

Investigating Preservice Elementary Science Teachers' Understanding of Climate Change from a Computational Thinking Systems Perspective

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ABSTRACT

There is a need to approach environmental education (EE) topics, such as climate change, with a framework that productively reflects its inherent complexity. This study investigates how computational thinking (CT), specifically systems thinking (ST), may prepare educators to teach climate change. As scientists increasingly rely on computational techniques in their studies of complex EE topics, it is incumbent on science education to provide learners with computational thinking opportunities. We investigated how elementary preservice teachers (PSTs) in a science methods course ($N=35$) adapted a curricular resource on the climate change topic of sea level rise to integrate the CT practice of ST. Changes in their thinking were analyzed. Findings suggest that PSTs prior to instruction held a limited understanding of climate systems, often conflating weather and climate. Post instruction, their thinking expanded to consider the relationships between carbon dioxide, global warming, ice melt, and sea level rise. Further, many were able to describe these systems in a future EE teaching activity for young learners. A major implication was the need to develop a continuum of CT practices for elementary educators, with an emphasis on ST, for complex environmental education topics, that could frame their pedagogical thinking for climate change education.

Keywords: computational thinking, climate change, systems thinking, preservice teachers

INTRODUCTION

As the consequences worldwide of climate change become more apparent in learners' everyday lives, ranging from sea level rise to extreme weather (McGinnis, McDonald, Breslyn, & Hestness, 2017), the need for climate change education becomes more urgent. At the same time, technological advances have resulted in more powerful interactive tools, such as enhanced satellite imagery and monitoring, modeling and simulation software, and data sharing opportunities. These tools contribute to our expanding knowledge and ability to understand climate change, and to enable young learners to investigate and explore climate in new and engaging ways.

In the U.S., climate change is oftentimes viewed as a sensitive issue (McGinnis & McDonald, 2011) and has only recently been added to the voluntary national science education standards (Next Generation Science Standards Lead States, 2013). The standards also include computational thinking, strategies for organizing and searching data, creating algorithms, and using and developing simulations of systems. Climate change provides a productive context for the teaching and learning of computational thinking practices as described in the NGSS as well as standards and curricula in other countries.

While there are multiple definitions of computational thinking we are drawn to a succinct description of CT by Berland & Wilensky (2015) as "the ability to think with the computer-as-tool" and as consisting of four practices: data, modeling and simulation, computational problems solving, and systems thinking (ST) as described in a CT taxonomy for mathematics and science education by Weintrop, et al. (2016). The four practices in the taxonomy

Contribution of this paper to the literature

- Describes how the CT can support the development of PSTs' understanding and teaching of a complex environmental education topic.
- Provides a conceptual framework for incorporating CT, with an emphasis on systems thinking, into preservice elementary science teacher education.
- Explores the influence of systems thinking on PSTs' teaching intentions.

provide a way for science learners to investigate and make sense of the complex topic of climate change. Systems thinking, in particular, offers a productive approach to examine the interrelationships between humans and the natural world and the consequences of climate change.

Presently, however, there is a dearth of research on systems thinking in climate change education, especially at the elementary level. Indeed, CT at the elementary level has been viewed as consisting of skills and dispositions that do not include systems thinking (Barr & Stephenson, 2011; Stephenson & Barr, 2012; National Research Council, 2011).

Both climate change education and computational thinking are recent additions to the education community and much research remains to be done, especially in science teacher education (McGinnis, 2018). Little is known about how teachers adapt curriculum to incorporate computational thinking, especially systems thinking practices, with complex science topics such as climate change.

PURPOSE OF STUDY

Computational thinking has been proposed as an essential analytical ability, along with reading, writing, and analysis (Wing, 2006) and even a new form of literacy (deSessa, 2000; Wing, 2011). This creates an opportunity to address complex systems, like climate change, ecosystems, and environmental challenges, while allowing students to develop computational skills applicable to a wide variety of disciplines. Further, systems thinking and reasoning, a component of CT, is particularly suited to EE topics, and accessible to elementary age students (Hokayem & Gotwals, 2016). Preservice elementary teachers are an essential part of bringing this perspective into elementary schools and preparing students to continue their learning with complex topics in upper grades.

The goal of this study was to determine how preservice teachers (PSTs) learn about a complex EE topic like climate change, and how they planned to incorporate the topic in their own teaching, supported by a CT framework. Systems thinking, a component of CT, is particularly relevant to understanding and teaching climate change, and was the emphasis of this study. The research questions included:

1. *How does computational thinking, with an emphasis on systems thinking, support preservice elementary teachers' thinking about climate change, a complex environmental education topic?*
2. *How do preservice elementary teachers incorporate systems thinking in their proposed teaching of the environmental education topic of sea level rise?*

THEORETICAL FRAMEWORK

Our research is guided by a community of practice (CoP) framework (Lave & Wenger, 1991; Loughran, 2014; Parchmann et al., 2006). CoP seeks to gain insight into "elements that encourage teachers to change their practices, and more particularly, into the nature of teacher learning" (Loughran, 2014, p. 817). In our study, the PSTs, and ourselves as educators/researchers, were learning how to incorporate CT into environmental education, specifically, climate change education. Situated within an undergraduate methods course, as part of a four-year teacher education program, and located within the larger education community, PSTs are in the process of moving from peripheral towards more active participation in teaching as a profession.

In our study, PSTs were in their final year of teacher preparation and spent considerable time in the school environment, including preparing lessons and teaching students. With their increasing participation, our goal was to provide support to move them closer to fuller participation by developing their thinking and teaching about CT and complex systems. In doing so, our own understanding in this area was also developing as we participate in teaching and researching.

Situated in the context of an elementary science methods course in which the PSTs received instruction on integrating CT, we added a focus on computational thinking to provide a framework for teaching climate change to elementary students. Further, within the computational thinking framework, we focused on one component, systems thinking, as a tool to approach the teaching and learning of complex topics in science education.

Climate Change Education

Climate change is a complex topic consisting of multiple scientific, social, and political systems. With consensus among climate scientists that human-caused global warming is taking place (Cook et al., 2016), it is vital that students today develop an understanding of the mechanisms and consequences of climate change (Boon, 2010, Sharma, 2012). In the U.S., climate change is now included in the NGSS, although only overtly at the middle and high school levels. While this is an encouraging educational policy development, little time, an hour at most per year, (Plutzer et al., 2016) is typically spent on the topic in U.S. classrooms. Further, preservice and practicing teachers' own knowledge of climate change is often limited.

Shepardson, et al. (2009) investigated seventh grade students' conceptions of global warming and climate change and constructed a visual map to provide a holistic view of students' ideas. They extended their research to student understanding of climate as a system with a focus on human and nature systems and how they influence climate change (Shepardson, et al., 2012). McGinnis, McDonald, Breslyn, and Hestness (2017) addressed learners' developing understanding of climate change with a conditional LP that included the role of human activity, mechanisms, impacts, and mitigation and adaptation strategies for climate change.

To manage the complexity involved in teaching climate change, and to engage learners' interest by making the topic of personal and societal relevance, we decided to direct our efforts toward developing initial, hypothetical learning progressions for three of the major observable effects of climate change: Sea level rise (SLR); extreme weather; and the enhanced heat island effect (McGinnis, McDonald, Breslyn, & Hestness, 2017). Breslyn, McGinnis, McDonald, & Hestness (2016) then developed a conditionally validated learning progression for SLR with sixth grade middle school students. The LP focuses on student learning of four climate change constructs; human activity, mechanisms, consequences, and mitigation and adaptation. For each construct, four levels increasing in sophistication are presented to describe student understanding.

SLR represents a visible and understandable consequence of climate change. Previously in our research we developed curricular resources for SLR as part of the development of a learning progression. In our research we found SLR to reduce complexity by focusing on one visible and interrelated part of the climate change system.

Computation Thinking Frameworks

Many frameworks exist for CT in education; however, a consensus of what CT should consist does not exist (Atmatzidou & Demetriadis, 2016; National Research Council, 2010; Stephenson & Barr, 2012). Overall, most of the emphasis for CT has been on computer programming, although CT is also relevant to mathematics and science and becoming an area of interest in these disciplines. The current study is guided by CT frameworks relevant to mathematics and science proposed by Barr and Stephenson (2011) and by Weintrop, et al. (2016).

Barr & Stephenson (2011)

We were initially drawn to the work of Barr and Stevenson (2011) due to its focus on K-12 disciplines such as mathematics, science, and language arts. Developed through a consensus model of "thought leaders" in computational thinking and K-12 curriculum, they provide a description of CT concepts relevant to not only computer science, but other K-12 disciplines. These core CT concepts include data collection, data analysis, data representation, problem decomposition, abstraction, algorithm & procedures, automation, parallelization, and simulation.

Each concept is mapped onto a discipline and a brief representative example is provided. For science, the concept of *abstraction* could be to "build a model of a physical entity." For *parallelization*, "simultaneously run experiments with multiple parameters" and for *simulation* to "simulate movement of the solar system."

Defining CT in a manner that is relevant to other disciplinary contexts contributes to the ability of practicing teachers to understand and incorporate CT into their teaching. While examples are provided, we agree with Shute, Sun, and Asbell-Clarke (2017) that they are vague and do not provide sufficient guidance for practicing teachers. This is especially true in our context of working with elementary PSTs.

Problematic is that the framework does not suggest relationships between the CT concepts to be learned. Further, each concept is presented as a separate entity leading to a fragmented presentation of CT. This may be a result of negotiation during the consensus building process used to develop the framework. In this sense, the framework doesn't correspond with the type of science teaching PSTs in our study will experience as they transition from the university teacher education community of practice to the school community.

As we developed our climate change curriculum sessions for the science methods course it became evident that we needed a CT framework that reflected the complexity of the climate change topic. It needed to support accepted science teaching practices, be manageable for PSTs, and approach CC education with a CT perspective as Berland

and Wilensky (2015) described as “the ability to think with the computer-as-tool” (p. 630). We found the taxonomy developed by Weintrop, et al. (2016) to be supportive of this effort.

Weintrop et al. (2016)

In their taxonomy of CT practices, Weintrop et al. (2016) provide a framework that is specific to mathematics and science education. To develop the taxonomy, 34 high school science and mathematics lesson plans were analyzed. K-8 materials, as well as the CT extant literature, were also consulted in the development of the taxonomy (D. Weintrop, personal communication, September 6, 2018). Based on the analysis, CT practices were identified and placed in four categories; *Data, Modeling and Simulation, Computational Problems Solving, and Systems Thinking*. Each of the four categories is made up of individual CT practices such as Data Collection, Using Computational Models to Find and Test Solutions, or Troubleshooting and Debugging.

Currently the Weintrop et al. CT taxonomy for science and mathematics represents the most promising framework available for CT at the elementary level. While other frameworks exist, none focus specifically on science and math. With modification, we assert that the taxonomy can provide beneficial guidance at the elementary level for both educational research and in the training of undergraduate science methods PSTs.

Because the taxonomy is more oriented towards the research community with a focus on high school, there is a need to focus on select aspects to be developmentally appropriate in the elementary education context. Examples of modifications include providing age appropriate examples of CT and relevant science content, limiting the depth and complexity of CT practices, and allowing for the range of abilities present from early to upper elementary.

In the context of an undergraduate science methods course, the emphasis of the taxonomy on science and math is essential, grounding CT in the instructional context PSTs are learning to teach. The taxonomy has the added advantage of familiarizing PSTs with the type of thinking their students will be expected to undertake as they progress on to middle and high school.

In our elementary science methods when we turned our attention to preparing our PSTs to teach climate change, we began with a focus on the CT practices of data collection and analysis, looked at how modeling and simulation are based on data, and how the interrelationships between models can be used to investigate and understand complex systems such as climate change. Once our PSTs showed an understanding of and a confidence with these practices, we moved to a focus on ST. In their taxonomy, Weintrop, et al. identified five CT practices that make up the *Systems Thinking Practices* category. We provided our interpretation of each category as it applies to climate change and sea level rise, the complex science topic addressed in our study.

We based our research on the ST practices identified by Weintrop et al. while acknowledging that there are multiple definitions of such practices in the literature. These definitions vary based on the disciplinary context in which they are found and how they are measured. However, as we argued earlier, because the Weintrop et al. taxonomy was developed in the context of mathematics and science education, we found it to be relevant to our study of preparing teachers to teach a complex science topic (CT). A challenge we faced was that the data analyzed to develop the Weintrop et. al's taxonomy were from at the high school level whereas our present study took place at the elementary level. As a result, we needed to recognize and be sensitive to developmental learning issues associated with younger learners.

Researchers have suggested that systemic reasoning is appropriate for elementary students. For example, in a study of 1st through 4th grade students, Hokayem & Gotwals (2016) found that elementary students were able to systematically reason about the interactions in ecosystems. Further, younger students were found to be capable of simple causal reasoning. In a study of 4th grade students, Assaraf & Orion (2010) found most students were able to advance in their understanding of the components and processes of hydrological systems, as well as recognizing the interconnections between the components. Based on these findings, and the work of others (Evagorou et al., 2009; Hill & Redden, 1985), we decided that including a computational systems thinking perspective was worthwhile to attempt to study if it could be developmentally and pedagogically appropriate for PSTs in an elementary science methods course.

Based on the literature, our own examination of data collected that informed us of our teaching, and reactions of PSTs, we found the taxonomy proposed by Weintrop et al. to provide us with a viable theoretical and methodological framework. Our aim was to investigate PSTs' thinking about climate change and the teaching of it to elementary learners from a ST perspective as well as how they would incorporate developmentally appropriate computational systems thinking into their proposed teaching of an EE topic to young learners.

METHODS

To investigate our research questions, we studied a sample of preservice elementary teachers (N=35) in two science methods courses taught identically in the fall semester, 2017. The current study focuses on a two-week

segment on teaching a complex science topic, climate change, from a ST perspective (the lead instructor for the two-week segment was author one, assisted by author two, the primary instructor of the elementary course). In earlier investigations, we documented our efforts to prepare PSTs to teach climate change, but we did not take a CT perspective (McGinnis, Hestness, & Riedinger, 2011; Hestness, McGinnis, Riedinger, & Marbach-Ad, 2011). We first presented our pedagogical approach with a pilot section of the course ($N=17$) and then made modifications as needed to meet our instruction goals of our lessons and data collection instruments for the other two sections of the course ($N=35$). As a result, data from the separate section were not included in our analysis.

In this section we describe the context for the study, data collection and instrumentation, and discuss how we analyzed and interpreted data.

Participants

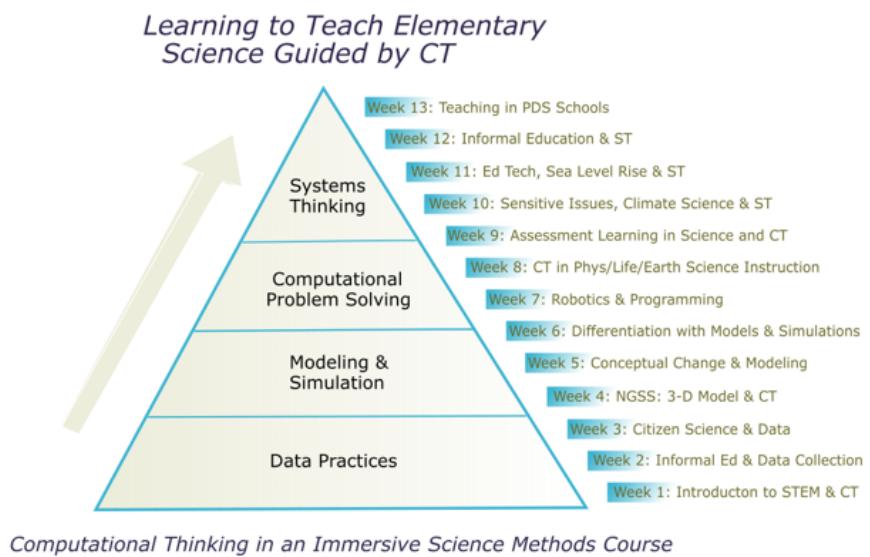
Participants were from of two sections of an undergraduate elementary science methods course. They were senior-level undergraduate students in their final year of the university's elementary teacher preparation program. Nearly all participants were women between the ages of 21-23 and were academically high performing. We did not collect data on participants' race/ethnicity; however, typically approximately 90% of the PSTs in the elementary education program were White.

During the thirteen-week semester, each week the participants took four three-credit courses (each class session extended for two hours and 45 minutes) and one one-credit classroom management seminar at the university spread out over two consecutive days. In addition, they spent the other three days of the week (8 a.m. to 3:30 p.m.) placed in a cooperating local elementary school with a mentor teacher. For three weeks of the semester, one in the first third of the semester and two consecutively at the end of the end of the semester, the participants spent the entire week at the cooperating school. During their initial teacher education program, the science methods course was their only exposure to learning how to teach science.

Elementary Science Methods Course

The semester-long course focused on the objectives, methods, materials, and activities for teaching science in the elementary school with an emphasis on evidence-based teaching strategies that prepare children to learn science. Field experience throughout the semester provides an opportunity to observe and practice these strategies in a local elementary school serving diverse populations of students.

Computational thinking served as the curricular framework for learning mainstream science education methods concepts such as the nature/epistemology of science, STEM education for all, conceptual change, learning progressions, science education policy, teaching in a hybrid manner, teaching sensitive/complex topics, and informal science education.



The course begins with Data Practices and culminates with System Thinking Practices (Weintrop, 2016). Week 10 and 11 were the focus of the current study where ST Practices were studied in the context of teaching climate change.

Instruments and Data Collection

To investigate PSTs' understanding of climate change from a computational thinking systems perspective, and their teaching intentions, we collected data at three key points, which are listed in **Table 1**.

Table 1. Instructional Activities and Data Collection

Activity	Description	Data Collection
Climate Change and CT (Week 10)	PSTs learn about assessment in the context of weather and climate change with an emphasis on the CT practice of systems thinking.	Data collected on PSTs understanding of various systems involved in climate change before and after instruction (online form completed in class).
Blended Learning, Sea Level Rise, and CT (Week 11)	PSTs continue with assessment and climate change with a focus on technology and blended learning. PSTs complete an online activity on sea level rise and how it will affect a geographic community using data and projections from the <i>Surging Seas</i> website (Climate Central, 2018).	Written responses submitted electronically as course assignment. PSTs describe the systems involved in sea level rise and explain how they would teach SLR and ST to upper-elementary students.
Follow-Up on Fossil Fuels and CC	PSTs (n=4) complete an optional online form with multiple choice items measuring their understanding of the connection between fossil fuels and climate change.	PSTs respond to questions from a previously validated instrument on climate change (online form).

After data collection and analysis, we identified a need to collect additional data to clarify PSTs' understanding of the role of fossil fuels in climate change. **Table 1** provides a description of each activity and data collected for the study.

Pre/Post PSTs' questions about systems involved in climate change

Prior to instruction, PSTs were asked to complete an online form about the systems involved in climate change. Rather than asking PSTs to list the systems they believed to be involved, they were asked to respond to the prompt:

List up to three science related questions you have about climate systems and climate change. This might involve the interrelationships between factors, how different factors affect each other, or connections between humans and climate change.

The intention of PST-generated questions was to avoid simple recall and elicit their thinking about connections between systems.

Instruction consisted of groups of two/three PSTs who were given several components of a climate system written on a puzzle piece cut from a sheet of poster paper. For example, how CO₂, trapped heat, and fossil fuels interact in the greenhouse effect or how mosquitos, global warming, and disease affect human health. Each group generated a diagram of their component on their puzzle piece. The pieces were then taped on the board at the front of the room to complete the puzzle.

As a class, the relationship between each groups' piece was discussed in relation to the others. The class then discussed how the activity could be used to help elementary students understand the relationships between systems in a complex topic like climate change.

After the activity, PSTs were asked to respond to the same question. Data were collected and coded for the number and type of systems in their pre and post responses. Based on initial codes, a codebook with examples was generated using data from the pilot section. Using the codebook, three researchers (the two authors and a recruited experienced qualitative data analyst) independently coded a subset of responses from the pilot course section. The independent interrater agreement was approximately 90%, with subsequent negotiation among the three raters resulting in over 95% agreement.

Systems thinking after investigating SLR online activity

After the introduction to systems thinking and climate change in Week 9, the following week PSTs engaged in instructional activities to extend their understanding of climate change and systems thinking practices. PSTs constructed a mental map based on interactive simulations from the Climate Time Machine (NASA, 2017) for global temperature, CO₂ concentrations, sea ice, and sea level rise.

While constructing their mental maps, two concurrent data collection activities took place. In the first, data were collected to demonstrate how ice melt led to increases in the water level in a container. In the second, data were collected on the expansion of water when heated with a sun lamp. Both activities were intended to both develop PSTs' SLR content knowledge and to demonstrate how data collection appropriate to elementary students could be conducted within a classroom.

After a discussion of their mental maps, they then received direct instruction on the relationship between increasing CO₂ concentrations and rising global temperatures and on systems thinking practices related to climate change.

After these activities PSTs spent approximately 45 to 60 minutes completing an online activity focused on one observable impact of climate change, sea level rise. The online activity, previously developed and tested (Breslyn, McGinnis, McDonald, & Hestness, 2016), introduced students to four aspects of sea level rise; human activity, mechanism, impacts, and mitigation and adaptation. A central feature of the activity involves using online simulations and GIS data to predict the impacts of rising seas. After completing the SLR activity PSTs responded to the following prompt:

Within the context of climate change, what systems/systems models do you now know inform a scientific understanding of sea level rise, and how would you use such models to teach upper elementary students how scientists think about the causes of sea level rise with an emphasis on systems thinking?

Using the instrument developed earlier, responses were coded and codes tabulated. While data were not collected prior to instruction for this prompt, the use of the same codes allowed for comparison with their responses in the previous section. PSTs' responses related to their teaching intentions were analyzed using a separate instrument.

Teaching SLR and climate change from a systems thinking perspective

Up to this point in climate change education, data collection focused on analyzing PSTs' content knowledge about climate change systems and their relationships. A next step was to collect data on PSTs' teaching intentions for climate change. Because they did not teach this topic at their cooperating school, the data represents their descriptions of how they intended to teach in the future when they were full time classroom teachers.

Data were coded based on the five system thinking practices identified by Weintrop (2016). These consist of *Investigating a Complex System as a Whole*, *Understanding the Relationships within a System*, *Thinking in Levels*, *Communicating Information about a System*, and *Defining Systems and Managing Complexity*. A codebook was developed and the first author coded the data. To ensure reliability, the data were cross-checked by a second coder (an experienced qualitative data analyst). Diverging items were discussed until agreement was reached. After clarification and modifications to the codebook the intercoder agreement reached above 95%. In addition, a third coder (the second author) coded a random selection of the data. The agreement among the three coders was above 95%.

PSTs' understanding of the role of fossil fuel use in CC

We identified during the data analysis that the PSTs did not include the role of fossil fuels in their discussion of the systems involved in climate change. It was also absent from their descriptions of teaching about SLR in the context of climate change and systems thinking practices.

To probe whether this was due to a lack of awareness of the relationships, or some other factor, a three-question instrument was administered to PSTs two months after the end of the course. Questions were taken from the Climate Science Knowledge Assessment Instrument (CSKAI), a valid and reliable instrument for assessing climate change knowledge (Drews, et al., 2017).

FINDINGS

In this section we report findings on PSTs' understanding of climate change from a systems thinking perspective as it developed during instruction, culminating with their explanation of how they intended in their future classroom practices to teach the topic to upper elementary students. Findings are first presented for PSTs' developing understanding of climate change and systems thinking and then on their teaching intentions.

Pre/Post PST Questions about Systems Involved in Climate Change

After the first class session for climate change education, PSTs' responses for the climate change and ST activity were coded and are reported in **Table 2**. For each code category, codes are tabulated for pre- and post-activity responses. Because the instrument was developed to analyze data for multiple datasets, some codes have zero responses. They are included here for consistency and comparison with data from the Sea Level Rise Online Activity in this study.

Table 2. Code Frequency for Pre and Post Data

			Impact of							
			Ice Melt	Humans/ Effect on Humans	Mitigate/ Reverse	Permafrost/ Methane	Sea Level	Earth Temp. Increase	Thermal Expansion (H ₂ O)	Weather (including hurricanes)
Biosphere, Atmosphere, Ecosystems Hydrosphere	GHE/CO ₂									
Pre	0	2	0	1	16	14	0	1	0	0
Post	7	1	13	0	11	7	5	1	0	4

Responses represent PSTs' questions about climate change and the systems involved. Their questions can be interpreted as how they think about climate change from a systems perspective. Questions require more thought than simple recall and provide more meaningful data to address our research questions.

The primary change in PSTs' questions before and after instruction was a shift from an emphasis on the relationship between weather and climate change towards the greenhouse effect and the role of greenhouse gases. For example, prior to instruction, a PST asked:

How does climate change affect hurricanes? How do scientists predict the severity of hurricanes? How do humans contribute to climate change?

After instruction, her questions reflect systems more directly related to climate change.

How does the climate change relate to the rise in sea level? How does human activities affect the greenhouse effect? What are some ideas for mitigation and adaption?

Similarly, another PST asked about natural disasters and weather prior to instruction:

1) *Why has the Earth experienced more severe natural disasters in recent years?*

2) *How has climate change impacted weather patterns?*

3) *What can we do to reduce the impact that climate change has on our weather?*

Afterwards her questions shifted from weather to the role of greenhouse gases and human health, indicating a more developed understanding of the climate change and the relationships between systems.

1) *How does human activity influence greenhouse gases?*

2) *What is the connection of greenhouse gases on climate change?*

3) *How will climate change impact human health?*

After instruction, PSTs also had fewer questions about how to prevent or mitigate climate change, as well as the relationships between climate change and humans. This may be due to their increased focus on the more mechanistic aspects of climate change or that their questions were addressed during instruction. Questions they had about the biosphere, atmosphere, and hydrosphere, as well as permafrost and methane, were likely due to these items being provided as examples during instruction.

Notably, PSTs did not include in their responses the role of fossil fuels or global warming in their pre or post questions. In addition, ice melt and sea level rise, two visible consequences of climate change, were seldom mentioned. This suggested that while PSTs shifted towards a more mechanistic view of climate change, involving CO₂ and the greenhouse effect, their view was still constrained and might not include key relationships between the systems involved in climate change.

Changes in Systems Thinking after SLR Online Activity

In the second class session for the climate change topic, PSTs had the opportunity to further develop their knowledge of climate change and ST practices, and to complete the SLR Online Activity. As a result, their responses were more representative of the scientific view of the systems involved in climate change and the relationships between systems.

Codes for each category were tabulated and are presented in **Table 2**. Coding was done with the same instrument used to analyze data in **Table 2**. This allowed for the comparison of both datasets.

After Session One, PSTs' thinking changed from viewing climate primarily as weather to focusing on GHG and CO₂. After the second session, which included the Sea Level Rise Online Activity, their understanding developed further to include global warming, ice melt, and sea level rise. In addition, weather was no longer present in their responses, suggesting they no longer considered it a primary component of climate change.

Of the 35 PSTs, 18/36 (51%) included four or more systems listed in **Table 3** in their responses and 11/35 (31%) had three systems. Only 6/35 (17%) of PSTs included fewer than three systems.

Table 3. Frequency of Codes for Systems in SLR Online Activity Responses

Bio/Atom/ Hydrosphere	Ecosystems	GHE/CO ₂	Ice Melt	Impact of		Permafrost/ Methane	Sea Level	Earth Temp. Increase	Thermal Expansion (H ₂ O)	Weather (including hurricanes)
				Humans/ Effect on Humans	Mitigate/ Reverse					
3	10	23	21	10	4	0	34	25	7	0

For example, a PST asked about the relationship between carbon dioxide, global warming, ice melt, and an increase in sea level.

Some systems that I learned about include carbon dioxide rising which makes the Earth warmer which causes ice forms to melt which can increase the sea level.

Likewise, the following PST also links carbon dioxide levels with increasing temperatures and sea level rise, but in a more direct, causal relationship.

For example, CO₂ affects the rising sea levels because as there is more CO₂ in the environment the temperature increases. As the temperature increases sea levels rise.

In addition, she listed several systems and includes models in her response.

As seen on the website that we used for todays exploration, sea ice, sea levels, carbon dioxide and global temperature are all models that inform our understanding of sea level rise.

I now know how to use models to show sea level rise as an interrelated issue that is caused by and that impacts many other systems. For example, global warming, global temperature, sea ice, greenhouse gases, carbon dioxide, and the sun are all parts of the environment that contribute to modeling why the sea level rises. Additionally, other systems on earth are influenced and impacted by sea level rise. Models should show the relationship into the water cycle, ecosystems, and climate systems.

The connection between CO₂ and the greenhouse effect, increasing temperatures on earth, ice melt, and sea level rise was frequently present in the PSTs responses and represented a major shift in their thinking about the systems involved in climate change. Of the 35 responses, 22 discussed the relationships between three or more systems.

Still absent from their responses was the relationship between fossil fuels and other drivers of climate change. While most, 23/35 (66%), included CO₂ or the Greenhouse Effect in their answer, and 25/35 (71%) rising temperatures on earth, there were no instances of fossil fuels in the data.

It may be that they expanded the boundaries of what they considered the climate system to include global warming, ice melt, and sea level rise but did not extend this to include the drivers of climate change.

As a result of their participation in instructional activities, PSTs increased their understanding of climate change and the relationships that exist earth systems affecting climate. Coupled with the science teaching pedagogy in the methods course, PSTs were asked to explain how they would teach sea level rise from a systems thinking perspective.

Teaching SLR and Climate Change from a Systems Thinking Perspective

After completing the SLR Online Activity PSTs' responses were coded using a taxonomy proposed by Weintrop (2016) for the presence of ST practices. In **Table 4**, each code category represents a systems thinking practice and includes our interpretation of the practice in the context of this study. The total below each column indicates the number of PSTs including their practice in their response.

Table 4. Systems Thinking Practices in PSTs' Responses

Investigating a Complex System as a Whole	Understanding the Relationships within a System	Thinking in Levels	Communicating Information about a System	Defining Systems and Managing Complexity
<i>In their teaching, PSTs address either major inputs or outputs of the climate system with an emphasis on SLR. Examples of inputs include deforestation, fossil fuel use, and release of other greenhouse gases. Outputs include the impacts on humans and ecosystems from climate change and SLR. Inclusion of migration/adaptation to climate change and sea level rise is also represented by this category.</i>	<i>In their teaching, PSTs describe how the interactions between systems occur. Examples include CO₂ causing warming, warming causing ice melt (or thermal expansion), ice melt and thermal expansion causing sea levels to rise. Connections between humans and ecosystems and sea level rise also should be counted. This code represents the mechanistic aspects of climate change and SLR whereas Investigating a Complex System as a Whole represents the drivers and impacts.</i>	<i>PSTs approach climate change and sea level rise on several levels. For example, a micro level addressing the actions of individuals connecting to a macro level of increasing CO₂ concentrations and global warming. A further example would be teaching the micro level of the behavior of atoms leading to the thermal expansion of water and rising sea levels. Stating "thinking in levels" without providing an example does not constitute this code category.</i>	<i>PSTs provide opportunities for students to communicate their ideas about the systems involved in climate change and sea level rise and how these systems interact. Examples include creating visualizations, infographics, written works, or concept maps. It may also involve group and class discussions about sea level rise, the systems involved, and how the systems are related. Discussion should include student generated artifacts, research, or ideas from teaching activities.</i>	<i>PSTs provide opportunities for students to define the extent of the climate and sea level rise systems. PSTs actively participate in defining the boundaries of what to include (e.g., human activity, thermal expansion of water, etc.) and what can be excluded while still having a useful system/system model.</i>
Total: 20	Total: 30	Total: 0	Total: 8	Total: 0

These findings show that describing how to teach a complex topic from a ST perspective that goes beyond considering it as a whole and as parts (our first two categories) represented a challenge for the PSTs. We found some evidence that by including opportunities in our instruction for PSTs to communicate information about the system some PSTs were able to enhance their thinking about the climate change system to include that category. For the two categories *Thinking in Levels* and *Defining Systems and Managing Complexity*, no instances were identified in the data.

Each category, along with sample resident responses and our interpretation, is presented below.

Investigating a complex system as a whole

This category represents the inputs and outputs of the climate system and how they are incorporated in PSTs' teaching intentions. As found throughout the data in this study, PSTs did not identify fossil fuel use as the primary input driving climate change. Several did, however, list human activity as an input but did not specify, or were vague, about the nature of the activities.

For example, PSTs wrote:

We could then wrap up with discussions of what we can do as a class to ensure we are positively impacting rather than contributing to these systems.

We can create our own model that connects these systems into one larger system (ex. one big train cause-and-effect model, what is driving the train, what components play a factor? Where is the train headed? How do people play a role?)

We could then brainstorm how to reduce this effect by reducing negative impacts of specific systems, that would then impact the greater system as a whole because its all connected.

Most PSTs focused on the impacts of climate change on humans and ecosystems as an output of climate change.

... we could discuss the impact the system has on them and the world around them. For example, the sea level rising directly affects the biosphere and the ecosystems for living organisms near water.

It would be a thought provoking experience to have them brainstorm how climate change will be impacting other systems such as human safety, economic activity, and ecosystems.

Therefore, while 20 PSTs were coded for this category, only three discussed inputs leading to climate change. It is possible that PSTs considered the outputs to be of greater interest and more easily understood by elementary age students. The nature of the SLR Online Activity may have also influenced their responses and led to an emphasis on the outputs rather than the drivers of climate change. However, the inclusion of relationships between CO₂, global warming, and ice melt suggests that PSTs have a broad understanding of climate change and view these systems as important to teach. Therefore, it seems likely they would also include fossil fuel use as an important driver of climate change.

One additional possibility is that PSTs intended to teach about the drivers of climate change in a separate lesson although there is no data to support this assertion.

Understanding the relationships within a system

Of the five categories representing PSTs' teaching intentions, *Understanding the Relationships within a System* was the most frequently coded. Most PSTs (30/35, 86%) described the relationship between two or more systems in their response. Over half (22/35, 63%) included three or more systems.

For example, in describing how they would teach about sea level rise, a PST stated:

I would then show them the maps of how overtime the global temperature increases, as does the rising sea level, and sea ice melting. I would finally show the CO₂ map and explain the greenhouse effect and how it relates to increased temperature...

In her response she describes using maps of global temperature, sea level, and CO₂ to show key relationships. Although she does not explicitly describe the relationships, she does state her intention to link CO₂, the greenhouse effect, and increasing temperature.

A different PST also provided students with representations to show the relationship between CO₂, temperature, and sea level rise.

Once watching each of the visuals, sea level rise, sea ice, carbon dioxide, and global temperature, we would notice how they each interconnect.

Additionally, the following PST had students more actively involved in researching the systems involved in sea level rise, including discussion of mitigation strategies.

After students research, we would come back together to share as a class. We would connect the systems back to climate change and the rising sea levels. I think it is also important to discuss possible solutions and necessary actions that should be taken in order to combat the changes going on in our planet.

In most cases, PSTs' responses included components of the activities they experienced during the two climate change implementation class sessions in the science methods course. For almost all, this was the first formal instruction they received on climate change. Coupled with their limited teaching experience and modest time available (about one hour to complete the SLR Online Activity), these responses suggested that for some PSTs a ST perspective on understanding the relationship may have started to develop.

Thinking in levels

There were no instances of PSTs describing how they would teach the systems thinking practice of *Thinking in Levels*. This is likely due to several factors. First, we did not emphasize this practice in the science methods course due to time constraints and due to the PSTs' limited, but growing, scientific understanding of climate change. Elementary-age students' ability to understand abstract representations, such as the atomic/molecular level, may have also resulted in the absence of this practice in PSTs' response.

Mitigation strategies at an individual and a larger societal level would constitute *Thinking in Levels*. However, an explicit link between the individual's actions and a larger societal impact would be necessary to be coded for this practice. For example, a response such as "as a class we could look at reducing our carbon footprint and encourage others to do so in order to reduce the amount of CO₂ in the atmosphere" would be coded as *Thinking in Levels*. PSTs responses did not exist or were too vague to be coded for this practice.

Communicating information about a system

In their responses, a total of eight PSTs included the practice of *Communicating Information about a System* appropriate to an elementary school context. For example, in a PST response, students research information and then communicate their findings to the class:

After students research, we would come back together to share as a class. We would connect the systems back to climate change and the rising sea levels ... discuss possible solutions and necessary actions that should be taken in order to combat the changes going on in our planet.

As seen in the above response, this category goes beyond class discussion and involves students in generating the content to be communicated. Other examples are student-generated graphs or flowcharts of the systems involved.

We would have a discussion on how the [student-generated] graphs look similar in their rate of change and what systems/systems models effect sea level rise.

A flow chart with the systems could also be created by students to show a connection and how students are and will continue to be affected by these systems.

While the number of PSTs including this practice was limited (8/35), this may be due to the amount of class time available to compose their responses or the nature of the activity which emphasized SLR and the systems involved. It is encouraging, though, that some PSTs did include the practice and began to develop this thinking.

Defining systems and managing complexity

There were no instances of this practice in PSTs' responses, likely because it was not emphasized in our instruction. In addition, at the elementary level, PSTs may see it as their role to manage complexity for students, especially with a topic like climate change. They therefore do not consider involving students in defining systems and managing complexity.

Returning to the absence of fossil fuels in PSTs' responses, it may be that they were defining the boundaries of the systems involved and managing complexity for their students. Even our own selection of SLR as a focal system was an attempt at managing the complex and varied systems involved in climate change for PSTs.

Follow-up data collection to probe PSTs' understanding of the relationship between fossil fuel use and CC

During data analysis we found that PSTs did not include the relationship between fossil fuels and climate change in their responses. Since fossil fuel use is a major driver of climate change we selected a subset of the PSTs to represent the range of responses of those who contributed to other data collection strategies used in the study. Data were collected from four PSTs using selected questions from the CSKAI (Drewes, et al., 2017) to gain a sense of PSTs' understanding of the role of fossil fuels in climate change, in addition, we asked PSTs for their interpretation of why fossil fuels were not included in resident responses. In **Table 5**, results from each multiple-choice question are presented.

Table 5. Responses to Select Climate Science Knowledge Assessment Instrument (CSKAI) Questions

Question	Responses			
1. There is strong evidence that there is more carbon dioxide (CO_2) in the atmosphere now than in the past several hundred years. What is most likely cause of the current increase in carbon dioxide?	0%	25%	0%	75%
	A. There's more toxic chemicals in the oceans and rivers.	B. Plants are releasing more CO_2 (carbon dioxide).	C. Volcanoes are producing more ash and gases.	*D. Humans are using more fossil fuels.
	0%	100%	0%	0%
2. Scientists believe that global temperatures are rising primarily because of:	A. an increase in the use of toxic chemicals such as pesticides and aerosols sprays.	*B. increases in the amount of carbon dioxide (CO_2) from burning fossil fuels.	C. a hole in the ozone layer allowing heat to enter the earth's atmosphere.	D. excess heat given off from energy generation in nuclear power plants.
	0%	25%	0%	75%
3. How is CO_2 (carbon dioxide) removed from the atmosphere?	A. Factories need carbon dioxide to run.	B. Carbon dioxide breaks down naturally.	C. Carbon dioxide escapes into space.	*D. Plants absorb carbon dioxide for food.
	0%	0%	100%	0%
4. Energy can be obtained from different sources. Which of the following forms of energy production releases the most carbon dioxide (CO_2) into the atmosphere?	A. Nuclear plants	B. Windmills	*C. Oil and coal	D. Solar power

The PSTs' responses to the selected CSKAI questions indicated they understand the connection between the use of fossil fuels, CO_2 , and global warming (Question #2). They also knew that oil and coal are sources of fossil fuels (Question #4). Most knew that plants remove carbon dioxide from the atmosphere (Question #3), suggesting that our participating PSTs had a basis for relating vegetation and the amount of atmospheric CO_2 . Intriguingly, one PST responded that the cause of the increase of CO_2 is due to plants releasing more CO_2 (Question 1), indicating possible confusion by our PSTs about the role of plants and climate change for this PST. Overall, the data indicated that PSTs understood the role of fossil fuels and did not include it in their responses for some other reason.

When asked why they thought they and the other PSTs did not include fossil fuels in their response to the SLR Online Activity, the four PSTs provided differing, and revealing, explanations. This included the political aspects of the teaching climate change (*Politicization of scientific findings and the models that we have seen are not easy to understand in reference to the history of climate prior to humans having the capability to track it back.*), teachers lacking prior instruction (*growing up they were never taught it*), the nature of the SLR Online Activity limited what they included in their proposed teaching of SLR (*Maybe I would do a little more on fossil fuels in the beginning, then still have a central focus on sea level rise*), and other issues competing for their attention (*It could be that people are just ego centric. ... There are many important issues to worry about. It's hard to think deeply about all.*)

DISCUSSION

Based on our experience developing and teaching an undergraduate elementary science methods course with the NGSS Core Science and Engineering Practice of “Using Mathematics and Computational Thinking” as our guiding framework, we believe the practice of ST can offer some major advantages if it is used to demonstrate how to teach complex environmental education topics such as climate change. Such a radical transformation of the elementary science methods course for preservice teachers requires a commitment to significantly rethink how to organize and present the curriculum in a science methods course. Overall, we assert that it is beneficial to incorporate CT to meaningfully enact the NGSS as well as to prepare young learners with the expected disciplinary core knowledge, practices, and cross cutting concepts that apply across a wide range of disciplines involving computation.

One challenge in our research was whether PSTs began to think about climate change through a systems perspective. Krathwohl (2002) differentiated between factual, conceptual procedural, and metacognitive in his taxonomy of thinking/learning. PSTs in our study expanded their factual knowledge, as well as their conceptual understanding of climate systems.

To differentiate between ST and conceptual knowledge we used the Weintrop framework for computational thinking. In doing so we built upon an established definition for ST which guided our instrument development and provided a framework for analyzing data.

For ST, even in a relatively short timeframe of a single science methods course, our PSTs developed a basic understanding for ST as a framework to understand and teach complex topics. Most went from being able to list only a few disparate elements of the climate system, to making causal connections between greenhouse gases, increasing global temperature, ice melt, and sea level rise. After instruction, 29/35 (83%) included three or more systems in their responses after the SLR Online Activity. Further, most PSTs were able to describe how they could apply this new knowledge to a classroom setting in discussing how they would teach SLR, with 30/35 (86%) coded for including the practice *Understanding the Relationships within a System* and 20/35 (57%) for *Investigating a Complex System as a Whole*. These findings were encouraging and suggested that ST could serve as an organizing framework for more connected and in-depth instruction on complex environmental topics.

For a topic like climate change, ST has the potential to support future elementary teachers to understand and teach climate change, and other complex topics in the NGSS, that reflects its complexity. Especially at the elementary level, where science is often underemphasized and when taught focuses on a transfer of a body of information (Banilower et al., 2013), understanding how topics are interrelated is essential to prepare elementary students for middle and high school science learning.

A ST perspective also supports how elementary PSTs plan instruction and identify the essential interrelationships between the elements of a system. For climate change education, this allows for learning about the individual elements, such as the greenhouse effect or sea level rise, in the context of the larger climate system. We found sea level rise to be a productive means to address essential climate elements such as carbon dioxide, global warming, and ice melt while providing a visible and relevant consequence of climate change.

Sea Level Rise as a Focal System Element

It has been suggested that climate change is too complex for even middle school students to approach from a ST perspective (Roychoudhury, Shepardson, & Hirsch 2016). Based on our experiences with elementary PSTs, and findings from research with elementary students (Assaraf & Orion, 2010; Evagorou et al., 2009, Hoykeyum & Gotwals, 2016), we believe that ST is possible to developmentally approach at the elementary level. However, a caveat is that context and depth must be managed. One solution we found is to focus first on a consequence of climate change and relate it to the larger system.

In our research we chose SLR due to its geographic relevance to the PSTs in our science methods course. SLR is also a visible and conceptually accessible element of climate change and therefore appropriate for the elementary level. We also have expertise in this construct (Breslyn, McGinnis, McDonald, & Hestness, 2016). The benefit of working with SLR was that we were able to model a number of science teaching practices, such as physical demonstrations with data collection and analysis, checking for understanding, interactive tools to visualize the phenomena, and class discussion. Building on these ideas it was then possible to relate SLR to other climate topics such as atmospheric CO₂ concentrations, global warming, and ice melt, as well as social consequences.

One unexpected result, however, of selecting SLR, a macroscopic effect of CC, as the focal instructional activity was that the PSTs did not voluntarily mention when asked to discuss drivers of climate change the crucial role CO₂ plays in human-enhanced climate change. In a follow-up member check, PSTs provided a variety of reasons for the omission of fossil fuels as a driver of CC, including their perceived political view of the nature of climate change, time, and lack of understanding of the mechanism of climate science. This points to the imperative need to

emphasize the inputs and drivers of climate change as well addressing other concerns PSTs may have. It also highlights the value of having an appropriate CT framework to guide planning and instruction. In our case, spending more time on the CT practice of *Understanding Complex Systems as a Whole* (Weintrop, et al., 2016) may have led to the inclusion of climate change drivers such as fossil fuels or deforestation.

A Conceptual Model for CT in Elementary Science Education

In the context of elementary preservice teacher preparation, we found the taxonomy developed by Weintrop et al. (2016) to be appropriate and generative for our PSTs. The taxonomy includes practices that support what we see as science teaching that authentically reflects throughout the K-12 continuum how science is practiced and is represented by the core practices in the NGSS. This includes data collection, analysis, and representation, modeling and simulation, use of technology, and systems thinking.

Since the taxonomy was primarily developed for the high school level, there are several modifications that are necessary for the elementary context. First, we see advantages in viewing Weintrop et al.'s CT taxonomy as increasing in complexity across the practices, rather than separate categories. Viewed as a continuum of interrelated practices, students engage with data collection and representations, use models and simulations based on data, and finally connect the models in a larger system. Second, *Computational Problem Solving* practices are not seen as a separate category, but rather, represent the tools that learners use to engage in CT and science. These tools support learning throughout the practices. In [Figure 1](#) we present our conceptual model for CT at the elementary level.

Computational Thinking Practices Continuum

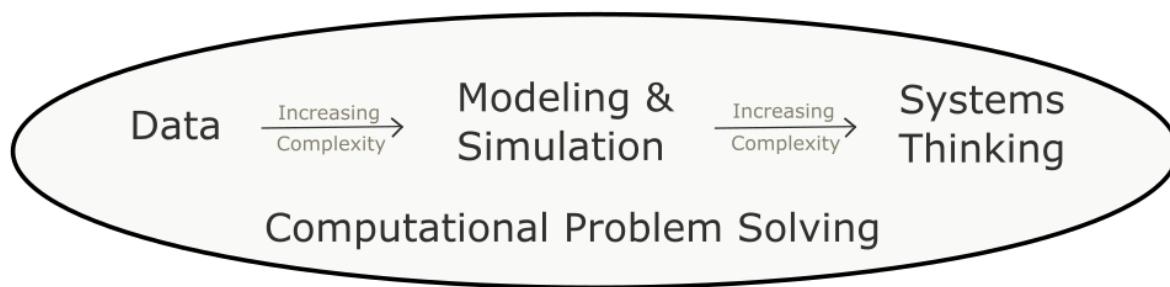


Figure 1. Computational Thinking as a Continuum of Practices

At the elementary level, we speculate that if *Computational Problem Solving* is considered as an opportunity to represent the tools and techniques used in *Data*, *Modeling and Simulation*, and *ST* practices, it would be developmentally appropriate. By doing so, teachers would prepare young learners to engage first with *Computational Problem Solving* in a tangible manner with engaging educational tools such as developmentally designed robots, which would prepare them to engage in a more conceptually and technical manner with the core practice in middle school science and beyond.

The SLR Online Activity in this study illustrates an enactment of the conceptual model in [Figure 1](#). PSTs started by collecting and graphing data about ice melt and thermal expansion. They then used interactive models based on global SLR datasets to visualize local increases in sea level. Finally, they placed SLR in the larger context of climate change (human activity, atmospheric CO₂ concentrations, global warming, and ice melt). Throughout the activity PSTs used computational tools, such as software to organize and visually represent data, models and simulations to predict the impacts of sea level rise, and flowcharts and mental mapping to explore the relationships between sea level rise and other elements in the climate system.

Our conceptual model in [Figure 1](#) therefore should be most productively considered as an organizational tool for elementary teachers to think about CT and student learning in science. It offers a way for PSTs to conceptualize CT in their elementary science classrooms and comprehensively plan instruction with a goal of guiding students towards a ST perspective. We believe that a CT perspective is productive for learners to start developing early and throughout their K-12 science education, so they may be prepared to scientifically make sense of the dynamic and interconnected nature of complex topics such as climate change.

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REFERENCES

- Assaraf, O. B.-Z., & Orion, N. (2010). System thinking skills at the elementary school level. *Journal of Research in Science Teaching*, 47(5), 540–563. <http://doi.org/10.1002/tea.20351>
- Atmatzidou, S., & Demetriadis, S. (2016). Advancing students' computational thinking skills through educational robotics: A study on age and gender relevant differences. *Robotics and Autonomous Systems*, 75, 661–670. <https://doi.org/10.1016/j.robot.2015.10.008>
- Banilower, E. R., Smith, P. S., Weiss, I. R., Malzahn, K. A., Campbell, K. M., & Weis, A. M. (2013). Report of the 2012 National Survey of Science and Mathematics Education. *Horizon Research, Inc. (NJ1)*.
- Barr, V., & Stephenson, C. (2011). Bringing computational thinking to K-12: What is Involved and what is the role of the computer science education community? *ACM Inroads*, 2(1), 48-54. <https://doi.org/10.1145/1929887.1929905>
- Berland, M., & Wilensky, U. (2015). Comparing virtual and physical robotics environments for supporting complex systems and computational thinking. *Journal of Science Education and Technology*, 24(5), 628-647. <https://doi.org/10.1007/s10956-015-9552-x>
- Breslyn, W., Drewes, A., McGinnis, J. R., Hestness, E., & Mouza, C. (2017). Development of an Empirically-Based Conditional Learning Progression for Climate Change. *Science Education International*, 28(3), 214–223.
- Breslyn, W., McGinnis, J. R., McDonald, R. C., & Hestness, E. (2016). Developing a learning progression for sea level rise, a major impact of climate change. *Journal of Research in Science Teaching*, 53(10), 1471–1499. <https://doi.org/10.1002/tea.21333>
- Climate Central (2018). [Interactive Map of Sea Level Rise Projection Based on Geographic Area]. Surging Seas: Mapping Choices. Retrieved from <http://sealevel.climatecentral.org/>
- Cook, J., Oreskes, N., Doran, P. T., Anderegg, W. R., Verheggen, B., Maibach, E. W., ... Green, S. A. (2016). Consensus on consensus: A synthesis of consensus estimates on human-caused global warming. *Environmental Research Letters*, 11(4), 048002. <https://doi.org/10.1088/1748-9326/11/4/048002>
- DiSessa, A. A. (2000). *Changing minds: Computers, learning, and literacy*. MIT Press.
- Drewes, A., Breslyn, W., McGinnis, R., Mouza, C., Hestness, E., & Henderson, J. (2017). *Designing and Validating a Climate Change Knowledge Instrument*. San Antonio, TX: Proposal Presented at American Educational Research Association Annual Conference.
- Evagorou, M., Korfiatis, K., Nicolaou, C., & Constantinou, C. (2009). An investigation of the potential of interactive simulations for developing system thinking skills in elementary school: a case study with fifth-graders and sixth-graders. *International Journal of Science Education*, 31(5), 655–674. <https://doi.org/10.1080/09500690701749313>
- Hestness, E. McGinnis, J. R., Riedinger, K., & Marbach-Ad, G. (2011). A study of teacher candidates' experiences investigating global climate change education within an elementary science methods course. *Journal of Science Teacher Education*, 22, 351-369. <https://doi.org/10.1007/s10972-011-9234-3>
- Hill, D., & Redden, M. (1985). An investigation of the system concept. *School Science and Mathematics*, 85, 233–239. <https://doi.org/10.1111/j.1949-8594.1985.tb09616.x>
- Hokayem, H., & Gotwals, A. W. (2016). Early elementary students' understanding of complex ecosystems: A learning progression approach. *Journal of Research in Science Teaching*, 53(10), 1524–1545. <https://doi.org/10.1002/tea.21336>
- Krathwohl, D. R. (2002). A revision of Bloom's taxonomy: An overview. *Theory into practice*, 41(4), 212-218. https://doi.org/10.1207/s15430421tip4104_2
- Lave, J., & Wenger, E. (1991). *Situated learning: Legitimate peripheral participation*. Cambridge University Press. <https://doi.org/10.1017/CBO9780511815355>
- Loughran, J. (2014). Developing understandings of practice: Science teacher learning. *Handbook of Research on Science Education*, 2, 811–829. <https://doi.org/10.4324/9780203097267.ch40>
- McGinnis, J. R. & McDonald, C. (2011). Controversial or sensitive topics in science education: A Literature Review. University of Maryland MADE CLEAR Climate Change Learning Sciences Research Team. Retrieved on

September 22, 2018 from <http://www.climateedresearch.org/publications/2012/Lit%20Review-on-Controversial-Topics.pdf>

- McGinnis, J. R. (2018, March). Climate change education: What do we know and how might that assist the science classroom teacher? A keynote presented at Paleoscience Day, Smithsonian National Museum of Natural History, Washington, DC. Retrieved on September 6, 2018 from www.climateedresearch.org/smithsonian/McGinnisTalkClimateChangeEducationFINAL3.28.18.pdf
- McGinnis, J. R., Hestness, E., & Riedinger, K. (2011). Changing science teacher education in a changing global climate: Telling a new story. In Jing Ling and R. Oxford (Eds.), *Transformative Eco-Education for Human Survival: Environmental Education in A New Era* (pp. 117-133). Charlotte, North Carolina: Information Age Publishing.
- McGinnis, J. R., McDonald, C., Breslyn, W. & Hestness, E. (March, 2017). Supporting the inclusion of climate change in U.S. science education curricula by use of learning progressions. In D. Shepardson, A. Roychoudhury & A. Hirsch (Eds), *Teaching and Learning about Climate Change: A Framework for Educators*, pp. 135-151. Routledge, New York. <https://doi.org/10.4324/9781315629841>
- National Research Council. (2010). *Report of a workshop on the scope and nature of computational thinking*. Washington, DC: National Academies Press. <https://doi.org/10.17226/12840>
- National Research Council. (2011). *Report of a Workshop on the Pedagogical Aspects of Computational Thinking*. National Academies Press. <https://doi.org/10.17226/13170>
- Next Generation Science Standards Lead States. (2013). *Next generation science standards: For states, by states*. Washington, DC: The National Academies Press. <https://doi.org/10.17226/18290>
- Parchmann, I., Gräsel, C., Baer, A., Nentwig, P., Demuth, R., & Ralle, B. (2006). "Chemie im Kontext": A symbiotic implementation of a context-based teaching and learning approach. *International Journal of Science Education*, 28(9), 1041-1062. <https://doi.org/10.1080/09500690600702512>
- Plutzer, E., McCaffrey, M., Hannah, A. L., Rosenau, J., Berbeco, M., & Reid, A. H. (2016). Climate confusion among US teachers. *Science*, 351(6274), 664-665. <https://doi.org/10.1126/science.aab3907>
- Roychoudhury, A., Shepardson, D. P., Hirsch, A., Niyogi, D., Mehta, J., & Top, S. (2017). The need to introduce system thinking in teaching climate change. *Science Educator*, 25(2), 73.
- Sharma, A. (2012). Global climate change: What has science education got to do with it? *Science & Education*, 21(1), 33-53. <https://doi.org/10.1007/s11191-011-9372-1>
- Shepardson, D. P., Niyogi, D., Choi, S., & Charusombat, U. (2009). Seventh grade students' conceptions of global warming and climate change. *Environmental Education Research*, 15(5), 549-570. <https://doi.org/10.1080/13504620903114592>
- Shepardson, D. P., Niyogi, D., Roychoudhury, A., & Hirsch, A. (2012). Conceptualizing climate change in the context of a climate system: Implications for climate and environmental education. *Environmental Education Research*, 18(3), 323-352. <https://doi.org/10.1080/13504622.2011.622839>
- Shute, V. J., Sun, C., & Asbell-Clarke, J. (2017). Demystifying computational thinking. *Educational Research Review*. <https://doi.org/10.1016/j.edurev.2017.09.003>
- Stephenson, C., & Barr, V (2012). *Defining Computational Thinking for K-12*. In Computer Science Teachers Association (CSTA) and Association for Computing Machinery (ACM): *Computer Science K-8: Building a Strong Foundation*. CSTA & ACM: New York.
- Weintrop, D., Beheshti, E., Horn, M., Orton, K., Jona, K., Trouille, L., & Wilensky, U. (2016). Defining computational thinking for mathematics and science classrooms. *Journal of Science Education and Technology*, 25(1), 127-147. <https://doi.org/10.1007/s10956-015-9581-5>
- Wing, J. (2011). Research notebook: Computational thinking—What and why? The Link Newsletter, 6, 1-32. Retrieved from http://link.cs.cmu.edu/files/11-399_The_Link_Newsletter-3.pdf
- Wing, J. M. (2006). Computational thinking. *Communications of the ACM*, 49(3), 33-35. <https://doi.org/10.1145/1118178.1118215>