The Role of Research in Online Curriculum Development: The Case of *EarthLabs* Climate Change and Earth System Modules

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ABSTRACT

This study reports on an effort to illustrate the coupling of educational research with ongoing curriculum development to promote effective and evidence-based online learning. The research findings have been used to inform the *EarthLabs* curriculum development team as they revise existing modules and create new modules, in order to represent the ways in which such research findings can be used to improve similar online curriculum materials and enhance student learning outcomes. *EarthLabs* curriculum is a suite of online inquiry-based activities that promote understanding of Earth system science. Assessments were employed to understand student learning about complex climate systems as a result of their engagement with the online *EarthLabs* curriculum. Collection of pre- and postcourse student assessment data ($n = 205$), classroom observations during implementation ($n = 6$), teacher interviews ($n = 7$), and eye-tracking data ($n = 49$) were included in the study. Qualitative and quantitative findings show that *EarthLabs* classroom implementation significantly improves students' conceptual and systems understanding and that students and external users are appropriately engaged with the online materials. These findings have been applied to evaluating the efficacy of the *EarthLabs* program in reaching target programmatic and learning goals, as well as to developing a broader understanding of the cognitive challenges students have in navigating complex Earth systems phenomena, where continued *EarthLabs* program revision has occurred through design-based research. *© 2014 National Association of Geoscience Teachers*. [DOI: 10.5408/13-060.1]

Key words: climate change education, online curriculum, *EarthLabs*, complex systems, eye-tracking

INTRODUCTION

Humans are modifying Earth without fully understanding how our actions affect the planet's major systems: atmosphere (air), hydrosphere (water), biosphere (life), and geosphere (land). Research indicates that increases in globally averaged temperatures of just a few degrees in this century will likely cause an increase in the occurrence of drought, floods, and extreme weather, and accelerate sea-level rise into the future (IPCC, 2007a, 2007b, 2007c, 2013). The inclusion of climate literacy in public education is necessary for society to develop strategies to address climate change, yet climate literacy demands cognitive and perceptual leaps for students and teachers (Grotzer and Lincoln, 2007) with respect to understanding complex interactions among the components of the Earth system. Understanding climate change requires grasping complex interactions among the atmosphere, hydrosphere (including the cryosphere), biosphere, and geosphere on multiple spatial and temporal scales. In a sense, climate change offers our most compelling context for helping students to learn Earth systems science and develop essential scientific thinking skills. Further, scientific practices and the essential thinking skills, such as modeling, have now been incorporated into the Next Generation Science Standards (NGSS), and thus their importance has been recognized in the larger context of science education (National Research Council, 2012; Achieve, Inc., 2013).

In parallel with the learning challenges that accompany the complexities of climate and Earth systems, we must keep in mind that remotely sensed data, model predictions, and ongoing direct observations continually change our understanding of climate. In a field where the most current and up-to-date science is critical for understanding the state of the problem, the flexibility of an online curriculum has benefits over static textbooks. Online materials allow students to access current science through near real-time data and use of authentic technological tools that support the perceptual and conceptual challenges learners may have with the unique features of the climate system (e.g., visualizing the temporal and spatial dynamics). Many online lessons and curricula are available to educators, including some that address climate phenomena. This wealth of resources makes it difficult for educators to identify empirically tested materials, understand them well enough to utilize them with students, and know which ones will be most effective in supporting their classroom learning objectives. As such, recent efforts to assist educators in easily accessing peer-reviewed materials have been made, including the Climate and Energy Awareness Network (CLEAN) (Gold et al., 2012) and the Diversity and

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Innovation in the Geosciences (DIG) Texas Project (Ellins et al., 2014). The *EarthLabs* modules have served as a pilot case in best practice for reviewing units and modules for the CLEAN Collection as an evidence-based curriculum that can be implemented "as is" in the classroom.

In order to meet student learning needs through effective curriculum, the coupling of education research with curriculum design is needed (Design-Based Research Collective, 2003). Design-based research (or DBR), originally developed by Brown (1992), has been gaining traction in the literature and is based on the following characteristics (Wang and Hannafin, 2005; Anderson and Shattuck, 2012): (1) It should design and test a significant intervention. (2) It should be practical, where the research refines both theory and practice. (3) It should be grounded in theory to inform the research design. (4) It should be iterative, interactive, and flexible, where designers are involved in the process and work together with participants, and iterative cycles of analysis, design, implementation, and redesign are used. (5) It should be integrative, where mixed method approaches are used in the research. (6) Finally, it should be contextual, where the research results are connected with the design process and have a practical impact on instructional practice within specific settings. The advantages of DBR are that it is tied to practice, creating opportunities for novel learning and teaching environments, raises important questions for continued research, contributes to theories about learning and teaching, advances and consolidates design knowledge, and increases capacity for educational innovation (Edelson, 2002; Design-Based Research Collective, 2003). DBR has also been described as especially applicable to technology-enhanced learning environments (Edelson et al., 1999; Linn et al., 2004; Sandoval and Reiser, 2004; Wang and Reeves, 2006), such as the *EarthLabs* project described herein. The project described in this study is part of a larger project (Ledley et al., 2012) that includes curriculum development, teacher training, and a research program with the programmatic goals of: (1) developing informed teachers confident in using the *EarthLabs* online curriculum; (2) creating curriculum that has been informed by master teachers and tested with students; (3) investigating how the curriculum supports student conceptual understanding of the climate system; (4) understanding how students engage with the *EarthLabs* curriculum so that it can effectively meet their learning needs; and (5) considering the ways in which the *EarthLabs* curriculum should be modified to address research findings. This study will focus on items 3–5. Item 2 will be addressed in further detail in a companion paper in this special issue (Ellins et al., 2014).

COGNITIVE CHALLENGES OF SYSTEMS THINKING

Climate change has been shown to be a difficult concept for learners at all levels to understand fully, from decision-making adults (Leiserowitz, 2008) to young children (Francis et al., 1993). Although noncognitive variables, such as political and religious orientation (McCright and Dunlap, 2011; Leiserowitz, 2008), can influence perceptions of climate change, basic conceptual understanding is likely significantly influenced by an individual's ability to engage in "systems thinking" (Assaraf and Orion, 2004; Gautier and Rebich, 2005; Rebich and Gautier, 2005; Hmelo-Silver et al., 2007). Grasping the nature of systems is vital to developing coherent mental models of climate.

A student's ability to reason about complex Earth phenomena depends upon how well new ideas are integrated with preexisting mental models (Vosniadou and Brewer, 1992; Chi, 2005). In the study by Sell et al. (2006), most college students were unable to articulate processes that are key to how Earth changes over time and space, suggesting a limited ability to understand Earth system science and to think across spatial and temporal dimensions. Research into student conceptions about Earth (Vosniadou and Brewer, 1992; Dove, 1998; Blake, 2005; Libarkin, 2006; Libarkin and Kurdzeil, 2006) shows that students have a range of nonscientific ideas about how Earth changes over time and space. Studies of student understanding of geologic time (Ault, 1982; Schoon, 1992; Oversby, 1996; Marques and Thompson, 1997; DeLaughter et al., 1998; Trend, 2001; Dodick and Orion, 2003; Dahl et al., 2005; Libarkin and Anderson, 2005) suggest that students are more comfortable with relative time than absolute, perhaps because people of all ages have difficulty comprehending differences between large numbers and larger numbers (e.g., thousands vs. millions; Greeno, 1991; Libarkin and Anderson, 2005).

Systems thinking requires recognition that observed phenomena result from underlying processes, and that these processes can interact to produce complex phenomena. Systems thinking also requires one to understand that not all interactions are purely linear (Herbert, 2005; Raia, 2005). In the climate system, for example, positive and negative feedback loops generate fluctuations in temperature that may not be obvious from initial inspection of the system. Another possible explanation for conceptual difficulties with climate change results from its multidisciplinary nature (Sell at al., 2006), such that understanding climate change requires crossing boundaries between geology and geography, physics and chemistry, and atmospheric and ocean sciences.

Research evidence suggests that the use of multiple representations that include technology and hands-on activities (McNeal et al., 2008), explicit identification of spatial characteristics of phenomena (Black, 2005), and discussion of the impact of climate change on society (Gautier and Rebich, 2005) may effectively assist students' conceptual understanding of complex Earth processes. Edelson's (2001) work with the online software platform "My World GIS" demonstrated how authentic scientific tools and technology can be used to support students' spatial understanding. Furthermore, research applying the use of hypermedia to complex systems has been shown to be effective (Jacobson, 2008; Liu and Hmelo-Silver, 2009) while also increasing student motivations towards science (Wang and Reeves, 2006).

With the increase in affordability and availability of technology tools, Web-based learning has been amplified in the K–12 classroom (Picciano and Seaman, 2009), while climate change and Earth system concepts have also increased in their prevalence in national science standards (National Research Council, 2012; Achieve, Inc., 2013). However, evidence-based online curriculum that employs educational research to specifically address the K–12 classroom (Means et al., 2010), teacher training in technology use in the classroom (Kleiman, 2000) and climate change content (Sweeney and Sterman, 2007), and curriculum units that utilize current pedagogical approaches such as inquiry-based activities, constructivist learning principles, and proper evaluation methods are needed (Mioduser et al., 2000). These needs are especially important given the large amount of and vastly growing collection of online climate change materials available to educators (for examples, see http://cleanet.org and http://www.camelclimatechange.org).

RESEARCH QUESTIONS: STUDENT UNDERSTANDING AND ENGAGEMENT WITH COMPLEX SYSTEMS

This work evaluates the efficacy of online curriculum materials through a research design that embeds pre- and postcourse student testing, teacher interviews, classroom observations, and eye-tracking studies applied to the case of the online *EarthLabs* project. The *EarthLabs* program includes the development of Earth Science and environmental science curriculum materials that engage high school students in a combination of Web-based activities, hands-on experiments, and scientific data analysis, with the ultimate goal of providing easily accessible, inexpensive, and effective inquiry-based experiences (Ledley et al., 2012). In this paper, we report on student understanding of and engagement with complex Earth systems. Specifically, we sought to answer the questions: (1) How does the online *EarthLabs* curriculum assist students in developing understanding of temporal and spatial dynamics and system interactions of climate? (2) How do users engage with and navigate the online *EarthLabs* curriculum?

METHODS

Curriculum Development

The *EarthLabs* project (Ledley et al., 2012) addresses nine subjects using the following live modules: *Hurricanes*, *Corals*, *Fisheries*, *Drought*, *Climate and the Cryosphere*, *Earth System Science*, *Climate and the Biosphere*, *Climate and the Carbon Cycle*, and the *Climate Detectives* (teacher guide: http://serc.carleton.edu/EarthLabs; student portal: http://serc.carleton.edu/eslabs). An *EarthLabs* module consists of five to nine sequenced labs intended to build on the knowledge and skills learned in the previous labs. Activities consist of a combination of online reading, data manipulation and visualization using software applications such as Google Earth and ImageJ, hands-on activities, and outdoor explorations. Each lab within an *EarthLabs* module contains "Checking In" and "Stop and Think" questions that assist students and teachers in gauging learning progress. The *EarthLabs* teacher portal provides teachers with relevant background information; lab overviews; lists of required materials, technical resources, and online tools; additional science content support; and suggestions for assessment and extension activities.

In this paper, we focus on two of four modules that address climate and Earth systems, with emphasis on the classroom implementation and research surrounding the *Earth System Science (ESS)* and *Climate and the Cryosphere (Cryosphere)* modules. Feedback from the research results, including teacher professional development (Ellins et al., 2014), of these two modules is currently being incorporated into the revision of all modules.

The local to global scale approach to teaching and learning has been used effectively in geography education (Geography Education Standards Project, 1994). As such, the *ESS* module begins by having students examine Earth system processes on the temporal and spatial scales that are most familiar to them. The first few labs focus on the local scale—the scale that students experience every day, such as their schoolyard, a neighborhood park, or other common area within the local community. The next labs focus on the regional scale and emphasize the boundaries of a region and the interactions among components. The last few labs focus on the global scale and highlight circulation patterns, the water cycle, and change over time. The *Cryosphere* module similarly begins with the local and evolves into the global scale, and it focuses on snow and ice, melting and freezing processes, observations of how land and sea ice change over time, interactions and feedbacks that contribute to increased melting within the cryosphere, and how these processes relate to global climate. Each module contains seven labs and specific learning goals (Table I). The third and fourth modules, *Climate and the Biosphere* and *Climate and the Carbon Cycle*, have benefited from this effort by incorporating feedback from emerging research data. *Climate and the Biosphere* focuses on climate processes, the relationship and differences between weather and climate, and the impacts of weather and climate on Earth's biomes. *Climate and the Carbon Cycle* focuses on the role carbon plays in influencing climate.

The *EarthLabs* Design-Based Research Approach

We implemented an online curriculum with embedded student research and followed a create–test–revise–implement–revise iterative process. This process incorporated the following elements:

(1) Create. Curriculum developers designed explicit student learning goals and developed curriculum level assessments while online materials were generated, following modified backwards design (Wiggens and McTighe, 1998, 2005) procedures, and generating a framework for project researchers to align the evaluation and research components with the *EarthLabs* curriculum.
(2) Test. Researchers developed appropriate research questions and coupled research quality assessments before and during the curriculum development process and worked with developers to ensure that assessment content was aligned with *EarthLabs* curriculum goals and materials.
(3) Revise. Discussion between researchers and curriculum developers occurred continuously to generate feedback and continual revision of student learning goals, research questions, and developed assessments before curriculum implementation.
(4) Implement. Appropriate qualitative and quantitative approaches were employed to address the research questions generated in order to triangulate data, enhance robustness of interpretations, and maximize data collection opportunities. Validity and reliability measures were implemented.
(5) Revise. Collected data and results were shared with curriculum developers well before upcoming implementation stages so that adequate modifications

TABLE I: Student learning goals and labs for the *Cryosphere* and *Earth Systems Science EarthLabs* modules.

	Cryosphere	Earth System Science
Learning Goal	Students will learn about the thermodynamic, dynamic, and feedback processes in the cryosphere	Students will learn to identify the parts of the Earth system and the processes that connect them
Students will Address	What is the cryosphere? How and why does the cryosphere change over time and space? What are the timescales associated with changes in the cryosphere? How do climate and the cryosphere influence each other?	What is Earth system science? How can we describe Earth as a system? How are energy and matter exchanged among the four main components of the Earth system (atmosphere, biosphere, hydrosphere, pedosphere)? How does the Earth system change over time? How is life affected by changes in the Earth system?
Lab 1	Frozen in Time	Think Globally, Act Locally
Lab 2	Sea Ice Thermodynamics	Drawing Local Connections
Lab 3	Sea Ice Dynamics	Discovering Local Data
Lab 4	Land Ice Thermodynamics	A Bird's Eye View: Exploring your Region
Lab 5	Glacier Dynamics	It's all Connected: Global Circulation
Lab 6	Climate History & the Cryosphere	Air, Water, Land & Life: A Global Perspective
Lab 7	Future of the Cryosphere	A Year in the Life of the Earth System

could be made to the *EarthLabs* curriculum materials. This helped to ensure that materials incorporated the research evidence collected about student learning.

(6) Iteration. Opportunities for revision and re-testing of materials were incorporated during ongoing studies to increase the robustness of efficacy testing of curriculum materials and student learning.

In the described project, the *EarthLabs* research and the evaluation efforts were conducted by the same unit/team and were complementary/overlapping activities. However, often, research and evaluation are distinct efforts conducted by different parties. For instance, in an ongoing *EarthLabs* project, the research team is specifically focusing on the student learning outcomes and addresses research questions as a result of the designed curriculum, providing robust research evidence to modify generated curricula. A separate evaluation team aims to assess the program as a whole; specifically, they collect information about teacher professional development activities and the curriculum development process, and they serve as unbiased third-party reviewers to the research design and findings. Evaluators in the ongoing project will utilize the summative student research results, in combination with the other project data, to evaluate the overall programmatic effort. In essence, research and evaluation efforts are uniquely tailored to the individual projects; however, in general, research efforts often address specific research questions, and evaluation efforts often address the project's programmatic goals—although a combination can exist, such as the case of the work presented here.

Assessment

Analysis of the efficacy of a complex curriculum requires multiple qualitative and quantitative assessments. To this end, we developed a process that incorporated multiple levels of data collected from a wide array of potential users, including teachers, high school students, and external users. This information was analyzed and then reported back to curriculum developers for consideration in future curriculum revisions and new development. In general, the use of two rubrics (which are further described below) for pre/post-assessments, thematic analysis of interview and open-ended responses, and the use of descriptive statistics and parametric or nonparametric tests were employed during analysis of the results. Validity and reliability were established through: alignment of assessment questions with the curriculum goals, teacher, expert, and curriculum developer review of assessment instruments and subsequent modifications, and inter-rater reliability calculations on qualitative measures. Specifics about each of the instruments and methods employed with each student population, including the validity and reliability as appropriate, are described in further detail below.

Student Assessments

High school students completed assessment surveys for both the *ESS* and *Cryosphere* modules before and after classroom implementation (see supplemental materials). Pre/postassessments included four to six open-ended response questions that were aligned to curriculum learning goals and materials, six demographic items, and one self-confidence item for each question set. Responses were scored using a conceptual understanding rubric (score 0–5; Table II) for all questions on the *ESS m*odule, and a systems understanding rubric was used for all questions on the *Cryosphere* module and one question on the *ESS* module (Table III). For the conceptual understanding rubric (Table II), scores of 0 to 5 were made based on the number of facts, connections made, and misconceptions present in student responses. For the systems understanding rubric (Table III), student responses were parsed into actions and processes (usually represented by the use of a verb), inputs and outputs (usually represented by the use of a noun), and connections between them (usually represented by the use of a conjunction). Statistical analyses of pre/postcourse differences were conducted using a paired Student's *t*-test when assumptions of the test were satisfied, including normality of the data and homogeneity of variance; otherwise, a

TABLE II: Explanation and scoring system for the conceptual understanding rubric.[1]

Level 0	Simple restating of the question.
Level 1	Statement of a single correct fact.
Level 2	Statement of multiple correct facts.
Level 3	A. Statement of multiple correct facts, with a single connection between facts. OR B. Statement of multiple correct facts, with multiple connections between facts. Misconceptions equal to or dominate over scientific conceptions.
Level 4	Statement of multiple facts, with multiple connections between facts. Misconception(s) present, but scientific conceptions dominate.
Level 5	Statement of multiple facts, with multiple connections between facts. Misconceptions not present within a story that is cohesive; misconceptions about concepts outside of the core message may be present.

[1]Misconceptions may or may not be present in levels 0–3.

TABLE III: Explanation and scoring protocol for the systems understanding rubric.

Symbol	Description	Points
Arrow	Actions/Processes (Usually a verb)	1 point
Boxes	Inputs/Outputs (Usually a noun)	2 points
Connections	Between Actions/Processes or Inputs/Outputs (Usually a conjunction)	3 points

Wilcoxon signed ranks test was used for nonparametric analysis. A nonparametric two-tailed Spearman's correlation analysis of student self-reported pre/postcourse confidence and overall scores was also completed. Inter-rater reliability was conducted with 10% of the student responses scored by two researchers, resulting in a minimum of 90% inter-rater agreement for both surveys. All disagreements were discussed and resolved, allowing a single researcher to continue coding all remaining responses. Experts in climate science also responded to each questionnaire, providing a basis for comparing student responses to those of expert scientists.

Classroom observation offered information about student interaction and engagement with the *EarthLabs* materials. This method provides critical feedback about students' time-on-task and offers supporting evidence that their content knowledge was likely strengthened by their experience with the implemented curriculum materials. Classroom observers used a formal protocol (see supplemental materials for instrument) to record student time-on-task while engaging with the *EarthLabs* curriculum and were trained to use the classroom observation tool to help ensure internal consistency (modified from Stallings, 1980). Observers recorded what students were doing as they worked in groups (e.g., organizing, listening, and discussing, as well as time off-task) every 5 min for a 30 min period. Average student time-on-task in each category was then determined over the entire observation duration. The instrument was reviewed by a team of researchers and piloted by multiple observers to ensure a 90% or greater inter-rater reliability between observers.

Teacher Feedback

At the end of the classroom implementation year, teachers were also interviewed via telephone for the purpose of identifying opinions about what did and did not work, how students responded to the curriculum, and whether teachers believed the learning goals of the curriculum were met. Interviews were semistructured with predetermined questions, and probes were added dynamically in reaction to interviewee responses. Interviews lasted 30–45 min and were conducted in the presence of a moderator and a note-taker. Teacher responses, including direct quotes and analysis of themes, were used to inform the curriculum developers of teachers' perspectives of the *EarthLabs* classroom implementation.

External User Assessments

Eye-tracking data provide a window into the nature of student engagement with online materials. This is an important step in the materials development process, particularly for labs that contain significant interaction with online environments. As noted, the *EarthLabs* modules are designed for advanced high school students; eye-tracking data were collected from a population of entry-level college undergraduates. The eye movements of six to seven students were tracked and recorded for each lab within the *Cryosphere* and *ESS* modules. Participants were told to complete the module as though it were a class assignment and were given as much time as they needed to complete the task. After completing the experiment, participants were asked to discuss their experience with the *EarthLabs* site and comment on what they found most/least useful. Both eye-tracking data and participant comments were used to make recommendations for lab revisions.

Research Context and Participants

Human subject research approval was obtained by the appropriate institutional review boards, and participant consent was obtained for this research project. Information about each study population (teachers, students, external users, and experts) is included in Table IV.

Students

In total, 205 ninth- to twelfth-grade students participated in the *EarthLabs* classroom implementation (Table IV). Six of the students were enrolled in a chemistry course, 12 were in an environmental science course, 24 were in an astronomy course, 91 were in an Earth and space science course, and 72 were in either a regular environmental science course or an advanced placement (AP) environmental science course. The majority of these students ($n = 163$) completed the *ESS* module, and the remaining students ($n = 42$) completed the *Cryosphere* module. Most of the students were from the same school district in central Texas, although some were from other locations throughout the state. Student paired responses to questionnaires were analyzed,

TABLE IV: Demographics of participant populations.

Participant Type	Number	Gender (Male/Female)	Ethnicity[1]
Teacher	7	1/6	C: 6; H: 1
Student: 9th–12th grade	205	92/111	C: 87; AA: 27; H: 78; A: 11; NA: 1; O: 1
External users—*Cryosphere*	26	12/14	C: 20; AA: 2; A: 4
External users—*ESS*	23	6/17[2]	C: 18; AA: 3; A: 3; NA: 1
Experts	3	2/1	C: 3

[1]C = Caucasian; AA = African-American; H = Hispanic; A = Asian; NA = Native American; O = other.
[2]One male is coded as AA, A, and C.

with missing pre- or postcourse responses excluded from the data set.

Teachers

Seven high school educators, who taught the students described in the previous section, in Texas, implemented the *EarthLabs* curriculum in a chemistry, environmental science, astronomy, Earth and space science, or AP environmental science public high school classroom (Table IV). Seven classrooms were observed, with a total of 205 students completing pre- and post-tests from these classrooms.

External Users

In all, 49 entry-level undergraduates at a large Midwestern institution engaged in 1 h instructional sessions, where 26 completed one of the labs in the *EarthLabs Cryosphere* module, and 23 completed either Lab 5 or Lab 6 in *EarthLabs ESS* module (Table IV). These students were 18–20 y old and were enrolled in an entry-level college geography/geoscience course or had taken no Earth-related science course beyond high school.

Experts

Three experts that held a doctoral degree in a geoscience field and were actively conducting relevant geoscience research were recruited to complete assessments in order to have a comparison for a likely maximum score we could expect from our instruments. The experts were recruited from a large geoscience department at a southern U.S. university and a national U.S. research laboratory (Table IV).

RESULTS

Student Results

Classroom Observations

Results from local classroom observations indicate that students were engaged with the *EarthLabs* materials more than 98% of the time. The majority of student time was spent working on the online curriculum (61%), engaging in hands-on activities (18%), discussing the materials (17%), or organizing materials (16%). We take these on-task results as strong indication that changes in students' conceptual and systems understanding and confidence levels are likely a result of the classroom instruction.

Conceptual Understanding

Students completing the *Cryosphere* module ($n = 42$) exhibited significant increases in general awareness of the existence and underlying concept of the cryosphere when asked to "define and describe the cryosphere." Pre/postcourse conceptual understanding scores indicate significant improvements. For example, one student progressed from, "I don't know, sorry," to, "The sphere with ice, snow, sleet, etc." after instruction. Overall, 42% of students responded, "I don't know," prior to instruction, whereas only 18% responded, "I don't know" postinstruction. Additionally, over 57% of student postinstruction responses included the word "ice," whereas only 33% of pre-instruction responses included the word "ice." However, postinstruction responses indicate that numerous misconceptions persisted despite instruction, with some students indicating that the cryosphere is: "The ice-shelf biome" and "Where vegetation occurs." The first student does in fact understand that the cryosphere has something to do with ice on Earth; however, they relate it to a "biome" and exclude land ice or snow, showing that there may be confusion about what a biome is versus an Earth system. The second student seems to think that the cryosphere is a place on Earth that defines where vegetation occurs, illustrating a lack of understanding of what comprises Earth's cryosphere. Cumulative scores on the assessment as a whole also showed overall pre/postinstruction gains in classrooms that implemented the entire *ESS* and *Cryosphere* modules (pre-instruction $M = 4.17$, postinstruction $M = 6.18$, $\rho < 0.05$; Fig. 1).

For the *ESS* module, results of the conceptual understanding rubric show that students improved on all items from pretest to post-test (Fig. 2). The highest gains occurred on question one (Fig. 2), with mean pre-instruction scores less than 0.10 and postinstruction scores greater than 0.70. Analyses of example responses to specific items illustrate how the conceptual knowledge rubric was used to show specific patterns in the data. Students were asked to "describe and define Earth system science in your own words." Analysis of the responses using the conceptual knowledge rubric (Table II) indicates statistically significant differences ($\rho < 0.05$) between pre- and postinstruction scores (pre-instruction $M = 0.067$, postinstruction $M = 0.75$). For example, one pre-instruction student response, "the research of the way that the Earth operates... this show us how the Earth is changing as a whole," is less complete and nuanced than the same student's postinstruction response, "The work of geography such as biosphere, pedosphere, atmosphere, and hydrosphere used to find information and solve facts for future use and help us find out more about the way our planet works." Students were also asked to, "Please look at the two images provided [one of global precipitation in August and a second of global precipitation in February] and explain what makes the two images similar/different" (see supplemental materials). Analysis of pre/postinstruction conceptual understanding scores for this question indicate statistically significant ($\rho <$

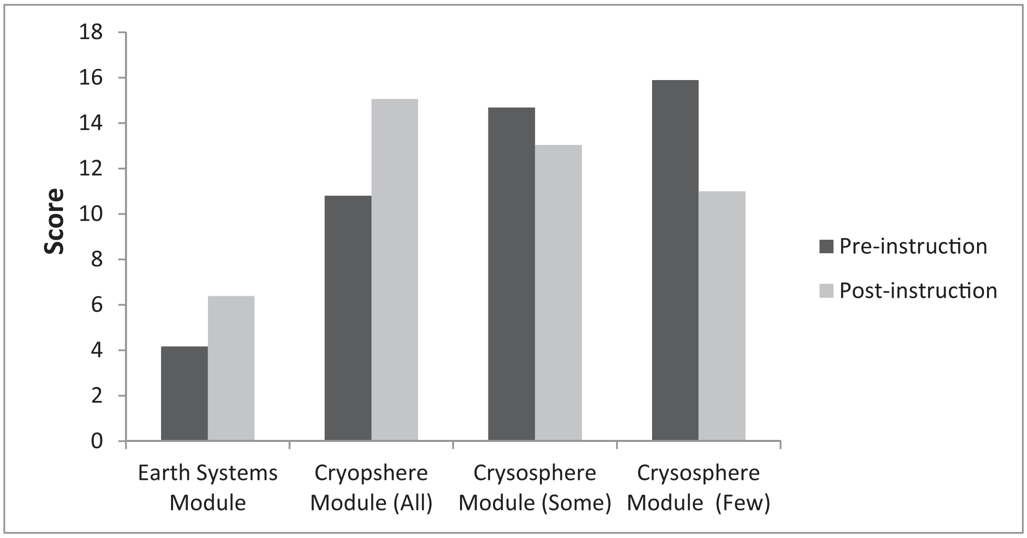

FIGURE 1: Average pre/postinstruction conceptual understanding scores for the *Earth Systems Science* (*ESS*) module and average pre/postinstruction systems understanding scores for the *Cryosphere* module. The *ESS* module is aggregated for all classrooms. Each classroom is shown for the *Cryosphere* module to show effect of different time exposures on learning outcomes. All = the classroom that implemented all labs. Some = the classroom that implemented some of the labs. Few = the classroom that implemented only a few or limited labs.

0.05) improvements, with postinstruction scores ($M = 1.09$) almost double the pre-instruction scores ($M = 0.65$). Another example shows how a student progressed from explaining, "It rains more in February" (pre-instruction), to, "It is very hot over the equator so water from the oceans evaporates up to form clouds and then is carried over the continents by wind and then rain over the continents." This second explanation is much more nuanced and comprehensive. Postinstruction, approximately 35% of the students identified seasons as a cause for change in precipitation, 13% deciphered differences between the Northern and Southern Hemispheres, 33% identified the equator in the provided map, 17% linked color intensities in the map to precipitation amounts, and 2% provided other scientific reasons for differences between the provided precipitation images.

Systems Understanding

For the *Cryosphere* module, results show that students engaged in all of the module's labs had significant ($\rho < 0.05$) pre/postinstruction systems understanding learning gains on individual assessment items after implementation (pre-instruction $M = 2.53$; postinstruction $M = 3.57$). Three of the four pre/postinstruction assessment questions showed improvements for students that participated in all aspects of the *Cryosphere* module (Fig. 3). Examples of a student and an expert response are illustrated in Figure 4 to show how the systems rubric was applied in the *Cryosphere* module. For this example, the question asked students to "explain why the ice extent in each of the images are different" upon viewing a satellite image of sea-ice extent over a 270 d period (see supplemental materials). Analysis

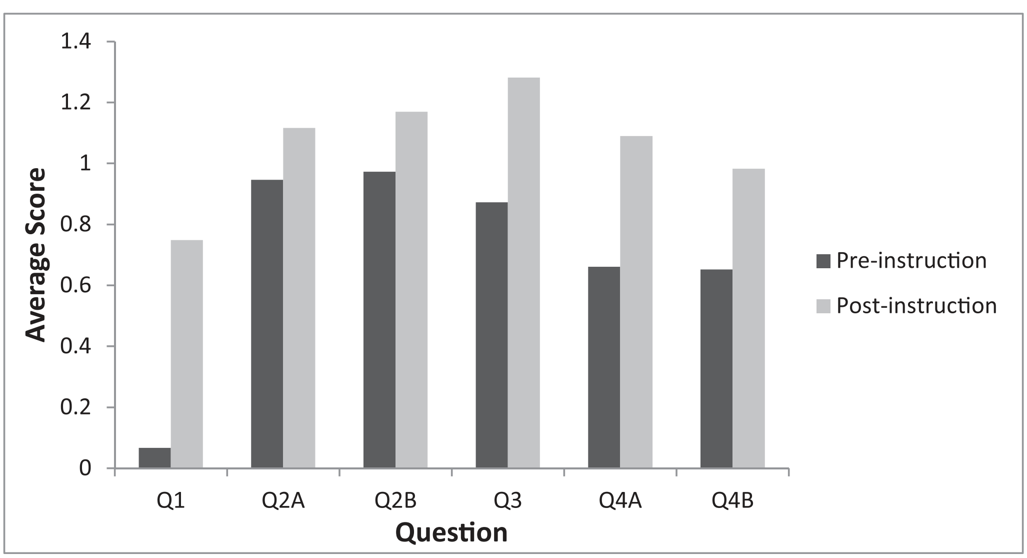

FIGURE 2: Student average pre/postinstruction conceptual understanding performance on individual items on the *Earth Systems Science* module assessment.

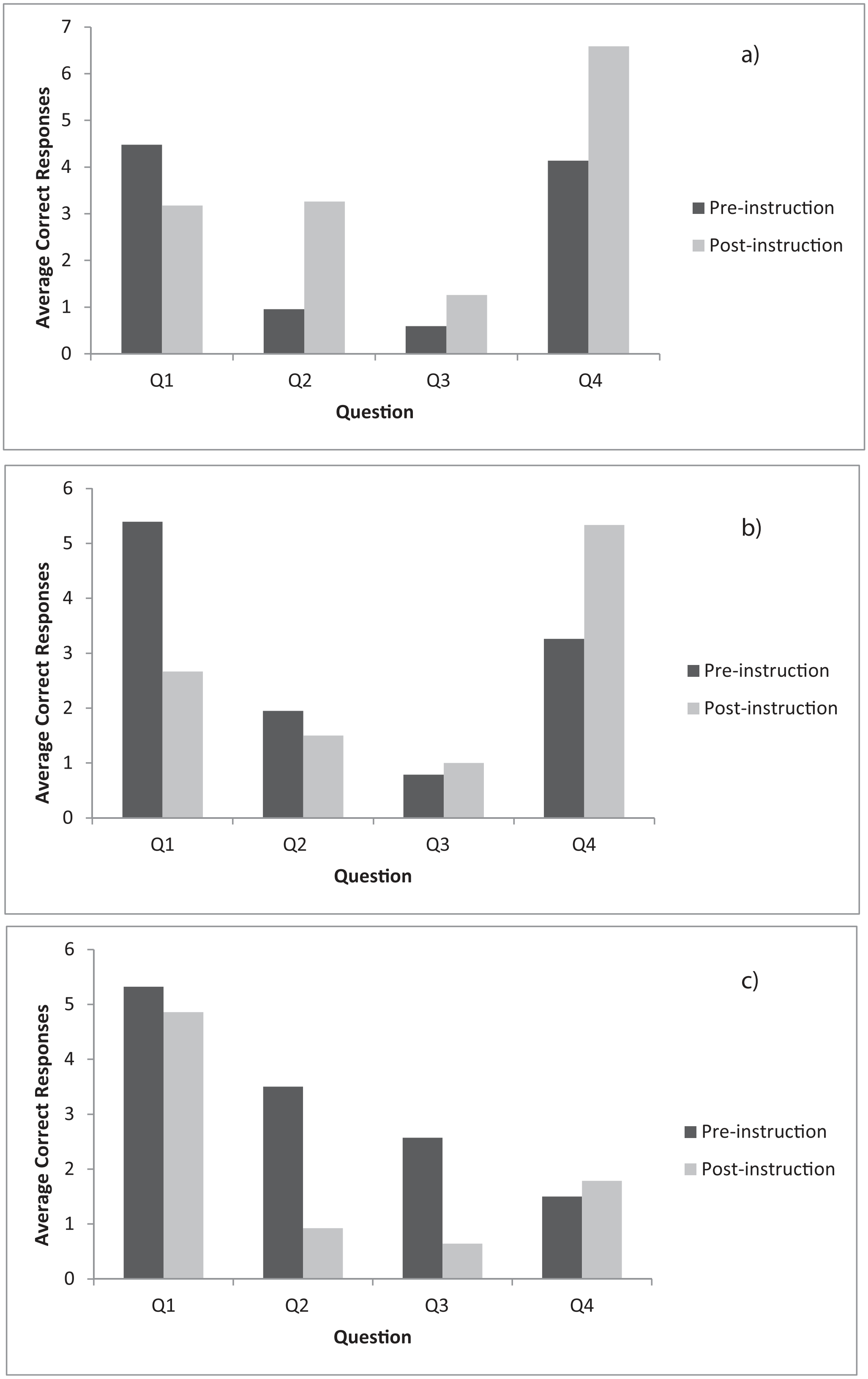

FIGURE 3: Student mean pre/postinstruction systems understanding performance for individual items on the *Cryosphere* module assessment for each implementing classroom: (a) the classroom that implemented all labs, (b) the classroom that implemented some labs, and (c) the classroom that implement few labs.

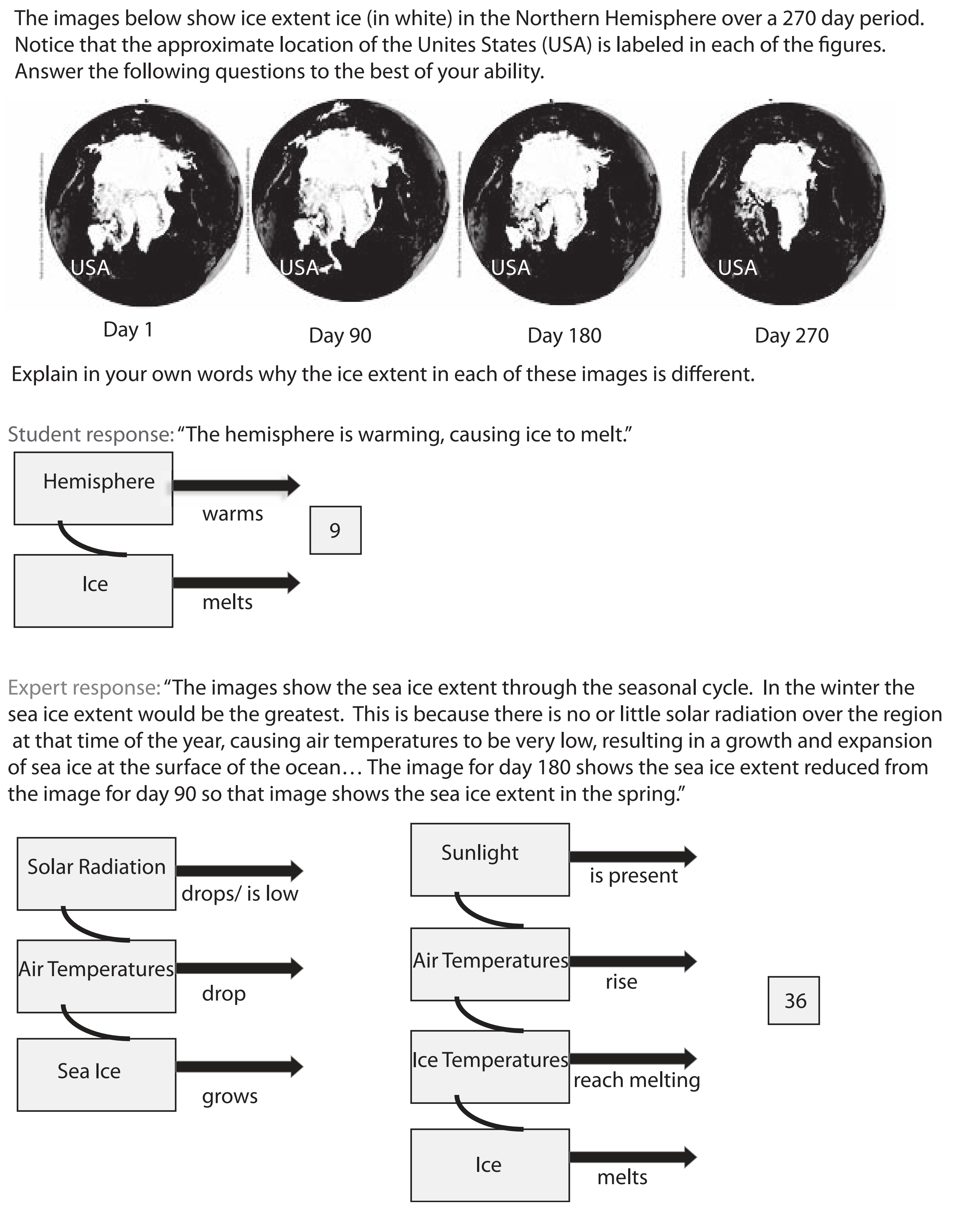

FIGURE 4: An example open-ended *Cryosphere* pre/postinstruction assessment question and student and expert responses as scored by the systems rubric in response to, "Explain why the ice extent in each of the images is different."

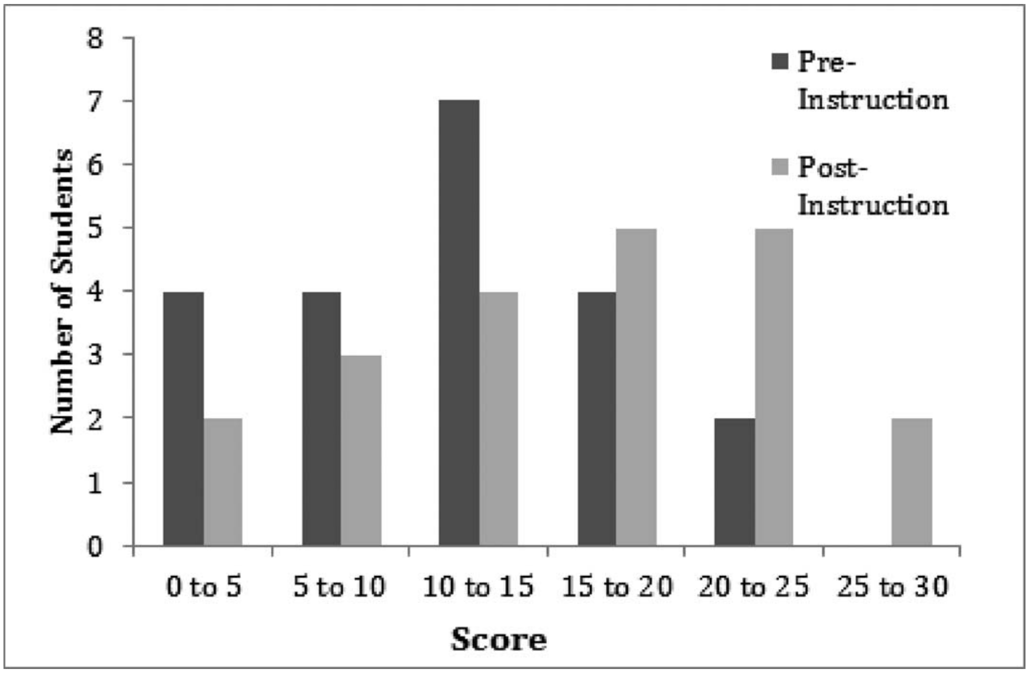

FIGURE 5: Pre/postinstruction cumulative student scores for all questions on the *Cryosphere* module using the systems rubric.

of the distribution of systems understanding scores for all questions indicates that cumulative scores were below 25 points in pretests but reached as high as 30 on post-tests (Fig. 5). Over approximately half of the student respondents scored higher than 20 points in the postassessment. Pre- and postinstruction systems thinking scores differed significantly on a Wilcoxon signed ranks test ($\rho = 0.08$, $Z = -1.74$). Interestingly, students who completed only a portion of the labs exhibited no statistically significant improvements postimplementation ($\rho > 0.05$), whereas those engaged in all seven labs of the modules and those who spent nine in-class hours over the course of 4 weeks on these materials showed statistically significant improvements postimplementation ($\rho < 0.05$).

On the *ESS* module assessment, increased systems understanding is illustrated by student responses to "**draw** and **label** arrows to represent ALL of the important processes that move or change energy, water, or chemicals in this region" (Fig. 6). Analysis indicates that students showed significant increases in the number of arrows drawn (pre < 3, post > 5). Furthermore, paired Student's *t*-test analysis indicates statistically significant differences ($\rho < 0.05$) on pre/postinstruction mean scores using the systems rubric (Table III; pre-instruction $M = 8.72$, postinstruction $M = 12.81$). When expert geoscientists ($n = 3$) were asked to complete the same task, the average number of arrows drawn was 10, and an average score of 34 was achieved (Fig. 6c).

Confidence Scores

Finally, all students ($n = 205$) were asked to reflect on their confidence with regard to understanding the material, using a Likert scale (1–4) to rate their ability to answer questions about the *EarthLabs* content. Self-assessed pre-/postinstruction student confidence on the *ESS* module increased from an average of 1.20 to 1.94. Similar results were observed for the *Cryosphere* module, where students either maintained or increased their confidence level from 1.94 to 2.90. A Student's *t*-test showed pre- and post-instruction confidence score increases were statistically significant for both modules (*Cryosphere* $\rho = 0.000$, *ESS* $\rho = 0.004$). A Spearman's correlation analysis showed that student confidence scores and student performance were significantly ($\rho < 0.05$) positively correlated (corr. coeff. $= 0.655$).

Teacher Postimplementation Interviews

Seven teachers were interviewed by phone postimplementation about their perceptions of student learning. Teachers were asked whether they believed their students better understood specific objectives (e.g., physical change over multiple time scales, dynamic interactions among Earth's systems, relevance to students' own lives) after the implementation of the *EarthLabs* modules.

With relation to time scales of cryospheric change, one teacher responded,

> *"Interestingly, enough kids keep bringing in the* Deadliest Catch *[a reality TV show on commercial fishing] because they are always showing ice over the Bering Sea and ice coming down depending on time of year. So kids caught onto that idea 'over time,' because they could relate it to the fishermen and how the sea ice moves and changes and how quickly it can move and change."*

Another teacher indicated that their students gained a partial understanding:

> *"...they got part of change and fluctuations. Larger time-scales...understood more of seasonal aspects, not sure how many got change over longer period of time."*

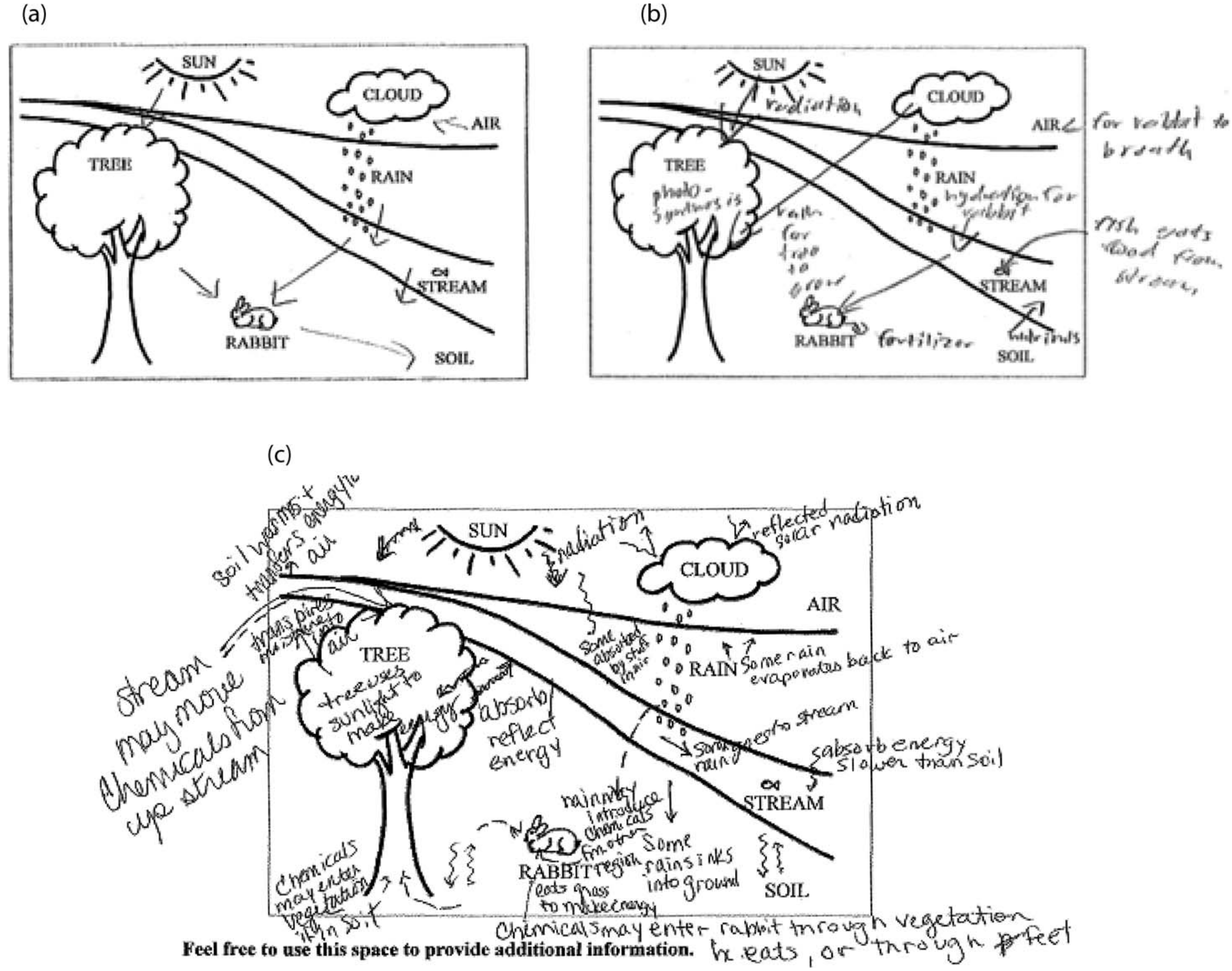

FIGURE 6: Pre- and postinstruction *EarthLabs ESS* drawing illustrating systems understanding (a) before and (b) after implementation, and (c) an expert geoscientist drawing in response to, "The following diagram represents a region in the continental United States. Draw in and label arrows to represent ALL of the important processes that move or change energy, water, or chemicals in this region."

When teachers were asked about whether their students better understood dynamic interactions among Earth's systems, one teacher responded,

"I think they got a better idea of it, of how things are interrelated, how a change in one place can end up being a change in another…They were starting to see that."

A second teacher provided a more nuanced view, stating that their students did have

"Some [improvements] in terms of the Earth's system [components], but maybe not the bigger [Earth] system..."

Yet another teacher replied,

"In AP environmental course we try to look at Earth as system…the EarthLabs *tied in the big picture much better than I have been able to do in the past."*

When teachers were asked whether students have a concept of the relevance of complex Earth systems and the importance of the cryosphere to their own lives, one teacher responded,

"I believe so…all mentioned to me they actually enjoyed doing it because they did learn something new and it was interesting for them because it was so new to them. Kind of new for all of us. One of those areas that has been neglected in Earth Science—does play such an important role…global warming issue has brought it to the forefront."

At the same time, some teachers did note that students had some troubles relating the cryosphere to their own lives in Texas; many students did not have firsthand experience with frozen precipitation. These teachers felt students were "too far removed" and unable to see their personal "connection" to snow and ice.

Overall, teachers commented that the strengths of the materials included the use of many visuals, movies, and graphs that engaged the students and forced them to think about the problem. One teacher commented that he/she "would enjoy having a lot more resources like [EarthLabs]." Teachers largely felt that the materials supported students' ability to learn about the cryosphere and Earth systems science.

External Users

Eye-tracking data provide information about the areas of the online curriculum that attract novice viewer gaze, and hence with which viewers are likely engaged, and these data can be coupled with interviews. Recall that all data discussed here were collected from non-science-major college students ($n = 49$) who completed one lab only. Although too rich to discuss in their entirety here, we provide examples from the *Cryosphere* module's "Sea Ice Dynamics" lab to illustrate the value of this research technique for informing curriculum design.

A heat map aggregating the gazes of multiple viewers ($n = 6$; Fig. 7) indicates that viewers are both engaged by the core text in the "Sea Ice Dynamics" lab and are not distracted by ancillary objects (e.g., heading, table of contents). However, students were mainly engaged with the text and not the images. Alternatively, a comparison of gaze paths for two individuals, showing the path students' eyes took across a page (Fig. 8), indicates that the amount of attention students pay to external Web links varies significantly. Figure 8 illustrates the range of engagement observed via eye tracking; as noted, most students exhibited a high level of engagement (as in Fig. 8b) at the start of the lab with decreasing engagement over time (as in Fig. 8a).

Overall, data indicate that students spent between 23 and 32 min completing the lab, engaged less with images than with text, and had difficulty engaging with some materials posted on external sites, such as graphs depicting change in climate indices over time. Eye tracking of student interactions with other labs yielded similar results, suggesting that: (1) labs are sufficiently engaging for students; and (2) materials hosted by external sites (e.g., National Aeronautics and Space Administration [NASA], National Oceanic and Atmospheric Administration [NOAA]) may need to be modified by the currculum team before students can engage effectively with them.

The nature of participant interactions with pages and elements within pages varied greatly across individuals and over time. We note that the first page of each lab attracts significant attention to all elements within the page. Attention to text elements in subsequent pages was significantly reduced, suggesting increased fatigue or waning interest as participants worked through the labs. Participants also did not always utilize external sites linked from the *EarthLabs* modules, and viewing of external sites was much more cursory than engagement with the *EarthLabs* pages themselves. Finally, participants were asked to discuss their experience with the *EarthLabs* modules and comment on what they found most and least useful. In general, participants found charts, graphs, and questions embedded in text most useful (64%), followed by videos and external Web sites (32%). Only one student indicated that the text components of the lab were helpful for learning about the climate system. This low level of valuation coupled with waning attention to text over time suggest that reduction of text might be helpful for engaging students over the amount of time needed to complete the labs.

DISCUSSION

The collaboration of curriculum developers, education researchers, external evaluators, professional development specialists, teachers, and their students provided an exciting venue for developing and assessing the *EarthLabs* climate change modules as an exemplar of evidence-based online curriculum development. This work shows the results of student learning during classroom implementation of the *EarthLabs* online modules. It also provides feedback and research-quality results to the curriculum developers about how further *EarthLabs* materials should be refined.

How Does the Online *EarthLabs* Curriculum Assist Students in Developing Understanding of Temporal and Spatial Dynamics and System Interactions of Climate?

As a result of the *EarthLabs* implementation, students' conceptual and systems understanding significantly improved, as evidenced by significant changes in pre/post-instruction assessment scores and systems understanding scores. The complex interplay of climate acting over multiple Earth systems requires an understanding of the temporal and spatial nature of climate system dynamics. The attention paid in *EarthLabs* to concepts of scale within specific climate phenomena, such as in the *Cryosphere* module, afforded students many opportunities to wrestle with changes that are observable over human life spans, as well as those that occur over periods of time, or over scales, that are outside human perception. According to the student learning goals (Table I) for these modules, both modules focus on change over time; however, the *ESS* module focuses more on connections between parts of a system.

Despite marked improvement, students did not reach mastery levels on par with expert responses. This lack of mastery is expected for high school students in early stages of learning about systems. In addition, the cognitive hierarchical structure of systems thinking that includes "stages" or cognitive steps in development of the next higher-order thinking skills (Assaraf and Orion, 2005) predicts a disparity between experts and novices in grappling with the causal behaviors and functions of complex systems (Hmelo-Silver et al., 2007). We would not expect these students to reach the level of experts, of course, but would like to note that this improvement in systems thinking ability aligns with expectations of the systems crosscutting concept recently codified in the Next Generation Science Standards (Achieve, Inc., 2013). Despite a lack of mastery, it is important to note that the majority of students experienced significant changes in their understanding even after only one *EarthLabs* module exposure. Students also increased their content knowledge and confidence in engaging with complex climate concepts during the time frame of the implementation, where significant correlations between student performance and

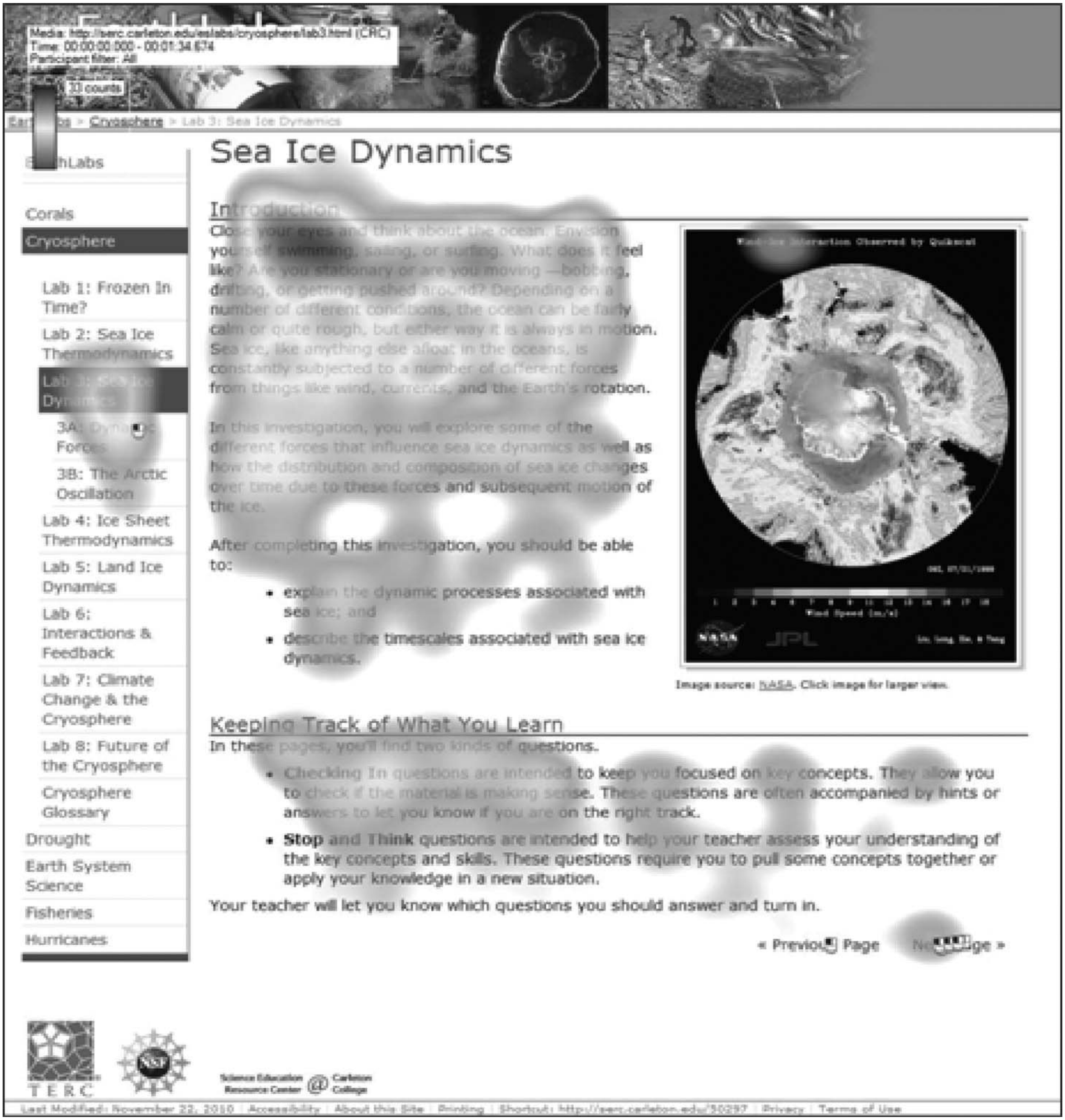

FIGURE 7: Heat map of student ($n = 6$) attention to the "Sea Ice Dynamics" page of Lab 3 in the *EarthLabs Cryosphere* module. Gray clusters indicate areas of viewer attention. Darker areas represent more attention.

confidence were measured. Teachers also reported that students achieved many of the *EarthLabs* learning goals. Furthermore, interviews and feedback from teachers suggest that more intentional teaching about temporal and spatial changes in the Earth system is needed in high school curricula, identifying that *EarthLabs* modules may help build capacity for environmental science courses to meet student learning needs.

How Do Users Engage with and Navigate the Online EarthLabs Curriculum?

Classroom observations combined with eye-tracking measures of external users indicate that the *EarthLabs* modules were engaging to users. However, some modifications in page content could be made to increase the long-term engagement of users as they navigate through the modules. For example, these data indicate that students do

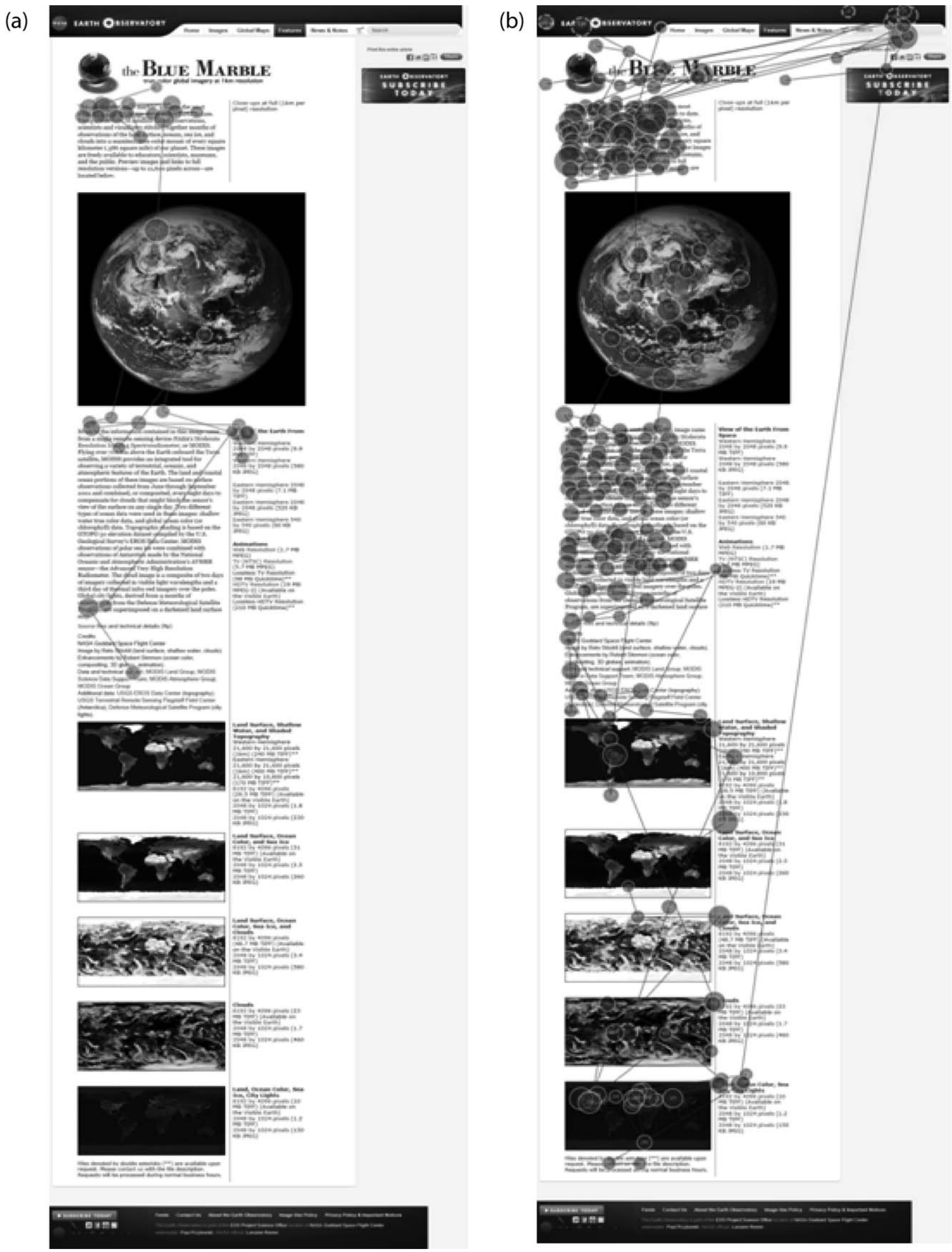

FIGURE 8: Two individual gaze paths for Blue Marble site (external link on *EarthLabs ESS* module). Path (a) is cursory and is typical of most participants, and path (b) is a participant with significant attention.

TABLE V: Synthesis of the design-based research theory, the *EarthLabs* research–curriculum design cycle, and example activities and outcomes.

Design-Based Research Theory	*EarthLabs* Research–Curriculum Design Cycle	Example *EarthLabs* Curriculum and Research Activities and Outcomes
It should design and test a significant intervention.	**Create.** Curriculum developers designed explicit student learning goals and developed curriculum level assessments while online materials were generated.	EarthLabs *Cryosphere* and *ESS* modules and learning goals were developed (see Table I).
It should be grounded in theory to inform the research design.	**Test.** Researchers developed appropriate research questions and coupled research quality assessments (based on existing literature) before and during the curriculum development process and worked with developers to ensure that assessment content aligns with *EarthLabs* curriculum goals and materials.	*EarthLabs* research questions were developed:
		How does the online *EarthLabs* curriculum assist students in developing understanding of temporal and spatial dynamics and system interactions of climate?
		How do users engage with and navigate the online *EarthLabs* curriculum?
It should be interactive and flexible, where designers are involved in the process and work together.	**Revise.** Discussion between researchers and curriculum developers occurred continuously to generate feedback and continual revision of student learning goals, research questions, and develop assessments before curriculum implementation.	Modifications to initially developed assessments were made through feedback from curriculum developers to ensure alignment to learning goals and "big ideas."
It should be integrative, where mixed method approaches are used in the research.	**Implement.** Appropriate qualitative and quantitative approaches were employed to address the research questions generated in order to triangulate data, enhance robustness of interpretations, and maximize data collection opportunities. Validity and reliability measures were implemented.	*EarthLabs* final assessment instruments were developed (see supplemental materials).
It should be practical, where the research refines both theory and practice.	**Revise.** Collected data and results were shared with curriculum developers well before upcoming implementation stages so that adequate modifications could be made to the *EarthLabs* curriculum materials.	Dynamic and embedded animations that assist students in visualizing flow of energy and matter in a variety of Earth systems were made.
		Figures and videos were directly embedded; text to describe images was added; direct references to images within the text body were added; and larger text blocks were shortened.
It should be contextual, where the research results are connected with the design process and have a practical impact on instructional practice within specific settings.		Emphasis on implementation of all labs with suggestions for how best to implement portions of the modules throughout the year to meet NGSS and state science standards.
An iterative cycle of analysis, design, implementation, and redesign is used.	**Iteration.** Opportunities for revision and re-testing of materials were incorporated during ongoing studies to increase the robustness of efficacy testing of curriculum materials.	Findings from *EarthLabs* research have been incorporated into the *Cryosphere* and *ESS* modules as well as ongoing studies in the development of *EarthLabs Climate* modules.

not always click on external links or watch videos as expected by curriculum developers. Additionally, the data indicated that students do not always spend a significant amount of time looking at images and attention may wane in longer text segments. Eye-tracking studies of these new design elements are ongoing.

EarthLabs Curriculum Changes as a Result of the Research Findings

The research outcomes from the *Climate and the Cryosphere* and the *Earth System Science* modules were reported back to the *EarthLabs* curriculum developers and have been incorporated into the *Climate and the Cryosphere*, *Climate and Biomes*, and *Climate and the Carbon Cycle* modules, which are currently undergoing revisions, and another cycle of revise and test is under way. Table V illustrates how the design-based research theory from the literature was incorporated into the *EarthLabs* research-curriculum design cycle, where example outcomes and research-informed curricula modifications are shown.

Research showed that scaffolding was needed to help students to view images by incorporating more references to the images in the text and embedding images in text where possible. In response, curriculum developers reworked text pages to embed figures and videos, including text directly into the *EarthLabs* pages instead of as an external link, assisting viewers to better utilize these features of the curriculum. Developers have integrated additional text that describes images; incorporated more direct references to images within the text body; and separated and shortened larger text blocks.

Additional findings suggest that the *EarthLabs* curriculum may need to provide increased scaffolding to students in regard to developing higher-order thinking skills, specifically in regard to making connections between systems, in order to assist students to reach a mastery level of understanding and to continue to build their confidence. In response, curriculum developers have built their own dynamic animations that are embedded into the *EarthLabs* modules that assist students in visualizing flow of energy and matter in a variety of Earth systems.

Our findings also suggest that those students exposed to all labs of the *Earthlabs Cryosphere* module had greater learning gains than those that only completed a portion of the labs, while multiple exposures to a series of *EarthLabs* modules in an entire semester-long course will likely result in the strongest conceptual changes. In response, the *EarthLabs* professional development efforts have emphasized that teachers implement all labs in a given module in order to achieve the intended learning outcomes. In school settings, it can be difficult to spend 2 to 3 weeks on each module, so suggestions have been made to teachers by staff and teacher leaders in how best to implement portions of the modules throughout the year to meet NGSS and state science standards over a continual basis in order to cover all labs in an *EarthLabs* module and maximize potential for students to reach the intended learning outcomes.

CONCLUSION

Careful development of curriculum materials is important for effective instruction, and particularly for those domains that will influence the way in which society grows and evolves in response to social, economic, and environmental needs. This study illustrates how research-driven online curriculum that allows learners to navigate near real-time data representing spatial and temporal changes and complex Earth and climate interactions can be conducted. We note that it can be difficult to engage in a full cycle of create–test–revise–implement–revise for any one curriculum due to limitations in personnel, time, and funding. In the *EarthLabs* case, the collection of curricular efficacy data was used to revise existing materials and inform the development of new materials in ongoing, follow-on projects. In an age when materials are widely disseminated via the internet, we as scientists and educators must be diligent in ensuring that we are creating and sharing materials proven to be effective. As such, implementations of *EarthLabs* in classrooms by teachers and their students have been tracked during the research activities highlighted in this paper. Results have indicated that the online *EarthLabs* modules improve student understanding of temporal and spatial dynamics, and Earth system complexity, and that the learners are engaged with the curriculum as evidenced by classroom observations and eye-tracking experiments. The quantitative and qualitative findings from the research conducted in this study were employed to make recommendations for curricular improvements for the next round of classroom implementations. The *EarthLabs* curriculum–research model is an example of how research can be used to inform curriculum development, and it serves as a model for best-practice in online curriculum design and research.

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