# Research on Students' Conceptual Understanding of Environmental, Oceanic, Atmospheric, and Climate Science Content

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## Introduction

At the interface between atmosphere, hydrosphere, and biosphere, this theme covers content that is societally crucial but publicly controversial and fraught by misconceptions and misinformation (Figure 1).

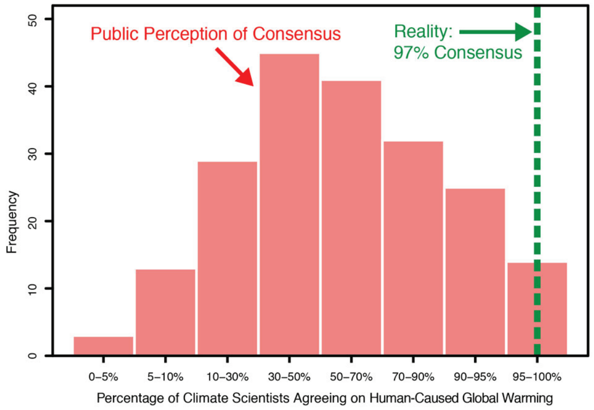


Figure 1: From Skeptical Science; data from 2012 Pew Survey. The disconnect between public perception and scientific consensus continues to persists today as demonstrated by other recent surveys.

Climate science is an interdisciplinary field that straddles the natural and social sciences; understanding its processes requires system-thinking, understanding mathematical models, and appreciation of its human and societal components. Recent data show that extreme weather and climate events have become more frequent in the past decades (EASAC, 2018). These include extreme temperatures, floods, like the ones associated with the series of very powerful hurricanes that made an unprecedented number of landfalls in August and September 2017 (Figure 2) and unusual drought conditions and forest fires across the Western US in the summer of 2017 (Figure 3).

Studies like these emphasize the complexity of climate science and highlight the importance of climate change adaptation. However, there is a significant disparity in the distribution of vulnerability and readiness to impacts of climate change with most of Africa and South Asia disproportionately more vulnerable and less equipped to deal with them (Swanson, 2015).

We have identified five Grand Challenges to the conceptual understanding of environmental, oceanic, atmospheric and climate science, and proposed strategies for the geoscience education research community.

## Grand Challenges

### Grand Challenge 1: How do we identify and address the challenges to the conceptual understanding specific to each discipline: environmental science, ocean sciences, atmospheric sciences, and climate science?

Misconceptions, pre-conceptions, partially correct conceptions, or naive conceptions are a challenge to students' conceptual understanding of the core science. Identifying common misconceptions that are specific to each discipline of the fluid Earth is the first step in addressing these alternative conceptions and ultimately achieving a higher level of conceptual understanding.

### Grand Challenge 2: How do we teach complex interconnected Earth systems to build student conceptual understanding of, for example, climate change?

Teaching about complex systems, like changes in climate over multiple temporal and spatial scales, represents a challenge that has been studied extensively. Reviewing existing studies, proposed learning strategies, and drawing from other disciplines would be a valuable contribution to the Geoscience education research community.

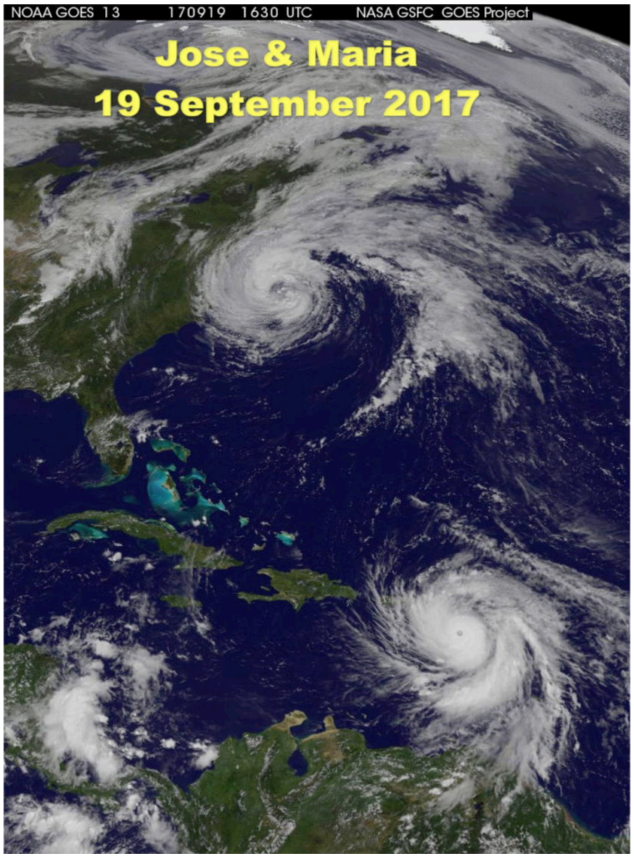


Figure 2: Category 5 hurricanes José and Maria on September 19, 2017. Hurricane formation and evolution involve complex interactions between ocean and atmosphere. They are connected to the climate system and affect environmental change. Research on how to effectively foster students' conceptual understanding of this and other Earth systems' phenomena is important to teaching and learning in the geosciences. Image courtesy of NOAA.

### Grand Challenge 3: What approaches are effective for students to understand various models (numerical and analytical) that are used for prediction and research in atmospheric, oceanic and climate sciences, including model limitations?

The study of the atmospheric, oceanic, and terrestrial systems is based on models that help simplify these complex systems and are used for prediction. Knowledge of computer programming and advanced math is needed to create, validate or understand these models, making the field less accessible to the broad student population. Thus, instruction in the geosciences needs to increase advance math and programming skills.

### Grand Challenge 4: How do the societal influences, affective elements, personal background and beliefs, and prior knowledge impact students' conceptual understanding of Earth system sciences?

Wildfire smoke crosses the U.S. via the jet stream on September 4, 2017, affecting air quality in the northern and central part of the continent. How to effectively use models of atmospheric circulation is one area in which education research can inform teaching practice. Images courtesy of NASA.

Students enter classes with a complex array of beliefs and personal history that shapes their learning and their perception of the relevance of what they are learning within their own lives. Literature about cognitive and metacognitive aspects of learning shows that these external factors have significant influence on students' conceptual understanding, particularly on topics perceived as controversial. Therefore, instruction in these fields requires sensitivity to the context and the prior knowledge and belief systems of students.

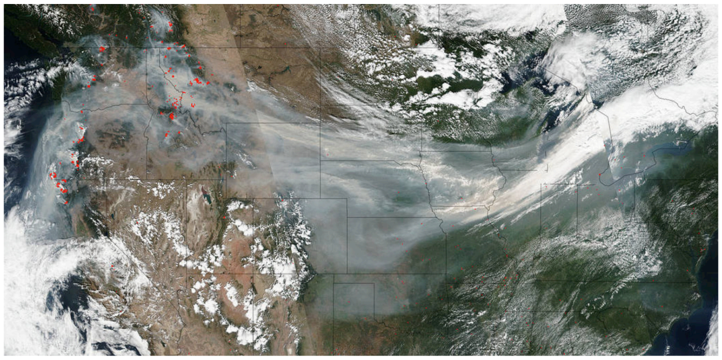


Figure 3: Wildfire smoke crosses the U.S. via the jet stream on September 4, 2017, affecting air quality in the northern and central part of the continent. How to effectively use models of atmospheric circulation is one area in which education research can inform teaching practice. Images courtesy of NASA.

**Grand Challenge 5: How do we broaden the participation of faculty who are engaged in educational research in environmental sciences, atmospheric sciences, ocean sciences and climate sciences and encourage implementation of research-based instruction?**

In the U.S. there are approximately 1,200 faculty in oceanography and atmospheric science/ meteorology at 4-year institutions, and four times as many faculty are in the broad field of geology or solid Earth. Overall, there are 75 faculty that identify themselves as Earth science education researchers nationwide, and most of them have a background in geology. This relatively small number of faculty members in fluid Earth science is reflected in the small fraction of the community that is engaged in education research. Such small numbers make it challenging to create a research agenda for this field.

# Grand Challenge 1:

## How do we identify and address the challenges to the conceptual understanding specific to each discipline: environmental science, ocean sciences, atmospheric sciences, and climate science?

### Rationale

As we define the best undergraduate geoscience learning experience, we build longitudinal connections with K-12 education, in which core Earth science concepts are well defined and articulated. Earth systems, Earth and human activity, weather and climate, natural hazards, and human sustainability are disciplinary core concepts in the Next Generation Science Standards that represent the foundation to the conceptual understanding of environmental science, ocean sciences. atmospheric sciences, and climate science. These disciplines are also central to the Big Ideas in the Earth Science Literacy Principles that identify the Earth as a complex, constantly changing system on which life evolves and modifies it (Big Ideas 3, 4, 6 and 9). Humans' dependence on natural resources and the risk that hazards pose to humans are the theme of Big Ideas 7 and 8, while the role of water on the planet is Big Idea 5.

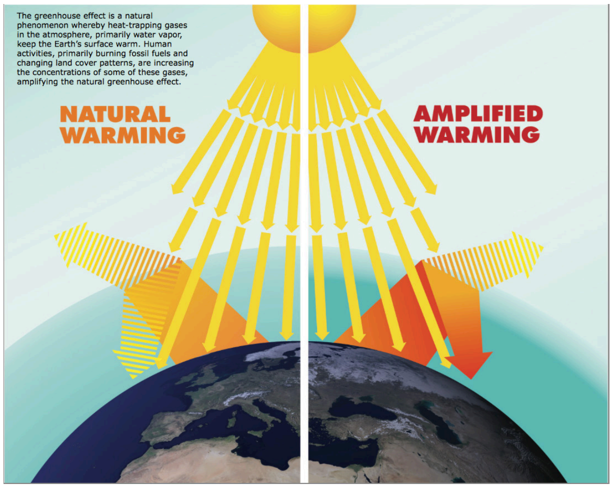
Misconceptions, pre-conceptions, partially correct conceptions, or naive conceptions are a challenge to students' conceptual understanding. Identifying prior conceptions that are specific to each discipline of the fluid Earth is the first step in achieving a higher level of conceptual understanding. This can be done using concept inventories, surveys, or focus group interviews (e.g., Arthurs et al., 2015; Robelia & Murphy, 2012).

Project 2061 contains assessment items that target core concepts and misconceptions in the Earth, life, and physical sciences. Each question contains data on the percentage of middle and high school students that answered it correctly. It also contains information on the misconception held by students who answered incorrectly (Prud'homme-Generaux, 2017). There are more than 80 documented misconceptions in the weather and climate theme, including basic concepts and seasonal differences. The website also includes an extensive list of references to studies that explore or unveil misconceptions. Since they are challenging to replace, it is likely that misconceptions held by middle and high school students will persist in college, making the Project 2061 information very valuable for the GER community (Prud'homme-Generaux, 2017).

A review of the literature on misconceptions is available for the solid Earth (Francek, 2013) but research on conceptual understanding of the fluid Earth is scattered among several journals: misconceptions related to tornadoes (Van Den Broeke and Arthurs, 2015), climate change (Huxter et al., 2015), environmental issues (Khalid, 2001; Robelia and Murphy, 2012), ozone formation (Howard et al., 2013), atmospheric pressure (Tytler, 1998), air motion (Papadimitriou, 2001), ocean acidification (Danielson and Tanner, 2015), the greenhouse effect (Boyes & Stanisstreet, 1993; Harris & Gold, 2017)(Figure 4), and sea-level rise (Gillette and Hamilton, 2011). Making available a compilation of common misconceptions to educators through an organized review would be a valuable contribution of the GER community.

## Recommended Research Strategies

1. The most common barrier to conceptual understanding are existing misconceptions or pre-conceptions, thus identifying them is the first step. Assessment instruments, like the Force Concept Inventory used in physics or the Geoscience Concept Inventory, are commonly used to identify misconceptions: we recommend the creation and/or dissemination of concept inventories about oceanography, climate, and weather as a valuable contribution from the GER community to educators. The Fundamentals in Meteorology Inventory assessment exam (Davenport et al., 2015) could be used as a starting point. The Climate Literacy Principles (USGCRP, 2009) could be used as a compilation of the big ideas in climate science and to organize common misconceptions.



The greenhouse effect is a natural phenomenon whereby heat-trapping gases in the atmosphere, primarily water vapor, keep the Earth's surface warm. Human activities, primarily burning fossil fuels and changing land cover patterns, are increasing the concentrations of some of these gases, amplifying the natural greenhouse effect.

Figure 4: The Greenhouse Effect (From USGCRP, 2009), is one topic in which misconceptions persist in the undergraduate student population.

2. Existing literature focuses on specific misconceptions within the fields of oceanography, environment, climate and weather science for specific populations. An extensive overview of misconceptions on weather and climate is included in Project 2061 but this tool is not widely used by college instructors. A literature review that summarizes what we already know, why students hold these conceptions, and how they compare in different populations, will be a useful guide for future research and educators.

# Grand Challenge 2:

## How do we teach complex interconnected Earth systems to build student conceptual understanding of, for example, climate change?

### Rationale

Teaching about complex systems (e.g. Scherer et al., 2017, Holden et al., 2017), like changes in climate over multiple temporal and spatial scales, represents a challenge that has been studied extensively. Reviewing existing studies, proposed learning strategies (e.g. Gunckel et al., 2012, Mohan et al., 2009; McNeal et al., 2014; Bush et al., 2016), and drawing from other disciplines would be a valuable contribution to the Earth science community. Learning progression research conducted in the K-12 realm (Songer et al., 2009) can inform instruction in higher education, in particular within the area of interconnected Earth systems. Learning progressions are "descriptions of the successively more sophisticated ways of thinking about a topic that can follow one another as children learn about and investigate a topic over a broad span of time." (Duschl et al., 2007). An example of a tool that explores the history of life on Earth within a deep-time plate tectonics and climate framework to inform students about future climate change is HHMI Changing Planet: Past, Present, and Future (Figure 5).

### Recommended Research Strategies

Figure 5: Opening image of HHMI Changing Planet site. Not only is an interconnected Earth systems perspective important for understanding modern Earth conditions, it is important for considering the causes and consequences of change in the geologic past and future.

1. Recent literature reviews on student learning of complex Earth systems (Holder et al., 2017; Scherer et al., 2017) provide the GER community with a foundation that can be used to study the conceptual understanding of climate change. Identifying examples from other disciplines (e.g., engineering) can provide a broader context for future research.

2. Inquiry and problem-based education have shown promise in enhancing learning of complex systems like climate change (e.g., Bush et al., 2016). We propose to expand testing of instructional strategies that have shown impact on learning to a broad range of learning environments (e.g., online, introductory, upper-level undergraduate, pre-service teachers, informal) and student populations.

3. Examination of learning progression research conducted in and developed for the K-12 setting can inform GER strategies used to research undergraduate students' development of understanding complex Earth systems. Adapting such research findings and strategies also has the potential to better align and understand the knowledge that students hold upon entering the higher education system to study earth and environmental sciences.

4. Study how conceptual understanding evolves from introductory to upper-level courses within different programs (oceanography, atmospheric sciences), and how we should prepare geoscience majors for graduate school and the profession (Mosher et al., 2014).

# Grand Challenge 3:

## What approaches are effective for students to understand various models (numerical and analytical) that are used for prediction and research in atmospheric, oceanic and climate sciences, including model limitations?

### Rationale

The study of the atmospheric, oceanic, and terrestrial systems is based on models that are used for prediction and for the conceptual understanding of these complex systems (Figure 6). Knowledge of computer programming and advanced math is needed to create, validate or understand these models, making the field less accessible to the broad student population (Ledley et al., 2011; Hamilton, 2015; Hamilton et al., 2015). One possible approach to reduce the mystery in the ‘black box’ approach to computer models is through the use of simple, familiar models like flow charts, graphs, and pictures, and physical models, like sand tanks for groundwater flow (Harrison and Treagust, 2000; Schwartz et al., 2009).

Another challenge to the use of systems models in atmospheric science is the fact that uncertainty is inherent in them, yet education research shows that novices are not comfortable with uncertainty. This requires a simplification of the models to adapt them to the student population and the implementation of targeted approaches (e.g., Gold et al., 2015).

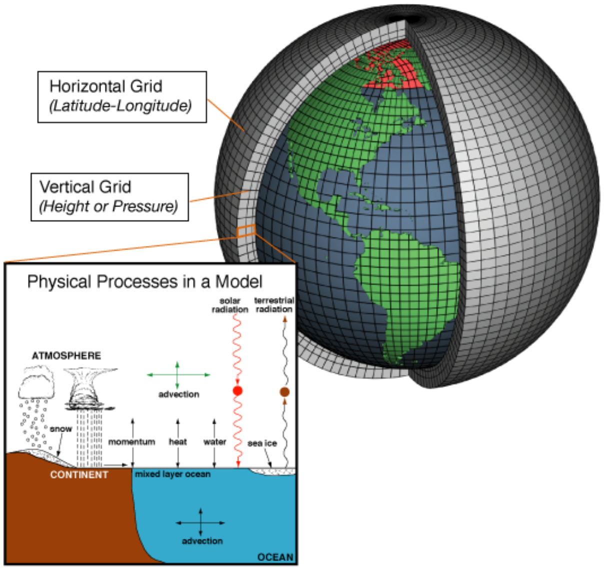


Figure 6: This image shows the concept used in climate models. Each of the thousands of 3-dimensional grid cells can be represented by mathematical equations that describe the materials in it and the way energy moves through it. The advanced equations are based on the fundamental laws of physics, fluid motion, and chemistry. To “run” a model, scientists set the initial conditions (for instance, setting variables to represent the amount of greenhouse gases in the atmosphere) and have powerful computers solve the equations in each cell. Results from each grid cell are passed to neighboring cells, and the equations are solved again. Repeating the process through many time steps represents the passage of time. The complexity inherent in these models make them conceptually challenging for undergraduate students. Image source: NOAA.

Unanticipated changes in the forcing functions of the system resulting from unpredictability of human behavior (Konikow, 1986) that commonly involve activities such as increased water use and land conversion further demands continuous upgrade and creation of new models (Oreskes, 2003). Therefore, time-to-time update in our modeling curriculum makes it challenging for students to grasp completely new materials.

### Recommended Research Strategies

1. Two working groups (Cognitive - Spatial and Temporal Reasoning, and Cognitive - Problem-Solving, Quantitative Reasoning, and Models) are focusing on the cognitive understanding of complex systems. Other DBER communities (like ecology) have conducted research in educational approaches that are effective for the understanding of models. The science education community

has studied extensively how best to teach students about models (Gilbert, 2011) and we can apply what they have learned to weather and climate models. If the difficulty is related to understanding the concepts of deterministic vs. probabilistic models, perhaps research in statistics education can provide valuable information. We recommend that education researchers refer to contributions of these groups to identify research paths for the fluid Earth community.

2. An important aspect of teaching models is to be able to minimize, or even eliminate, the widespread skepticism students have about outcomes of the models. We recommend expanding research on learning impacts of various models that can be broadly divided into two groups: i) models that have their validation index reported or that can be validated with existing data, and ii) models that lack validation measures. What is the learning impact of one vs. the other group within the realm of weather and climate models?

3. Research students' attitudes towards models and modeling, and the efficacy of different approaches to stimulating students' interest to learn about models. For example, one could show and test the use of models as decision-support tools in the context of resource management.

# Grand Challenge 4:

## How do the societal influences, affective elements, personal background and beliefs, and prior-knowledge of students impact their conceptual understanding of Earth system sciences?

### Rationale

Students enter classes with a complex array of beliefs and personal history that shapes their learning and their perception of the relevance of what they are learning within their own lives. Literature about cognitive and metacognitive aspects of learning shows that these external factors have significant influence on students' conceptual understanding, particularly on topics perceived as controversial (e.g., Vaughn & Robbins, 2017; Walker et al., 2017). Religious beliefs, political inclination, and social identity are strongly correlated with the acceptance or rejection of perceived controversial science topics like evolution, vaccination benefits, and climate change (Walker et al., 2017).

The strong disconnect between scientific views of climate change and the public perception of the scientific consensus (Figure 1), fueled by media and various interest groups, is a formidable challenge for educators (Walker et al., 2017) and has striking similarities to challenges encountered in teaching evolution in the United States.

Social identity theory hypothesizes that people sort themselves into groups based on perceived similarities (e.g., religion, political inclination) and that they hold onto the opinions of the group to remain part of it, a phenomenon known as identity-protective cognition (IPC, Kahan et al., 2007; Kahan, 2010). Studies have shown that, for example, teaching the evidence of climate change is not sufficient, or even counterproductive (Maibach et al., 2009; Kahan, 2015; Walker et al., 2017). However, a recent study shows that students' perception of risks associated with climate change increases with their level of knowledge of climate change science (Aksit et al., 2017). Addressing the connection between student identity and acceptance of certain scientific conclusions (Walker et al., 2017), building from personal background and beliefs, rather than challenging them (e.g., Nadelson & Southerland, 2010; Catley, Lehrer, & Reiser, 2005), and focusing on solutions as well as challenges (McCaffery & Buhr, 2007) are powerful teaching approaches.

### Recommended Research Strategies

1. We recommend the use of research-based evidence in developing curriculum and formal and informal instructional guides for instructors in how to approach teaching about controversial topics like climate change. Instructional guides, like the ones available for teaching evolution, would focus on best practices for teaching students about identity-protective cognition (i.e. the tendency of individuals to selectively credit and dismiss evidence in patterns that reflect the beliefs predominant in their group) and acknowledging external influences on scientific opinions (Kahan, 2017).

2. The perceived controversy about anthropogenic climate warming is created by groups that organize climate change deniers; learning more in detail about the efforts and agenda of these

groups can be used to inform students about misinformation. The GER community should draw on literature in the information sciences, specifically on the importance of information literacy in higher education (Flierl, 2017) and the use of misinformation as a teaching tool (Bedford & Cook, 2013).

3. Incorporating feedback of human-induced alterations in complex natural system and realizing effects of extreme events of climate change in society requires collaboration between natural and social scientists. Connecting with social scientists doing similar work to create multidisciplinary research and then spreading the resulting messages to community would broaden the impact of this field (Morss et al., 2016; Morss & Zhang, 2008).

# Grand Challenge 5:

## How do we broaden the participation of faculty who are engaged in educational research in environmental sciences, atmospheric sciences, ocean sciences and climate sciences and encourage implementation of research-based instruction?

### Rationale

In the U.S. there are approximately 1,200 faculty in oceanography and atmospheric science/meteorology at 4-year institutions, and four times as many faculty are in the broad field of geology or solid Earth. Overall, there are 75 faculty that identify themselves as Earth science education researchers nationwide, and very few of them have a background in oceanography/atmospheric science/meteorology (Wilson, 2016). This difference in numbers is reflected in the size of the community engaged in education research in the fluid Earth field, which makes it challenging to create a research agenda for it (Figure 7).

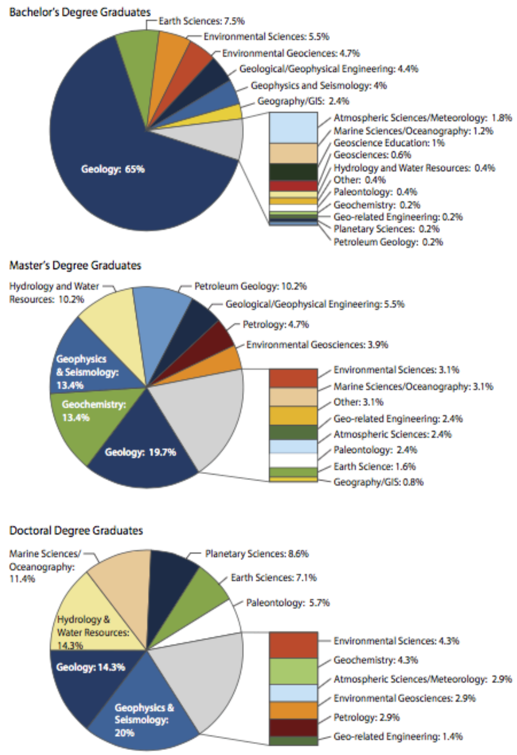


Figure 7: Breakdown of degree fields of geoscience graduates in the U.S. from Wilson (2016). Note that the PhD graduates in the environmental, ocean, atmospheric, and climate sciences are only about 15% of all doctoral graduates. A smaller fraction of these will enter academia, accounting for the small number of faculty in these fields that are engaged in GER.

Calls for a more research-based approach to understanding student learning were made a decade ago (e.g., Charlevoix, 2008), and with only limited GER in the environmental science, atmosphere, ocean, and climate science (compared to solid Earth science), there is reluctance for university departments to dedicate faculty lines to education research in these fields. The interdisciplinary nature of GER is also a challenge for many universities as it relates to tenure-track positions with the tenure process being either less clear or more onerous (O'Meara & Rice, 2005; Trower, 2008; O'Meara, 2010). Efforts and collaborations are underway in the social sciences to connect the research, application, and operation aspects of atmospheric sciences. The GER community could learn from this group as we develop and expand our community (Jacobs et al., 2005; Feldman & Ingram, 2009). Making the work of GER meaningful to faculty across the country can help broaden participation.

### Recommend Research Strategies

1. Information on the importance and relevancy of GER is critical to our ability to engage additional faculty in the GER community as well as institutionalize GER within the Earth and environmental sciences. The value of GER to the university community should be communicated in terms of the benefits to students, the individual institutions, and the disciplinary field. This would

contribute to growing the DBER/SoTL community within the fluid Earth disciplines. Resources like the GER Toolbox would be helpful for faculty who are interested in expanding their research into SoTL/DBER. Additionally, documenting and adapting lessons learned from partnerships between social scientists and operational scientists can inform the methods in which GER advocates for and informs faculty of research-based instruction. This in turn would generate interest in implementing research-based instructional strategies.

2. Grow the footprint of GER at professional society meetings and functions. The professional societies of NAGT, GSA and AGU have been important in the growth of the Earth science education research community. More engagement with NSTA and NARST would also help. Efforts should continue to link DBER who attend NAGT, GSA and AGU meetings with DBER working in the atmospheric and oceanic sciences. The AMS has a small group of atmospheric sciences education researchers not connected to the NAGT/GSA/AGU established communities. A presence of NAGT at the AMS Annual Meeting could engage those DBER who do not attend annual meetings of the GSA, AGU, or Earth Educator's Rendezvous.

3. Survey the entire atmospheric science community to assess their interest, support, value, and recognition of DBER/SoTL research and/or research-based teaching practices. This would provide useful information to better quantify the size of the DBER/SoTL community, and identify what kind of support there is within the broader community. The survey could be administered by AMS.

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# Figures

Figure 1.
**Provenance**: Skeptical Science Graphics by Skeptical Science, Retreieved from https://skepticalscience.com/graphics.php?g=78.

Figure 2:
**Provenance**: NOAA

Figure 3:
**Provenance**: NASA, Retrieved from https://www.nasa.gov/multimedia/guidelines/index.html

Figure 4:
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Figure 5.
**Provenance**: HHMI BioInteractive, Retrieved from https://www.hhmi.org/biointeractive/changing-planet-past-present-future