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The Need to Introduce System Thinking in Teaching Climate Change

Abstract

Research related to teaching climate change, system thinking, current reform in science education, and the research on reform-oriented assessment indicate that we need to explore student understanding in greater detail instead of only testing for an incremental gain in disciplinary knowledge. Using open-ended items we assessed details in student successes and challenges in thinking about climate change and climate system. Twelve teachers of the 7th and 8th grades and 457 students from four schools in a Midwestern state participated in this study. Statistical analysis of student responses on the pre- and post-test showed a significant ($p<.0001$) gain in knowledge but more importantly, qualitative analysis of student responses showed that they learned that our climate is changing but had constructed a linear connection between variables such as surface temperature and drought. The students did not develop a connected body of knowledge or an understanding of climate as a system. Future research needs to focus on curriculum development, effective system pedagogy, assessment, and teacher development in the context of climate change as an interlinked system.

Keywords: system thinking, climate change, teaching

Introduction

Scientists are unequivocal about the impact of climate change on nature and living organisms (IPCC, 2013). Yet, the public and media appear to believe that it is a controversial issue because they perceive that scientists are not yet convinced of it (Reardon, 2011); even some teachers believe it to be a debatable issue (Wise, 2010). This scientific topic is frequently viewed through the lenses of political and business interests and its inclusion in school curriculum sometimes becomes a subject of debate (Hesteness et al., 2014). On the other hand, current reforms in science education as described by *A Framework for K-12 Science Education* (NRC, 2012) and the *Next Generation Science Standards (NGSS)* (Achieve, 2013) recommend that all students from middle school onwards should understand the causes, effects, and methods of mitigating climate change.

There is a large body of research on student misconceptions about climate change and related concepts (e.g., Andersson & Wallin, 2000; McCuin et al., 2014; Osterlind, 2005; Rye et al., 1997; Shepardson et al., 2009); however, there are few studies on the teaching of the topic. Even less is known about what students know in regard to climate as a system and how student knowledge can inform curriculum development and teaching. In the following sections we review the research on student misconceptions, teaching climate change, and system thinking. Based on these reviews, we developed the research questions that framed the current study.

Findings from Relevant Research

Research on Student Misconceptions and Teaching

Climate change, undoubtedly, is an important global issue of our time but there are a plethora of misconceptions held by students and adults. Many researchers have studied students' understanding and beliefs about the greenhouse effect and climate change. Due to space limitations, we provide only a brief summary of the key findings in this area (see Shepardson, Niyogi, Choi, & Charusombat, 2009 and McCuin et al., 2014 for a detailed summary of misconceptions about climate change). Most of the studies examined secondary students' understanding of climate change. Students think pollution and the ozone hole cause global warming; some middle school students think that carbon dioxide causes ozone depletion that in turn causes global warming (Rye et al., 1997). Cordero and his colleagues (2008) found similar ideas among undergraduate students. Other researchers found that students believe that greenhouse gases constitute a layer or a roof that bounces "heat" back to the earth (Andersson & Wallin, 2000; Shepardson et al., 2009; Osterlind, 2005). Students also think of global warming as a change in temperature and mostly ignore its relationship to precipitation (Shepardson et al., 2009; Kilinc, Stanisstreet, & Boyes, 2008). They do not consider the varied effects of global warming at different geographic locations in the United States or the world (Boyes & Stanisstreet 1993). Only a few studies (Gowda, Fox, & Magelky 1997; Pruneau et al., 2003) have explored student understanding of the distinction between weather and climate, even though this concept is fundamental to understanding climate change. These studies showed that students fail to understand climate as a long term (over decades) average of meteorological patterns, which implies that these students are unlikely to understand that changes in climate happen over decades, that climate change cannot be directly experienced as weather and that mitigation would take a long time before its benefits could be observed.

Research on Teaching Climate Change

It is essential that students understand climate change and be able to make informed decisions about this issue and its impact on society, both locally and globally. Research on teaching climate change, curricular development, teacher professional development, and student learning is beginning to emerge. Several studies report student knowledge gain as a result of teaching specific concepts regarding climate change and addressing common misconceptions. McCuin et al. (2014) compared the pre-, post-, and delayed (by two weeks) post-test scores of 197 students in an introductory earth science course who were randomly assigned to a traditional reading-based instruction (TRI) or a misconception reading-based instruction (MRI). Both groups read common materials that focused on discrete accepted/scientific concepts about the greenhouse effect and climate change. In addition, the TRI group (n=83) read materials that consisted of scientific concepts and the MRI group (n=114) read materials that addressed common student misconceptions. The test for this study consisted of 64 true/false items. The students in TRI and MRI groups gained significant knowledge but MRI students retained more knowledge than the TRI group. The authors concluded that addressing the misconceptions via reading was more effective for long-term retention of climate change and related concepts.

Another group of researchers (DeWaters et al., 2014) report a study in which middle and high school students were taught using project-based climate change instructional modules. Comparison of middle school (MS) and high school (HS) student (MS: n= 227 and HS: n=200) scores on a climate literacy questionnaire consisting of cognitive and behavioral subscales showed significant gain in both areas after they participated in the modules. However, the authors also pointed out that the mean post-questionnaire scores were low for both MS and HS students, indicating only a small impact from the modules used in the study. The lack of impact suggests that the curriculum and instruction both need further investigation to determine their effectiveness.

McNeill and Vaughn (2012) examined how students' attending an urban high school made positive gains in their understanding, beliefs and actions about climate change. They used a written test consisting of 16 multiple-choice and three free-response items and interviews as pre- and post-measures to determine the impact of two units on urban ecology and climate change. They collected written data from 75 students and interviewed 22 students. Students gained significant knowledge about the greenhouse effect, warming of the climate, and human impact on climate. They also reported taking personal actions to conserve energy usage.

All of these studies report significant gains in student knowledge of climate change and the greenhouse effect. They also report an increase in student interest in mitigation of the adverse effects of climate change or their active engagement in mitigation efforts. These studies suggest pathways to educate students about climate change but they do not provide any information about student understanding of the climate as a system, its variability, and the feedback loops in the interactions of the components of the system. The multiple-choice questions used by most of these studies resulted in identifying which pieces of knowledge students have acquired but they provided little insight into how students connect disparate components of knowledge into a coherent understanding of climate as a system.

The nature of the tests used to assess students' knowledge is crucial, particularly when we are targeting a relatively new domain such as climate change. In addition, we wanted to know about how students used evidence-based reasoning - a practice of science prioritized by Frameworks (NRC, 2012) and NGSS (Achieve, 2013). Students' knowledge of science content can be tested with multiple-choice items but their expertise in using a well-connected body of content to reason and explain their observations may require other modes of investigation. Researchers, who aim to discover what students learned as well as their difficulties need to use open-ended items (Gotwals & Songer, 2013; Walker & Sampson, 2013).

Taken together, the research on teaching climate change, current reform in science education, and the research on reform-oriented assessment indicate that we need to explore student understanding in greater detail than in previous studies. Furthermore, in order to develop a connected body of knowledge about climate change students need to have some understanding, however rudimentary it may be, about the climate system and we need to know how students think about complex systems such as climate.

Research on System Thinking

Climate is a naturally complex system and system thinking is necessary to understand its variations, causes, and effects. Researchers have been studying system thinking in many contexts. For example, studies have been carried out on evolutionary processes (Centola, Wilensky, & McKenzie, 2000), the aquarium system, (Hmelo-Silver, Marathe, & Liu, 2007); social systems (Booth-Sweeney, 2000), the hydrologic system (Ben-Zvi-Assaraf & Orion, 2010), the dynamic and cyclical nature of the Earth's crust, and the rate and direction of chemical reactions (Stieff & Wilensky, 2003). Based on the research on system thinking, and their own research on student thinking in the context of water cycles, Ben-Zvi-Assaraf and Orion, (2010) delineated a system thinking hierarchical model. This model projects that, at the simplest level, students will be able to analyze the components and processes within the system. Students at the next higher level will be able to synthesize the relationships in the system; they will be able to identify the relationships among the components and their dynamics to organize the components within a framework of relationships, and to identify the cyclical nature of the system components. Students at the highest level will be able to generalize their understanding of the system they are learning about, understand the dimensions of the system, think temporally, and make predictions.

The studies discussed above, however, do not clearly address the teachers' role in incorporating systems thinking in classrooms. Some researchers (Jacobson & Wilensky, 2006; Hmelo-Silver et al., 2007) point out that system thinking is essential for deeper understanding of many topics in science, yet it is not a regular facet of teaching. They recommend more research on system thinking pedagogy and ways to incorporate it in the teaching of science.

Based on our previous work on climate change education, we had proposed a visual representation of the climate system and a conceptual framework for teaching about the climate system (Shepardson, Niyogi, Roychoudhury, & Hirsch, 2012). The framework focused on the climate system components – the Sun, atmosphere, oceans, land, vegetation, and ice – and the absorption, emission, and reflection of the Sun's and other forms of energy by the components of the system. The other major foci were the difference between weather and climate, the Earth's energy budget, feedback loops, variations in the components due to natural (e.g., volcano) or anthropogenic (e.g., land use) and energy transfer between the components of the system. The framework consisted of three conceptual levels describing increasing degrees of understanding for each of the topics listed. To translate this framework into specific curriculum and pedagogical goals, resources, lessons, and performance expectations as described by Achieve (2013), requires that we gather more details about student successes and challenges in learning about climate change. To this end, we constructed the following two research questions to frame our study:

Research Question

i. Is there a significant difference between middle school student knowledge of climate change before and after instruction as captured by free-response questions?

ii. What are the educational implications of these findings about student knowledge of climate change?

The Study

Method

This is exploratory research aimed at finding patterns in student responses to open-ended items of a content knowledge test relevant to the topics taught by middle school teachers. We used written data instead of interviewing a few students so that we could look for patterns in the responses of a larger number of students. Twelve teachers of the 7th and 8th grades from four schools in a Midwestern state in the USA volunteered to teach climate change and collaborated with the researchers in this study. All teachers were licensed to teach in middle schools and six of them had advanced degrees in biology, earth science or environmental science. Four had at least a bachelor's degree in a science domain while the other three had taken science courses required for a middle school teaching license. Thus, most of the teachers were expected to be well versed in system thinking in their own domains and in the importance of a connected body of knowledge. These teachers worked with the researchers and developed curricula suitable for their students, field tested the lessons and modified them where they deemed necessary.

Over a 9-11 week period, the teachers taught the following topics: a. Earth's Energy Budget; b. Differential Heating of the Earth's Surface; c. Weather and Climate (including Climate Variability); d. Greenhouse Effect; e. Carbon Cycle; and f. Global Warming and Climate Change Impacts. Each topic consisted of multiple lessons that used a variety of materials such as hands-on experiments, readings, physical models, visuals, simulations, and extant data on climate factors. Interactions among the components of the climate system - the Sun, the Earth (ocean, land, and atmosphere), and human impact undergirded the curriculum. Four hundred and fifty-seven students from one urban and three rural schools participated in this study.

Instrument and Data Analysis

The research team, consisting of a science educator, an earth scientist, a physicist, and a climate scientist developed the content test *Understanding Climate and Climate Change* (UCCC) and the participating teachers reviewed and provided feedback on the questions, and helped finalize the test. This collaborative process of developing the test established its content and face validity. The test consisted of 16 questions, some of which had multiple sub-parts. Some questions assessed student knowledge of essential facts (e.g., identifying greenhouse gases) while others assessed student reasoning and explanations. The test was administered before and after the teachers taught the climate change topics.

Four members of the research team independently conducted a content analysis of written responses to the questions to identify the patterns in student responses (Erickson, 1986; Patton, 2002). After coding a set of 15 tests in the first round the researchers compared the codes and arrived at a consensus in their interpretations and revised the coding scheme accordingly. This allowed an initial triangulation, reduced the subjectivity, and increased the validity of our interpretation of the student responses (Patton, 2002; Corbin & Strauss, 2008). This process was used iteratively two more times with additional tests and 89% - 91% agreement was reached as a result of this process. The final coding scheme was vetted by the climate scientist and the physicist for conceptual correctness and then used by the researchers to code the entire written data set. The test assessed three broad topics: greenhouse effect, weather and climate, and climate change. Table 1 shows examples of questions, student responses, and the scores assigned to the responses.

To find out the overall changes in student knowledge of climate change and related concepts, we conducted paired t-tests of the total scores obtained by individual students. We also conducted t-tests for each of the three clusters mentioned: Greenhouse Effect (GHE), Weather and Climate (WCL), and a Climate Change (CLChange). The total number of questions was different for each cluster. GHE consisted of 7 questions (1 to 7), WCL consisted of 5 questions (8 to 12) and CLChange of 6 questions (13 to 16 which has four subparts). Because the questions were open ended and this study is exploratory in nature we did not assign a predetermined score to any item; thus the score for each question varied according to the details the students provided. Since we are exploring

Table 1. Exemplars of codes with scores

Question	Student response/score	Rationale
Exemplars from the greenhouse effect cluster		
2. What gases make up the Earth's atmosphere?	Oxygen/1 Nitrogen/1 Hydrogen/0 Carbon dioxide/1	Each correct answer received one point; knowledge of proportional makeup of the atmosphere was not expected.
3. Which of the gases you listed above are the greenhouse gases?	Carbon dioxide/1 Oxygen/0 Nitrogen/0 Water vapor/1 Air/0	Each correct answer received one point.
4. Why are they called greenhouse gases?	Absorb the Sun's rays/ energy/Sun/1 Because they react with the Sun and heat the Earth/1 They come from greenhouses or help plants/0	Any response that showed that a student understands that greenhouse gases absorb some form of radiation (infra-red or even if students called it heat or light) received 1 point.
Weather and climate cluster		
Jack and Diane were trying to decide if the following newspaper stories were talking about weather or climate. A. Indiana had more snow last winter than normal. Over 20 inches of snow fell during the winter. B. Indiana's precipitation has been increasing every year since the 1970's. Today, there is 5 inches more precipitation than in 1970. C. Indiana had one of the coldest springs in history; temperatures were 5 degrees colder than normal. D. Indiana's average spring temperature is unchanged since the 1970's. This spring's temperature averaged 45 degrees compared to 44 degrees in 1970.	N/A	N/A
10. Which of the above stories do you think is about climate? (There can be more than one)*	A./0 B./1 C./0 D./1	The scoring was based student selection of the correct choice (understanding of the timescale).
11. Explain your answer choice for question number 10.	Because they talk about climate/1 Climate is a long time/1 Climate is average over 30 years/2 Talks about temperature or rain or snow/0	Understand that climate involves a longer time; Climate involves average conditions over decades – this is a more sophisticated understanding than just *longer* time and therefore received 2 points.
Climate change cluster exemplars		
16. Some scientists think that the Earth's climate is getting warmer.	N/A	N/A
a. If these scientists are correct what might happen to the oceans? Explain why you think that would happen?**	Ocean will warm causing its level to rise because of melting polar ice/3 Oceans will warm causing it to dry out or to evaporate more/0	For correct inference about ocean temperature trend (1 point), water level (1 point), and about other causes such as melting of polar ice (1 point).

* There were similar questions about weather
** There were similar questions about plants and animals as well as people and society

the changes in student knowledge and thoughts, the scoring procedure was deemed appropriate for this study. All the tests were conducted at the 95% confidence interval. The t-test results indicated that there was a significant difference between pre- and post-test scores for all the clusters. The data were analyzed using SAS 9.4, and the results are provided in Table 2.

Because of the large sample size, it was probable that the difference between the pre-and the post-test score would appear to be significant. Therefore, to determine the effect of teaching of each topic, the effect size was also calculated. The effect size compares the difference of the means to the pooled standard deviation (i.e., the root mean square of the individual standard deviations). The effect sizes

Table 2. t values with an asterisk had p<0.0001

cluster	n	variable	mean	std dev	effect size	t(456)
GHE	457	pre	7.71	4.15	0.92	18.06*
		post	12.27	5.16		
WCL	457	pre	2.88	2.58	0.69	11.92*
		post	4.88	3.22		
CLChange	457	pre	6.87	2.82	0.32	5.95*
		post	7.77	2.83		
Total	457	pre	17.45	6.94	0.92	19.10*
		post	24.92	9.19		

indicate that the CLChange cluster had much smaller improvement in scores compared to the other two clusters.

For sample sizes greater than 30, a normality test need not be carried out (Ghasemi 2012). Nevertheless, we conducted one for completeness of the analysis. The Shapiro-Wilk results indicated that the distributions were not normal at the 95% confidence level. Therefore, as a check, we conducted the Wilcoxon signed-rank test, a non-parametric test, which is used instead of the t-test in situations of non-normal distributions. The results agree with the t-tests, that is, there was significant difference between the pre- and post-tests for all the clusters.

Findings

Students gained significant (p<.0001) knowledge about all the topics related to climate change that were tested with a large effect size (.92), however, their gains about different clusters of concepts varied (Table 2). Their knowledge gain was the highest in the GHE cluster and it also had the highest effect size. We discuss student responses from the post-tests because these tell us student knowledge, claims, and explanations after instruction and hope that these point to the directions that future research may take.

Using a previously developed model from student responses (Shepardson et al., 2009) we found that 47% (n=215) of the students believed GHE was the same as a greenhouse for growing plants (an incorrect idea) and 25.7% (n=117) thought that GHE means there are some greenhouse gases in the atmosphere with no mention or explanation of the heating mechanism. There was a major shift in student understanding of the GHE as reflected by their responses on the post-test. Only 15.3% (n=70) students thought the GHE to be the same as a greenhouse, whereas, 35.6% (n=163) thought that greenhouse gases "trap" the sun's rays, heating the Earth and another 34.2% (n=156) thought that the Sun's rays are "bounced" or reflected back and forth between the Earth surface and greenhouse gases (the best model held by these middles school students). However, even this model is quite rudimentary and does not reflect any understanding of the climate system (Shepardson et al., 2012).

Student knowledge gain about weather and climate was also significant, with a moderate effect size (.69). Their understanding of the difference between weather and climate improved after instruction. They were able to distinguish between the two in terms of timescale from the statements provided (see Table 1: Weather and Climate cluster exemplar). Most of the students understood that climate is a pattern that exists over a long time period and they mentioned decades as the scale in their explanations. Likewise, they knew that weather is what happens over a short time period, now as opposed to over a year or a few years but not decades. On the post-test, most of the students (62%; n=283) listed geographic features, such as the distance of a location from the equator and sunlight, on the post-test as the reasons for variations in climate at different locations on the Earth. Many students (over 80%; n=366) also mentioned weather conditions (perhaps implying that climate is the average of weather) and temperature as determiners of the climate of a location. Only 24% (n=110) of the students mentioned proximity to oceans as a factor affecting the climate of location. Irrespective of the factors that the students mentioned, they did not explain how these features affected the Earth's climate in different locations, how these factors interacted, or how the interactions influenced the climate.

It is perhaps not surprising that the student knowledge gain was the lowest for the CLChange cluster, given the rudimentary nature of their knowledge about weather and climate. Even though student knowledge of climate change improved significantly after instruction, the effect size for this cluster is small – only .32. A majority of the students (83%; n=379) knew that the Earth's climate is getting warmer; however, fewer than half of the students (39%; n=178) provided any detail about the effects of climate change such as a reduction of the polar ice sheet and its possible consequences. None of the students showed any awareness of the related feedback loop between ice, ocean, and the atmosphere. A small fraction of the students (17%; n=78) mentioned human activities and increased carbon dioxide in the atmosphere as the reason for the elevated temperature.

In response to the questions about the effects of global warming on ocean, weather, plants, animals, people, and society, students mentioned that ocean levels will rise, weather will get warmer leading to more evaporation and drought or longer summers. Students thought that plants and animals will die and if they provided any reason then it was the increased temperature or heat. A few (less than 10%; n=42) mentioned an interaction between plants and animals (the food chain)—the animals will die because plants will die. A few other students mentioned that some plants would thrive in the warmer climate as well as some animals because they would have more food due to an increase in vegetation. Student responses about the impact of a warming climate on people and society were very similar to the ones on plants and animals. That is, people will die due to heat and lack of water or food or due to illness caused by warming (of the Earth). A few students thought that technological advances would provide solutions to global warming. In general, most students wrote only one effect of a warming of the climate and provided no reason for the effect they claimed would happen. They appeared to not be familiar with the scientific practice of providing evidence or theoretical support for a claim.

Implications

Our work was grounded in the literature on climate and climate change education and the findings from student pre-test data, which essentially corroborated the trends in the relevant literature. To complement the findings from that extant research on teaching climate change, we aimed at finding out details about middle school student knowledge in this domain, using open-ended questions. We posit that understanding of climate change should also include an understanding of the climate system. However, given the emerging nature of curriculum and instruction in this area, not much is known about student system thinking in this context. We hope that our findings would shed some light on student successes and challenges in learning about climate change and in thinking about the climate system and inform future research on climate change teaching and learning.

As in other studies (DeWaters, et al., 2014; Lee, et al., 2007; McCuin et al., 2014; McNeill & Vaughn, 2012), these middle school students gained significant knowledge about GHE. Additionally, they also gained knowledge about the difference between weather and climate and climate change, a fundamental concept that the other researchers did not address. In fact, others have noted that the students in their studies did not understand the timescale issue about climate change. The understanding of the difference between weather and climate is the foundation for understanding climate variability and change, particularly, the timescale underlying the change. With this basic idea, students may be able to understand that as it takes decades to establish convincing records of change in the Earth's climate and its impact, it might take a long time to mitigate these effects. Thus, there is a need for long-term policies and actions. They are likely to become aware of the importance and challenges of mitigation and participate in taking informed actions in their personal lives as members of society. This understanding may help them decide about what kind of light bulb they select or what kind of agricultural practice they adopt or whether they vote for increased use of renewable energy and similar energy-climate issues. Other researchers have noted the development of favorable attitudes toward mitigation and taking adaptive action in students after learning about climate change. Although we did not assess student attitudes, we interpret from student responses that being more informed will help them make better decisions.

Students in our study also developed a basic understanding of climate change as a warming of the Earth, as noted by other researchers (DeWaters et al., 2014; McCuin et al., 2014; McNeill et al., 2012). However, this understanding was quite superficial as the students showed only a linear view of climate change, in the sense that the warming will have a drying effect (e.g., drought) and people and animals will die or have to move to other locations. This rudimentary knowledge nonetheless forms an essential foundation on which more sophisticated understanding can be built later. This also points to a possible direction of future curriculum development and teaching.

Other studies (DeWaters et al., 2014; McCuin et al., 2014; McNeill & Vaughn, 2012) have tested student knowledge gain using multiple choice questions and have shown that students learned subsets of facts about climate change, but those findings did not inform us about students' overall thinking about climate change. Even the interview data collected by McNeill and Vaughn did not provide any information about student knowledge of the climate system. Indeed, by asking open-ended questions, we found that students did not construct a richly connected body of knowledge about GHE and climate change. They saw climate change to be the same as global warming. They also saw effects of climate change in terms of simple and linear relationships (e.g.,, warmer average temperature would melt ice or evaporate water) which indicated that they did not think of climate as a system with many components, and they did not show any understanding of interactions among the components. Another major limitation in their thinking was a lack of awareness of the interactions and the non-linear feedback loops that research on system thinking holds as fundamental to understanding the Earth's climate (Shepardson et al., 2012; Ben-Zvi-Assaraf et al., 2009). It was evident that students did not consider differential effects of global warming at different locations on the Earth, that an increase in the average temperature of the Earth does not mean a higher temperature everywhere. Also, they envisioned a hotter earth becoming drier and did not consider that warmer bodies of water can result in increased precipitation due to evaporation and condensation. These students' linear and incomplete thinking was evident in their description of polar ice sheet melting. They did not consider the consequences of ice melting, such as reduction in albedo and an increase in the "heat" absorbed by the ocean that, in turn, would impact the Earth's energy budget and have varied effects at different geographic regions. Furthermore, these students primarily thought about drought as an effect of global warming and did not mention the effect on ocean-level rising or the impact of climate change on increasing severe storms. Put another way, the students did not show an awareness of the multitudes of evidence of climate change that could show some awareness of the climate as a system. Although, from our current study, we cannot draw conclusions about the reasons for this kind of simplistic linear view of the Earth's climate and changes, we can consider the implications of such piecemeal knowledge gathering and linear thinking for future research in this domain.

In this section we will first describe our inferences about teaching and learning and then their implications. There could be many reasons why students responded the way they did. Discussion within the study team, including the teachers, led us to infer several possible reasons for student performances. First, the teachers may have taught a more complex view of climate change with an implicit reference to the underlying system but students only wrote about global warming because that is what they have heard about in the media and remembered. Second, the teachers may not have taught much more about climate change than a general view of global warming; they may have used only linear examples such as the drying effect of climate change. Third, students generally take multiple-choice tests and quizzes and are not accustomed to writing detailed explanations. Consequently, they could have assumed that writing down a short answer or one cause or one effect would suffice. Fourth, our expectation was that students would write complete explanations consisting of claims supported by evidence to the open-ended items, yet many studies have shown that the scientific practice of evidence-based reasoning has to be explicitly taught in school and even in college-level science courses (Osborne et al, 2004; Walker & Sampson, 2014). Fifth, the teachers may have taught many concepts regarding climate change, but did not explicitly engage students in connecting those together to promote a system view. As a result, students wrote only the most basic ideas as their responses. Sixth, even though more than half of the teachers had extensive knowledge of science (a bachelors degree in a science discipline) and five of them have advanced degrees, and presumably should have been quite familiar with system thinking, their knowledge did not result in effective pedagogy. The last is of small surprise as it is well known among educators that deep content knowledge does not generate effective pedagogical strategies. Although there can be other reasons for the students' simplistic answers and they could be addressed in other ways, we think that the reasons we inferred here have implications for curriculum development, teacher professional development, and instruction of content and the practice of science.

At the outset, we want to underscore that we agree with researchers (e.g., Sampson & Blanchard, 2012) who point out that teaching and assessment in most science courses – even at the undergraduate level – aim at acquisition of knowledge and this is the model teachers tend to embrace in their teaching. As a consequence, their students may not learn to write answers with explanations – something that we had expected to see in this study. Our study shows that students need to learn about the climate system, rather than facts about the changes and their causes. Understanding climate change involves understanding complicated evidence from various sources such as ocean, ice, atmosphere, land, human activities and the interactions among them (NASA, 2015). Some researchers (Ben-Zvi-Assaraf & Orion, 2010; Jacobson & Wilensky, 2006; Hmelo-Silver et al., 2007) recommend more research on system thinking pedagogy and the ways to incorporate it into the teaching of science. This may be the crux of the issue. Even teachers who have extensive knowledge of systems in their domains of science may not have the pedagogical resources to utilize this knowledge in teaching. Future research can begin with the conceptual framework for the various levels of understanding of the climate system (Shepardson et al., 2012) and translating it into lessons that promote system thinking appropriate for each level. Furthermore, research needs to explore what system thinking pedagogy might look like. What strategies should teachers adopt to promote student development of a connected body of knowledge about climate change? In what sequence should the components of the climate system – the Sun, atmosphere, oceans, land, and vegetation – be taught and in what sequence should the interactions among these components be taught? Given that teaching progresses linearly, at which point should the connections among the concepts be established and what pedagogical strategies should be tried in this regard?

Based on our findings and the literature we reviewed, we postulate that system thinking may need to come in the fore in curricula and in teaching about climate change. Future research needs to determine where in a curriculum the concept of climate as a system should be introduced, what the level of system thinking at which researchers would aim should be, at which points the understanding of climate system should be modified in light of new concepts, and how student understanding of climate system should be assessed. For example, we (the researchers and the teachers) conceptualized the lessons on Earth's energy budget with the flow of energy through the climate system as the core idea and flow of matter through the system in the carbon cycle. However, students did not connect the concepts, nor did they demonstrate any understanding of climate as a system, implying that future research needs to focus on how teaching, learning, and assessment can help students develop a connected body of concepts and think about climate as a system.

In summary, we think that future research needs to explore what integration of system thinking into teaching of climate change, beginning at the middle school level, would look like. Research also needs to focus on curriculum development, effective system pedagogy, assessment, and teacher development in the context of climate change.

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