute of Technology (MIT) Sloan School of Management, and 173 students from a wide variety of backgrounds including the above locations, Nanyang Technological University of Singapore, U.S. high school science teachers, and undergraduates at the University of Wisconsin, Milwaukee (Sterman et al., 2014). The first two evaluations indicated strong student support for and positive attitudes about the exercise, while the third showed statistically significant learning gains from pre- to post-instruction on questionnaire items concerning climate dynamics such as the impact of cutting fossil fuel emissions (Sterman et al., 2014).

These 11 toy models, video games, and visualization tools engage students by distilling complex ideas into simpler visual cues that help build conceptual understanding of AGCC. However, some simulations or games do not impart the complex reasoning skills needed to design hypotheses and experiments because of the occasionally simplistic manner in which students engage with scientific reasoning or methods. Not all studies involving such games, as a result, demonstrate full learning gains. However, more research is needed to determine their efficacy versus more complex technologies that engage students in actual scientific processes.

CONCLUSIONS

It is no simple task for educational researchers to shift the teaching of AGCC and Earth Science from lectures to technology-enabled inquiry. The body of research mentioned herein signifies a path forward and shows the potential rewards for making the shift. Educational researchers need to consider why certain technologies are adopted (Surry and Farquhar, 1997) because the answers are crucial to predicting how tools diffuse into classrooms and how instructors should be trained to use them. Ultimately, the implementation of technology, combined with special curricula, relies on instructors to make sense of both as they learn new materials (Borko, 2004). In this section, we provide a summary of AGCC factors that instructional designers must take into account when designing AGCC learning materials. We then identify where empirical research is needed to improve the effectiveness of technologies and curricula, where support could reduce lag between the development of technologies and making them available to nonexperts, and where professional development can aid in technological dissemination to instructors.

In sum, technology-based teaching shows promise in promoting robust AGCC understandings if associated curricula address mitigating factors such as the time constraints involved in incorporating technology and the need to provide support for teachers implementing AGCC and Earth Science experiments. In addition, it is important to continue to refine curricula and improve access to technology to promote learning. Table I provides a summary of

TABLE I: Strengths and weaknesses of inquiry-based AGCC and Earth Science curricula and technologies reviewed in this paper.

Case Study(ies)/Project Location	Technological Component	Strengths	Weaknesses	Further Potential Research
California State University, Northridge	ESRI ArcGIS and ERDAS	Improved core understandings of scientific process with remote-sensing technologies	Strong guidance to design projects at appropriate scales and identify/find correct data	Not contained in report
At 8,900 U.S. and 3,764 schools from 101 other countries	The Globe Network	Scientific mentorship by researchers; improved process skills/reasoning	Scheduling time throughout the year to continuously record and report data	Improve program emphasis on analytical skills that allow informed inferences based on data
Environmental Literacy and Inquiry project at Lehigh University	GIS and Virtual Globes	Promoted geospatial thinking and reasoning skills on five energy topics	Teachers pressed for time and did not enact the curriculum as designed	Replication/refinement of findings in different/ larger classrooms, observation of implementation
University of California, Santa Barbara	SBDART-EDU	Met expectations for learning about radiative processes	Strong guidance required on model usage until final project	Empirical data on cognitive processes, verification of results, pre- and post-tests to assess learning
No educational study found	EdGCM	Would meet new education standards	Time constraint, scarcity of curriculum material, and inadequate technology	Empirical research on classroom impacts and student knowledge gains
No educational study found	MAGIC-SCEN/GENN 5.3	Freely downloadable	No educational study found	Empirical research on classroom impacts and student knowledge gains
Study 1: Open University in Buckinghamshire (online course)	Java Climate Model		Study 1: Online course with model impeded by access, time constraints, need for stronger guidance	Study 1: Revise tutor interventions to develop online community of learners
Study 2: An Upper Midwest United States university		Study 2: Increase in modeling/model knowledge with complexity dependent on student age/ cognition		Study 2: Improve instrument, methodology, use younger sample
Michigan Technological University	Audio/Visual and YouTube	Field data and videos of ongoing scientific research	Not contained in report	Empirical research on classroom impacts and student knowledge gains
Workshops at Geological Society of America (GSA) NE/SE section 2010 meeting and Arizona State University, Tempe	J-DSP/ESE	Promoted conceptual understanding and knowledge of software	Did not convey why global temperature increases have slowed in the past decade	Develop tutorials in seismology, space geodesy, and environmental monitoring
University of Nebraska, Lincoln (online professional development)	My NASA Data	Improved access to scientific community; increased teacher knowledge and confidence	Myriad implementations with little empirical evidence on most effective curricula/uses	Empirical research on classroom impacts and student knowledge gains with trained teachers
NCAR (online professional development)	Digital communications, simulations, and videos	Ability to maintain access to scientific community; increases in teacher AGCC knowledge and confidence	Time needed for cycle of improvement between professional training offerings	Empirical research on classroom impacts and student knowledge gains with trained teachers

TABLE I: continued.

Case Study(ies)/Project Location	Technological Component	Strengths	Weaknesses	Further Potential Research
Lawrence University	Audio/visual and Microsoft Kinect	Improved understanding of landform change; monitor temporal/spatial change	Time constraints due to implementation/usage precluded other topics	Revisions to curriculum to address time constraints; empirical research on student knowledge gain
Two middle schools in Midwest and Northwest of United States	Google Earth, ArcExplorer 9, and GoNorth! ANWR	Data and geospatial technology contextualized global scales	Not contained in report	Empirical research on how geographical technology/pedagogy impacts learning
University in Seoul, Korea	Computer model of typhoon	Improvement in considering observation with established scientific ideas	Students struggled with background information to design research/ hypotheses	More research on strategies that ask students to evaluate, choose, and elaborate their own hypotheses
Upper-level university course in Massachusetts	Audio/visual (CAM Project)	Improved communication analytical skills and AGCC understanding	Student time management, task delegation, and leadership for time-consuming work	Not contained in report
Eight Colorado middle and high schools	Audio/visual (Public Service Announcements)	Engaged nonacademically motivated students with AGCC impacts and mitigation	Large time commitment for educators/mentors; needed training for mentors	Not contained in report
Learning for Collaborative Visualization Project at Northwestern University	Videoconferencing, visualizers, data sets, and virtual field trips	Connected students to scientific experts and improved student AGCC knowledge	Gradual approach needed to take students through data gathering, organization, and interpretation	Refinements to technologies and curricula to improve student confidence and offerings
U.S. elementary schools	Quest Atlantis	Focused on academic content in engaging manner	No statistically significant learning gains; impediment of existing classroom technology	Balancing curricula content between being too explicit or implicit, and the quality of context
No educational studies found (exception: broad meta-analyses)	Fate of the World, Ecochains: Arctic Crisis, and FutureCoast	Increased civic engagement with AGCC; fostered trust during community planning	No proven educational gains in scientific subjects	Empirical research on behavioral change, attitudes toward environmental policy, or scientific explanations of AGCC
EarthLabs at the Technical Education Research Centers	Satellite imagery, data sets, and visualizations	Improved Earth systems understanding and engaged students	Limitations of time, personnel, and funding when developing highly structured curricula	Further refinement of EarthLabs curricula and materials
Three middle school classrooms in United States	WISE	Gained the ability to make evidence-based decisions about energy use	Failed to integrate energy transformation or how human activities contribute to greenhouse gases	Investigations need to be structured to focus on distinguishing ideas
No educational study found	NASA PUMA	Simulated millennia in short amounts of real time; used inexpensive hardware	Not contained in report	Empirical research on classroom impacts and student knowledge gains
No educational study found	The Planet Simulator	Simulated millennia in short amounts of real time; used inexpensive hardware	Not contained in report	Empirical research on classroom impacts and student knowledge gains

TABLE I: continued.

Case Study(ies)/Project Location	Technological Component	Strengths	Weaknesses	Further Potential Research
Multiple universities (MIT; University of Massachusetts, Lowell; Nanyang Technological University of Singapore) and U.S. high schools	C-ROADS	Strong student preference for model-based World Climate exercise; statistically significant learning gains on topics like mitigation	Possible selection bias in study and need for replication with diverse audiences	Empirical research on student understanding of complex systems (feedbacks, stocks and flows, and delays); longitudinal study of enduring attitude/ behavior change

areas of strength and weakness in the more than 29 existing AGCC and Earth Science technology and curricula we examined. Individual sections of this paper show that inquiry technologies can help enhance learning in multiple ways. They distill complex ideas into simpler visual cues, they contextualize and localize the learning experience through audio/visual and geospatial technologies, they improve students' thinking skills based on global data, and they help students become familiar with fundamental scientific practices. All such inquiry strategies have led to robust understandings of AGCC science.

The need for the scientific community to collaborate with educational researchers continues. In particular, a scarcity of empirical research exists on how some of the above technologies impact classroom learning and, in cases with a wide variety of implementations, what constitutes best pedagogical practice. Our review also indicates a need for realistic educational tools that mirror scientific practices and require scientific knowledge to use. Not coincidentally, many of the scientific tools most recently made available by the scientific community require empirical testing to determine those that most effectively generate robust understandings of AGCC. Past surveys of inquiry-based educational efforts noted that planetary scientists can be influential in supporting the creation and dissemination of two standards-based products: content courses for teachers that translate research into classroom ideas and a limited number of data-driven inquiry products that focus on key scientific ideas (Slater et al., 2009). Our review suggests that the scientific community should focus on inquiry technologies that use scientific processes from AGCC research or the methods scientists utilize for examining how human society should respond to global change. The research into such technologies has shown they powerfully bring students into contact with actual scientists, data, research tools, and scientific methods.

While research into AGCC continues, the past 50 y have seen developments in the cognitive and pedagogical research on what constitutes best educational practice. The studies cited herein support AGCC teaching that actively generates technology-enabled student inquiry by using scientific research methods, real-world data, and the tools and ideas of the interdisciplinary field of climate science.

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