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Integrating Covariational Reasoning and Technology into the Teaching and Learning of the Greenhouse Effect

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This research study was designed to evaluate the extent and the ways in which sixth-grade students developed their reasoning about the greenhouse effect and covariation as a result of their engagement with an instructional module that seamlessly integrates environmental science, mathematics, and technology. Quantitative and qualitative data were obtained from a design experiment in two sixth-grade classrooms and were compared to the data from a control group of students in a third sixth-grade classroom. The results from the quantitative analysis indicated that students in the treatment group demonstrated a greater development than the control group. The findings from the qualitative analysis illustrated that students developed sophisticated forms of reasoning about the greenhouse effect and covariation through their engagement with dynamic simulations and careful task design that prompted students to explore the covariational relationships underlying the science of the greenhouse effect. We consider the design of this instructional module to be valuable for future efforts to develop integrated science, technology, engineering, and mathematics (STEM) modules.

Keywords: STEM curriculum, covariational reasoning, greenhouse effect, NetLogo

For the past few decades, there has been a global urgency in developing science, technology, engineering, and mathematics (STEM) education and the STEM workforce. To meet the growing demands of STEM-oriented careers and provide a greater number of students access to STEM education, the federal and state governments in the United States have drastically increased their investment in STEM education (Johnson, 2012). These investments include a five-year strategic plan for STEM education proposed by the federal government, in which the focus is on building a strong foundation for STEM literacy, increasing diversity, equity, and inclusion in STEM, and preparing the STEM workforce for the future (Gonzalez & Kuenzi, 2012).

In spite of these efforts, a large proportion of U.S. students remain unprepared in STEM subjects by the end of middle school (Stohlmann, Moore, McClelland, & Roehrig, 2011). For instance, the performance of U.S. students in international assessments such as the Program for International Student Assessment (PISA) has remained poor over the years. In the 2015 PISA study, among the 35 countries in the OECD, the U.S. performed around average in science and below average in mathematics (Belfali & Ikeda, 2016). While investigating the reasons behind the high STEM attrition rate in the U.S., researchers found that STEM subjects in schools are often introduced in discreet and uninspiring ways, with little to no focus on technology and engineering (National Research Council [NRC], 2014). As a result, students often find the content matter of the subjects difficult and unrelated to other disciplines and their regular lives (Christensen, Knezek, & Tyler-Wood, 2014; Stohlmann et al., 2011).

To develop a coherent platform for learners to have a meaningful STEM experience, STEM education should follow an interdisciplinary approach and "cut across subject areas and focus on interdisciplinary content and skills, rather than subject-based content and skill" (Wang, Moore, Roehrig, & Park, 2011, p. 3). Although there have been studies conducted to identify commonalities among the STEM practice standards and the ways that these can help learners discover cross-cutting themes connecting the different disciplines (e.g., Honey, Pearson, & Schweingruber, 2014), a limited number of them actually provide any evidence of how content integration may help students gain interdisciplinary knowledge. Integrating mathematics into science usually plays a service role, in which students use their existing mathematical knowledge for solving science tasks without developing any new mathematical types of reasoning during the process (Barnes, 2000; Honey et al., 2014; Tytler, Williams, Hobbs, & Anderson, 2019).

With these views in mind, in this study we aimed to develop STEM modules for middle-school students that seamlessly integrate Earth and environmental topics, mathematical thinking, and technology. In this paper, we report the results of two design experiments with sixth-grade students who engaged with a STEM module we developed that integrates the science of the greenhouse effect (science component) with covariational reasoning (mathematical component) through interactive dynamic simulations (technology component). The analysis reported in this study addressed the following research questions: a) To what extent and in what ways did students develop their reasoning about covariation and the greenhouse effect as a result of their engagement with the integrated STEM module?; b) What type of module activity contributed to students' development of their reasoning? The results of the present study illustrate the power of technology and covariational reasoning in developing students' understanding of science and demonstrate the forms of integrated STEM reasoning that are possible when students are engaged in such learning opportunities.

The Science and Mathematics of the Greenhouse Effect

The greenhouse effect is a natural phenomenon that warms the Earth's surface. When sunlight falls on the Earth's surface, a portion of the Sun's energy is reflected back to the atmosphere, and the rest gets absorbed by the Earth. A portion of this absorbed solar energy is reflected back to space in the form of heat. When the heat makes its way through the atmosphere, it is often re-radiated by greenhouse gases, such as carbon dioxide, methane, and nitrous oxide, which trap the heat energy in the Earth. This incoming and outgoing radiation is what keeps the Earth warm and makes the planet habitable.

Recent excessive human dominance over the Earth's ecosystem has altered the normal atmospheric condition of the Earth. Human activities, including large-scale burning of fossil fuels and excessive usage of available resources, have enhanced the emission of greenhouse gases (Vitousek, Mooney, Lubchenco, & Melillo, 1997). The amount of carbon dioxide in our atmosphere, which had been stable at 280 ppm for a thousand years, has increased exponentially since 1800 due to these human activities (Vitousek et al., 1997). Scholars have argued that if the carbon emission level of the world remains unchecked, global temperatures might rise between 2 and 5 degrees Celsius in the future (Boyes, Chuckran, & Stanisstreet, 1993). This rise in global temperature will melt polar ice caps and raise the sea level (Shepardson, Niyogi, Choi, & Charusombat, 2009). To decelerate the pace of the existing climatic disruption, researchers have suggested that it is essential to educate children from early childhood about their environment and its conservation (Heng, Karpudewan, & Chandrakesan, 2017; Shepardson et al., 2009).

The role of mathematics is vital because it can be used for understanding, predicting, and communicating issues related to climate. Government officials and policy makers develop laws and policies around environmental conservation largely based on predictions made by mathematical models of climate (Barwell, 2013). Therefore, mathematics educators have "ethical and moral responsibilities" (Abtahi, Gotze, Steffensen, Hauge, & Barwell, 2017, p. 2) to engage students in the study of complex and pressing issues such as climate change. Moreover, mathematics education should "concern itself with the development of the individual, in relation with our Planetary Ecosystem" (Karrow, Khan, & Fleener, 2017, p. 9). Therefore, in the present study we conjectured that if mathematics were integrated into the study of climate, students would be better prepared both to interpret and predict climate change and to work for the betterment of the climate as future decision-makers.

Theoretical Framework

In real life, most of the essential information about the greenhouse effect available in the news and public media is in the form of data and graphs.

However, research has shown that reading and interpreting graphs can be challenging for many students and also adults (Glazer, 2011; Monk & Nemirovsky, 1994). Students often focus on the shape of a graph, overlooking the underlying covariational relationships between the represented quantities (Monk & Nemirovsky, 1994). Research has indicated that students' lack of covariational reasoning can affect their ability to view graphs as representing relationships between quantities (Moore, Paoletti, Stevens, & Hobson, 2016). Covariational reasoning has been defined as a coordination between two sets of variables as the values of those variables change in relation to each other (Confrey & Smith, 1994). A student may reason in a covariational manner when they envision two quantities, for instance air temperature and height of sea level, *varying simultaneously* (Thompson, 1993). Research has shown that covariational reasoning, such as arguing that the height of sea level increases as the air temperature increases, can be the basis on which functional thinking can be developed and built in the later years of schooling (Confrey & Smith, 1994). Although it is not an explicit topic in the curriculum, it is embedded in content such as ratio and proportion, graphing, expressions, and equations.

Considering the above, we conjectured that the development of students' covariational reasoning in the context of the greenhouse effect could help students interpret some of the causes and consequences of climate change. To develop students' covariational reasoning, our attention was drawn to the Carlson, Jacobs, Coe, Larsen, and Hsu's (2002) framework of five *mental actions* that an individual may go through when involved in covariational experiences is an adaptation of this Mental Action of Covariational Framework, where in the third column we included examples showing what each mental action might look like in the context of the greenhouse effect.

Covariational reasoning has most often been explored using technology. Prior research on students' covariational reasoning showed the power of technology for helping students envision the change in quantities as well as to reverse change, which is not always practical with physical manipulations (Castillo-Garsow, Johnson, & Moore, 2013). Recent studies on covariational reasoning include the utilization of dynamic animations in environments such as Geometer's Sketchpad (e.g., Johnson, 2015), Desmos (e.g., Steven & Moore, 2016), and Geogebra (e.g., Ellis, Özgür, Kulow, Williams, & Amidon, 2015) to engage students in an exploration of covariational relationships. In line with this research, we decided to use technology in our module design to provide students with a discovery space (Jonassen, Carr, & Yueh, 1998) where they can explore the covariational relationships underlying the greenhouse effect. In the following paragraphs, we describe how we used covariational reasoning and technology to engineer learning opportunities for students to explore the relationships underlying the greenhouse effect.

Table 1
Adaptation of the Mental Action of Covariational Framework by Carlson et al. (2002)

Mental Action	Description of Mental Action	Example of Observable Behavior
Mental Action 1 (MA 1)	Coordinating the value of one variable with changes in the other.	As air temperature changes, the height of future sea level changes.
Mental Action 2 (MA 2)	Coordinating the direction of change of one variable with changes in the other variable.	As air temperature increases, the height of future sea level increases.
Mental Action 3 (MA 3)	Coordinating the amount of change of one variable with changes in the other variable.	As air temperature increases by 0.5 degrees Celsius, the height of future sea level increases by 4 feet.
Mental Action 4 (MA 4)	Coordinating the average rate-of-change of the function with uniform increments of change in the input variable.	The average rate-of-change of the height of future sea level is 8 feet per degree Celsius.
Mental Action 5 (MA 5)	Coordinating the instantaneous rate of change of the function with continuous changes in the independent variable for the entire domain of the function.	There is a continuous linear relationship between the rise of air temperature and the height of future sea level.

Method

The whole-class *design experiment* methodology (cf. Brown, 1992; Cobb, Confrey, DiSessa, Lehrer, & Schauble, 2003; Confrey & Lachance, 2000) was chosen to engineer particular forms of covariational reasoning within the context of the greenhouse effect and to study those forms within the activity in which they were generated. Design experiments are conducted to develop and test theories about the learning ecology, which includes "both the process of learning and the means that are designed to support that learning" (Cobb et al., 2003, p. 10). These experiments are conjecture-driven in the sense that the research team forms some initial conjectures about the means of supporting a particular form of learning and these conjectures are open for modification as the experiment unfolds.

We conducted two iterations of implementation (cf. Cobb et al., 2003) to test and refine our conjectures and warrant some degree of generalizability.

We conducted design experiments in two sixth-grade classrooms in two public elementary schools located in an urban school district in the northeastern U.S. These two classrooms were considered the treatment group and consisted of 44 students (27 students in the first classroom and 17 in the second). Each whole-class design experiment lasted for five lesson periods of 45-50 minutes each, and the experiments were spread out over a week. While the teachers assumed the responsibility for instruction, the research team members sat with small groups of two to four students to "create a small-scale version of the learning ecology so that it can be studied in depth and detail" (Cobb et al., 2003, p. 9). Additionally, one of the participating teachers taught the greenhouse effect as he traditionally does without our STEM module in a third classroom. This third classroom acted as the control group and consisted of 31 students. The assignment of which classroom was the treatment or control was determined based on convenience because the research team could only video-record the treatment classrooms in the morning.

Simulations, Task Design, and Conjectures

Considering the role of technology for developing students' covariational reasoning, we used NetLogo, a multi-agent programmable modeling environment, to develop two simulations of the greenhouse effect, one of which is a modified version of an existing simulation. The NetLogo simulations aim to "represent changes in the states of systems over time" (Wilensky & Reisman, 2006, p. 177). They provide a more accurate and easier-to-understand picture of the many everyday complex phenomena of nature with a focus on patterns and relationships rather than as results of equations (Wilensky, 2001). Informed by this research, we conjectured that the animated outputs and result plots of NetLogo would help students understand the dynamics of the interaction between the different quantities included in the simulations (Zhu et al., 2018).

Simulation 1: climate change. The Climate Change simulation was adapted from the NetLogo library (https://ccl.northwestern.edu/netlogo/models/ClimateChange). It represents a model of heat energy flow in the Earth and includes two factors of the environment that impact global air temperature: the albedo of the Earth and the amount of carbon dioxide. The albedo of the Earth, otherwise known as terrestrial albedo, is the proportion of the Sun's radiation reflected by the surface of the Earth (represented by yellow dotted line segments in Figure 1). When sunlight is not reflected in the atmosphere, it is absorbed by the Earth (absorbed particles are represented by red dots in Figure 1). The user can manipulate the value of the albedo of the Earth (from 0 to 1) and notice that as the amount of albedo increases, the reflection of sun rays increases and air temperature decreases.

The simulation further allows users to increase and decrease the amount of carbon dioxide molecules (represented by green dots in Figure 1) and investigate the change in the value of global temperature. Users can determine the change in global temperature using the temperature monitor, which records the moment-to-moment value of temperature, or the time-series graph representing the value of global air temperature with respect to time (presented in the lower left on Figure 1).

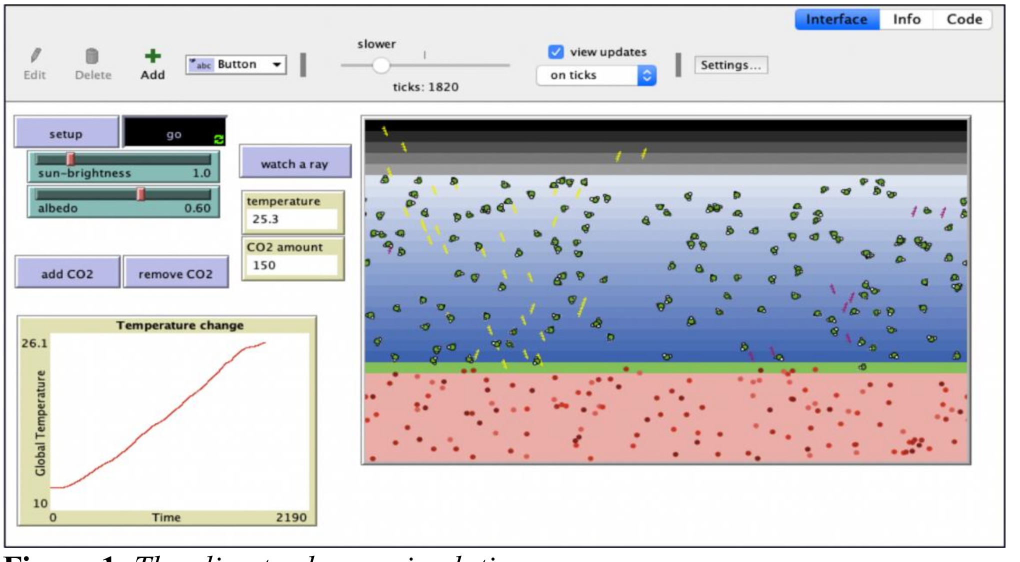


Figure 1. *The climate change simulation.*

Simulation 2: sea level rise. The Sea Level Rise simulation was developed by our research team. The intent behind the simulation design was to encourage students to recognize that if the current trend of temperature rise persists as a result of the increasing concentration of greenhouse gases, then the sea level will rise and shorelines will move inland by hundreds of meters, displacing millions of people from their homes. Users can drag the temperature rise slider and change the value of temperature rise from 0 to 4 degrees Celsius in half-degree increments to observe the impact of the change on the height of future sea level.

Task design. We designed tasks that would prompt students to reason about what quantity was changing and how it was changing as they engaged with each simulation. Both simulations were accompanied by covariational reasoning questions that provided students explicit and implicit prompts to navigate through the first three levels of covariational reasoning according to the Carlson et al. (2002) framework. We conjectured that by asking the students questions such as “What relationships do you observe?”, “What is the relationship between air temperature and carbon dioxide?”, and “What is the relationship between the rise of temperature and the height of future sea level?” during the simulation exploration, we could encourage them to focus on the direction of change of the two covarying quantities and to reason in terms of MA2. We also conjectured that by asking students in later tasks to use the simulation to collect data in a table, plot the ordered pairs in a graph, and reason about the relationship between different quantities they observe, they would be encouraged to focus on the amount of change of the two quantities and reach more advanced understandings of covariational reasoning such as MA3.

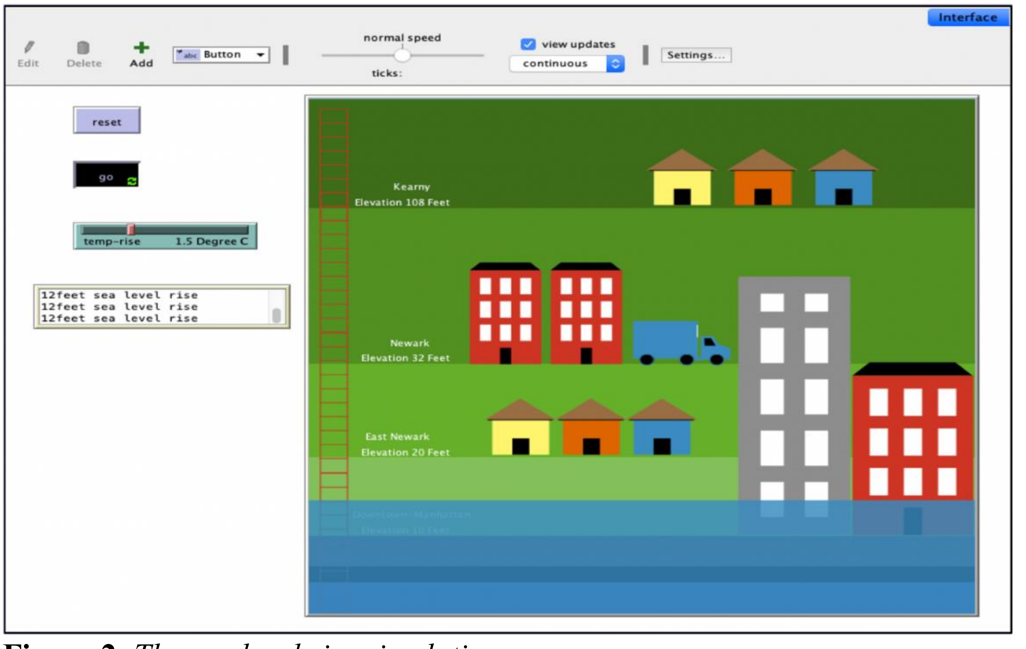


Figure 2. *The sea level rise simulation.*

Data Collection and Analysis

We collected both qualitative and quantitative data concurrently to address the different types of research questions in the present study (cf. Creswell & Plano Clark, 2007). To investigate the extent to which students developed their reasoning about covariation and the greenhouse effect (first part of research question *a*) a pre- and post-assessment containing 19 multiple-choice questions was administered to the treatment and control groups of students. The assessment included questions in which students were asked to reason about the relationships between carbon dioxide and air temperature, albedo and air temperature, and global temperature and height of sea level. The questions also included those in which students were asked to identify the covariational relationships in words (e.g., "Which of the following statements is true about atmospheric carbon-dioxide and air temperature?") and in graphs (e.g., "What relationship does the graph show?" or "Which of the following graphs correctly represents the relationship between Earth's albedo and air temperature?"). To analyze the scores of both the treatment and control groups in both the pre- and post-assessments, we used a linear mixed effect model. We used the R programing language (Team, 2014) to perform the linear mixed effect model analysis using the package nlme (Pinheiro et al., 2018) and utilized the tidyverse package (Wickham, 2017) to generate a visual figure of this analysis.

To investigate the ways that students developed their reasoning about covariation and the greenhouse effect (second part of research question *a*) and to examine the type of module activity that contributed to this development (research question *b*), we collected qualitative data in the form of audio- and video-recordings from small-group interactions between five students (two from the first cycle and three from the second) and the research team. To conduct a retrospective analysis (Cobb et al., 2003), we first viewed the session videos of the two cycles chronologically to identify students' episodes that illustrated forms of covariational reasoning as described by the Carlson et al. (2002) framework. For example, the student articulation "as the value of carbon-dioxide increases, the value of global air temperature also increases" was identified as MA2 reasoning, whereas, the articulation "when the number of computer hours is increased by 1, the amount of carbon-dioxide is increased by 36 Kg/year" illustrated students' MA3 reasoning as per Carlson et al.'s Mental Action Framework. The episodes were noted in chronological logs and meta-analyzed across the two design experiments to track the forms of covariational reasoning that emerged and the nature of the activities. It was the nature of the activities that provided students a constructive space to engage in particular forms of covariational reasoning. In particular, we examined how specific activities (e.g. exploration of specific simulations, graphing activities) and teacher questioning helped students reason in particular ways (e.g. in terms of MA2 or MA3 reasoning). In this manner, the development of a sequence emerged for identifying the diverse ways that students reasoned about covariation, the greenhouse effect and the means that supported these forms of reasoning.

Results

In this section, we discuss the results concerning the research questions by drawing on our quantitative and qualitative data analyses. To examine the extent to which students' engagement with the integrated STEM module enhanced their understanding of covariation and the greenhouse effect, we used a linear mixed effect model within the repeated measures framework to compare the treatment and control groups. First, we compared the pre- and post-assessments in both treatment and control groups, and the analysis showed that there was a significant difference ($p < 0.005$) in both groups (see Testpost_test in Table 2). Then we compared all of the pre- and post-assessments of each of the two groups (treatment and control) and found there was no significant difference (see Module_Treatment in Table 2). To examine whether the improvement was attributable to the module, we compared the post-assessment scores of the treatment and the control groups (see Testpost_test: Module_Treatment in Table 2) and found a significant difference ($p < 0.05$) between the treatment and control groups. As Figure 3 visually illustrates, the difference between the medians of the pre- and post-assessment of the treatment group was greater than the difference in the medians of the pre- and post-assessment of the control group. These results indicated that the students who worked with the STEM module (treatment group) showed a significant difference ($p < 0.05$) in improvement in their understanding of the greenhouse effect and covariation from the pre- to the post-assessment compared to their peers in the control group.

To illustrate the ways in which students developed their reasoning about covariation and the greenhouse effect (second part of research question *a*) and the type of activity that contributed to this development (research question *b*), we present a chronological account of the students' activities across the two experiments. This account includes examples of episodes from our small group interactions with five students: Trevor and Ani from the first macro cycle (MC1) and Myra, Gio, and Celine from the second macro cycle (MC2).

Table 2
Linear Mixed Effect Model

	Value	SD	DF	t-value	p-value
Intercept	11.74193	0.554	73	21.193	0.000
Testpost_test	1.48387	0.540	73	2.746	0.007
Module_Treatment	-0.21920	0.723	73	-0.303	0.762
Testpost_test:Module_Treatment	1.44794	0.705	73	2.052	0.043

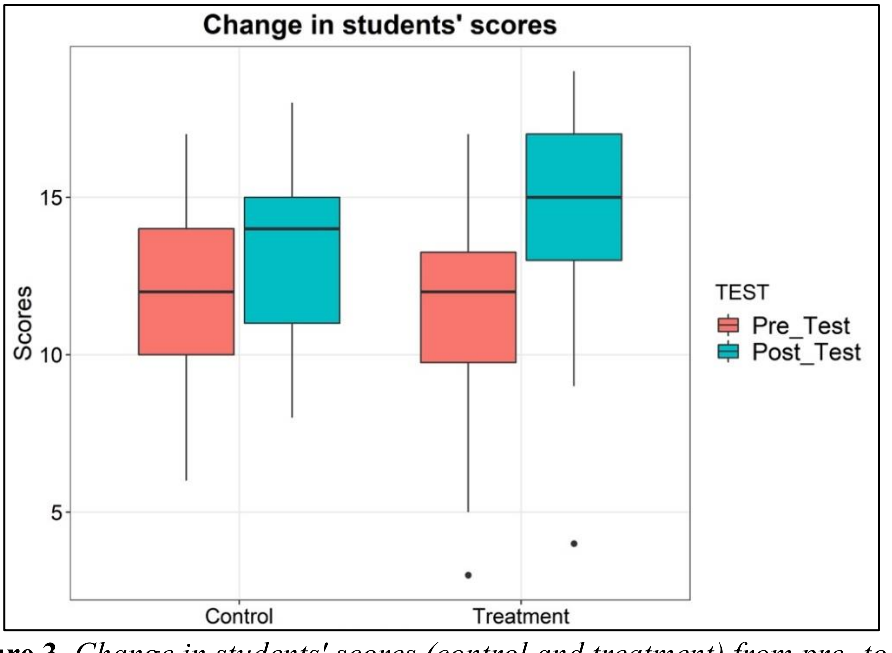


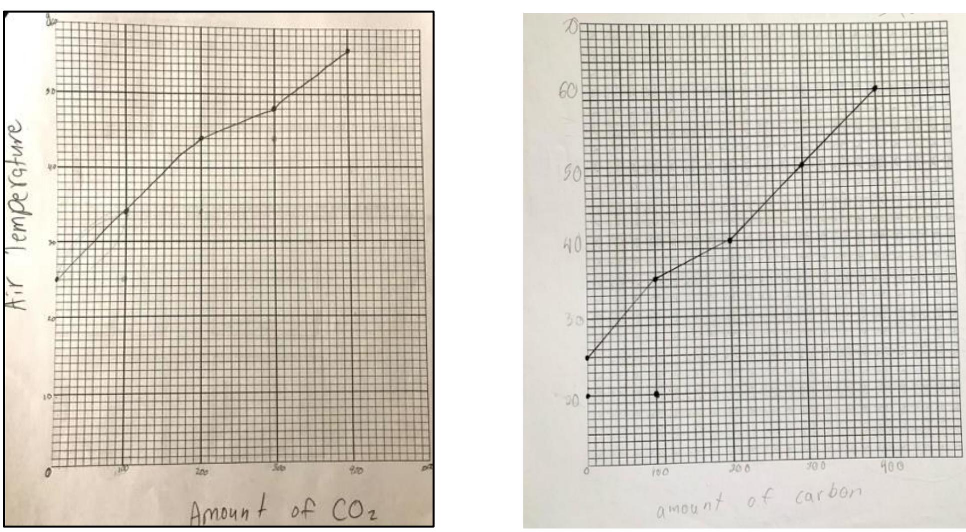
Figure 3. *Change in students' scores (control and treatment) from pre- to post-asassessment.*

At the beginning of the experiment, students were asked to explore the Climate Change simulation and identify the relationship between the albedo of the Earth and air temperature. By examining how the air temperature was changing as they were manipulating the albedo slider, all five students were able to coordinate the direction of change of the two quantities. For example, Gio (MC2) stated that "As the albedo decreases, temperature increases", illustrating a type of covariational reasoning that focuses on the direction of change of the two quantities, which is aligned to MA2 on the Carlson et al. (2002) framework. It was interesting to see that both Trevor and Ani (MC1) brought in the reflection of sunlight (viewed in the simulation as yellow line segments) as a third quantity to justify this relationship. For instance, Trevor argued, "The higher the albedo, the more sunlight it reflects, the lower the albedo, the less amount of sunlight it is reflecting".

Next, students were asked to use the Climate simulation to explore the relationship between carbon dioxide and air temperature. Similar to the previous generalizations, students exhibited a type of covariational reasoning aligned to Carlson et al.'s (2002) Mental Action 2 (MA2). For example, Myra (MC2) observed the values of air temperature for different amounts of carbon dioxide and stated, "as the carbon dioxide gets higher, the temperature rises". We then asked them to use the simulation to collect the values of air temperature for incremental values of carbon dioxide and plot the ordered pairs to graph the relationship. We found that this activity helped some students construct advanced forms of covariational reasoning. For example, when we asked Celine (MC2) to use her graph to predict the value of air temperature for 300 units of carbon dioxide, she focused on the non-uniform change of values of air temperature for each 100 unit interval of carbon dioxide and stated, "Each of them increases more than at least 5 (showing with her fingers each interval of carbon dioxide [0-100], [100-200]). So then next temperature would be 46 or higher". Similar to Celine, Ani (MC1) also noticed the non-uniform increase of air temperature for consecutive values of carbon dioxide. He pointed to the different intervals of carbon dioxide and argued, "this one from here has more space than this one from here, and from this one to here. This one has more space in between of them" (Figure 4b). Both Celine and Ani's reasoning indicated that by working with the graphical activity, they were able to focus on the amount of change in air temperature for the change in carbon dioxide, illustrating a type of reasoning aligned to MA3 in the Carlson et al. (2002) framework.

Next, the students were introduced to the Sea Level Rise simulation in which they changed the value of temperature rise and observed its impact on the height of future sea level. To help them connect the consequences of sea level rise with their own lives, we also introduced *total land area* as a third quantity and asked them to identify the impact of the increased height of future sea level. We found that all five students utilized covariational reasoning about the three quantities. For example, Myra (MC2) stated, "The higher the global temperature, the higher the height of the future sea level, and the less the total land area". Similar to Myra, other students were also able to coordinate the direction of change of the three quantities and illustrate a type of reasoning aligned to MA2 on the Carlson et al. (2002) framework. Their responses showed that the dynamic graphics of the simulation helped them to reach these generalizations. As Ani (MC1) explained, “because the more higher the sea level is, it takes over land. So, instead of land over water, it will be under water”.

Similar to the Climate Change simulation, we asked students to use the Sea Level Rise simulation to collect data in a table and then plot the relationship between global temperature and rise of sea level, aiming to engage them in more sophisticated forms of covariational reasoning than the covariational reasoning in which they would typically engage. Like before, Celine (MC2) and Ani (MC1) were able to reason about the amount of change of the two quantities involved. Celine focused on the graph of the relationship between temperature rise and height of future sea level (Figure 5) and stated, “every time you increase by 0.5 degrees, the sea level rises 4 feet”. Similar to Celine, when we asked Ani to identify and compare the relationship depicted in the temperature rise versus height of future sea level graph with the relationship on the carbon dioxide versus air temperature graph, he referred to the temperature rise versus height of future sea level graph and argued, “This one is straight [line] because when temperature rises, 0.5, it rises by 4 feet every time. Unlike the other graph, it was all mixed up. And each time it rises it was a different height”. Celine and Ani’s forms of reasoning illustrated MA3 (Carlson et al., 2002) as they were both able to coordinate the amount of change of the two quantities and identify that for every identical change of the air temperature by 0.5 degrees Celsius, the height of sea level increases by an equal amount of 4 feet.



(a) (b)

Figure 4. *(a) Celine’s graph and (b) Ani’s graph illustrating the relationship between carbon dioxide and air temperature.*

In sum, the chronological account shows that by engaging with our integrated module, students were able to reason about the relationships between albedo and air temperature, carbon dioxide and air temperature, and global temperature, height of sea level, and total land area. In terms of the science of the greenhouse effect, their reasoning showed that they identified the impact of albedo and carbon dioxide on the air temperature and subsequently recognized the impact of the rise of global temperature on the height of sea level and the area of the total land. In terms of mathematics, they were able to reason about how these quantities covary, the direction of the change of these quantities, and the amount of change of these quantities, illustrating forms of reasoning aligned to MA2 and MA3 on the Carlson et al. (2002) framework. In terms of the STEM activity that contributed to this development, we found that by engaging students in exploring the phenomenon using the simulations, they were able to study the dynamic change in each of the quantities and engage in covariational reasoning about the direction of change in these quantities; this type of reasoning aligned to MA2 on Carlson et al. (2002) framework. We also noticed that by engaging students in a graphical activity, we were able to encourage students such as Ani and Celine to extend their reasoning and identify the amount of change of the quantities, illustrating an MA3 understanding on Carlson et al. (2002) framework.

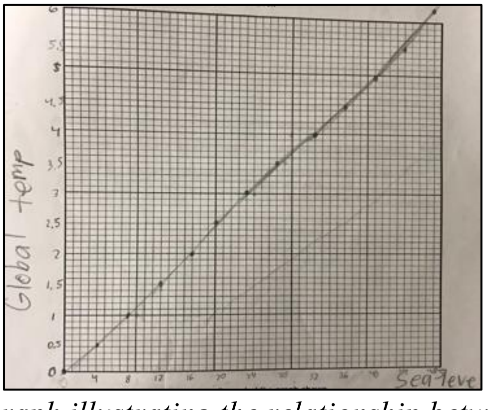


Figure 5. *Celine's graph illustrating the relationship between temperature rise and height of future sea level.*

Discussion

The aim of this study was to design and implement a STEM module that integrates the science of the greenhouse effect (science component) with covariational reasoning (mathematical component) through interactive dynamic simulations (technology component), and to provide evidence of how content integration may help students gain interdisciplinary knowledge. The results of the quantitative analysis helped us to provide empirical evidence about the extent to which students developed their reasoning about covariation and the greenhouse effect through their engagement with our integrated module. The comparison of the pre- and post-assessments of the treatment group showed a statistically significant improvement compared to the control group. This suggests that the STEM module was a significant factor in promoting this development.

The qualitative analysis of the video-recordings from the design experiment sessions helped us to gather insights into the ways that students developed their reasoning as well as into the type of activity that contributed to this development. By exploring the Climate Change simulation, students identified some of the causes of the greenhouse effect and reasoned that as the albedo of the Earth decreases, the air temperature increases, and that as the carbon dioxide increases, the temperature increases. By exploring the Sea Level Rise simulation, students identified one of the effects of climate change by reasoning that as the global temperature increases, the height of sea level increases simultaneously. Students not only reasoned about the direction of change in these relationships, but also about the amount of change (e.g., "every time you increase [the global temperature] by 0.5 degrees, the sea level rises 4 feet"), illustrating forms of reasoning aligned to the first three mental actions of the Carlson et al. (2002) framework. Students' forms of reasoning integrated both mathematics and science as one unified construct. In their generalizations, students did not distinguish between "math reasoning" and "science reasoning", rather their integrated reasoning showed that they developed "interdisciplinary content and skills" (Wang et al., 2011), avoiding disconnected disciplinary learning that has been noted in other studies (Barnes, 2000; Honey et al., 2014; Tytler et al., 2019).

The development of students' interdisciplinary knowledge, as evidenced by our findings, was likely due to the integration of a strong component of covariational reasoning into the module design. This is in comparison to the control group of students who just explored the same causes and consequences of the phenomenon without this integration. Hence, we would suggest that an explicit integration of covariational reasoning into science courses and educational activities may help bridge the two content areas. Similar to prior research into the role of technology in developing students' covariational reasoning (e.g., Ellis et al., 2015; Johnson, 2015; Stevens & Moore, 2016), we also found that the dynamic nature of the simulations and targeted questioning engaged students in reasoning about the direction of change of the quantities that covary. Then, as they collected data using the simulation and graphed the relationships, students engaged in reasoning about the amount of change of the covarying quantities.

Further studies can build on this research to design covariational situations of science that would develop students' reasoning of more advanced mathematical concepts such as proportions, rate of change, equations, and functions. In addition, the findings of this study can be used to design other STEM modules that integrate scientific phenomena with covariational reasoning through technology. In addition to the greenhouse module that we presented in this paper, we are currently designing NetLogo simulations to explore the covariational relationships underlying other science phenomena such as climate (e.g., the relationship between temperature and latitude), weather (e.g., the relationship between temperature and density of an air mass), and shadows (e.g., the relationship between angle of the sun and length of shadow).

To conclude, we believe that this focus on exploiting the covariational relationships of science through dynamic simulations, careful task design, and questioning supports the kind of integrated math and science reasoning that will eventually make STEM education a purposeful tool for thinking and problem solving. Such integrated curricula can better prepare our students to interpret the data they encounter in their out-of-school lives and think critically about the underlying phenomena of our environment.

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References

Abtahi, Y., Gotze, P., Steffensen, L., Hauge, K. H., & Barwell, R. (2017). Teaching climate change in mathematics classrooms: An ethical responsibility. *Philosophy of Mathematics Education Journal*, (32), 1-18.

Barnes, M. (2000). 'Magical' moments in mathematics: Insights into the process of coming to know. *For the Learning of Mathematics*, *20*(1), 33-43.

Barwell, R. (2013). The mathematical formatting of climate change: Critical mathematics education and post-normal science. *Research in Mathematics Education*, *15*(1), 1-16.

Belfali, Y., & Ikeda, M. (2016). *Country: Key findings from PISA 2015 for the United States.* Paris, France: Organization for Economic and Cooperation and Development. Retrieved from http://www.oecd.org/pisa/pisa-2015-United-States.pdf

Boyes, E., Chuckran, D., & Stanisstreet, M. (1993). How do high school students perceive global climatic change: What are its manifestations? What are its origins? What corrective action can be taken? *Journal of Science Education and Technology*, *2*(4), 541-557.

Brown, A. L. (1992). Design experiments: Theoretical and methodological challenges in creating complex interventions in classroom settings. *The Journal of the Learning Sciences*, *2*(2), 141-178.

Carlson, M., Jacobs, S., Coe, E., Larsen, S., & Hsu, E. (2002). Applying covariational reasoning while modeling dynamic events: A framework and a study. *Journal for Research in Mathematics Education*, *33*(5), 352-378.

Castillo-Garsow, C., Johnson, H. L., & Moore, K. C. (2013). Chunky and smooth images of change. *For the Learning of Mathematics*, *33*(3), 31-37.

Christensen, R., Knezek, G., & Tyler-Wood, T. (2014). Student perceptions of science, technology, engineering and mathematics (STEM) content and careers. *Computers in Human Behavior*, *34*, 173-186.

Cobb, P., Confrey, J., DiSessa, A., Lehrer, R., & Schauble, L. (2003). Design experiments in educational research. *Educational Researcher*, *32*(1), 9-13.

Confrey, J., & Smith, E. (1994). Exponential functions, rates of change, and the multiplicative unit. *Educational Studies in Mathematics*, *26*(2-3), 135-164.

Confrey, J., & Lachance, A. (2000). Transformative teaching experiments through conjecture research design. In A. E. Kelly & R A. Lesh (Eds.), *Handbook of research design in math and science education* (pp. 231-265). Mahwah, NJ: Lawrence Erlbaum Associates Inc.

Creswell, J., & Plano Clark, V. (2007). *Designing and conducting mixed methods research*. Thousand Oaks, CA: Sage.

Ellis, A. B., Özgür, Z., Kulow, T., Williams, C. C., & Amidon, J. (2015). Quantifying exponential growth: Three conceptual shifts in coordinating multiplicative and additive growth. *The Journal of Mathematical Behavior*, *39*, 135-155.

Glazer, N. (2011). Challenges with graph interpretation: a review of the literature. *Studies in Science Education*, *47*(2), 183-210.

Gonzalez, H. B., & Kuenzi, J. J. (2012, August). *Science, technology, engineering, and mathematics (STEM) education: A primer.* Washington, DC: Congressional Research Service, Library of Congress.

Heng, C. K., Karpudewan, M., & Chandrakesan, K. (2017). Climate change activities: A possible means to promote understanding and reduce misconceptions about acid rain, global warming, greenhouse effect and ozone layer depletion among secondary school students. In M. Karpudewan, A. N. M. Zain, & A. L. Chandrasegaran (Eds.), *Overcoming students' misconceptions in science* (pp. 323-344). Singapore: Springer.

Honey, M., Pearson, G., & Schweingruber, H. (Eds.). (2014). *STEM integration in K-12 education: Status, prospects, and an agenda for research*. Washington, DC: The National Academies Press.

Johnson, C. C. (2012). Implementation of STEM education policy: Challenges, progress, and lessons learned. *School Science and Mathematics*, *112*(1), 45-55.

Johnson, H. L. (2015, July). Task design: Fostering secondary students' shifts from variational to covariational reasoning. In K. Beswick, T. Muir, & J. Fielding-Wells (Eds.), *Proceedings of the 39th Conference of the International Group for the Psychology of Mathematics Education* (Vol. 3, pp. 129-136).

Jonassen, D. H., Carr, C., & Yueh, H. P. (1998). Computers as mindtools for engaging learners in critical thinking. *TechTrends*, *43*(2), 24-32.
Karrow, D., Khan, S., & Fleener, J. (2017). Mathematics education's ethical relation with and response to climate change. *Philosophy of Mathematics Education Journal*, (32), 1-27.
Monk, S., & Nemirovsky, R. (1994). The case of Dan: Student construction of a functional situation through visual attributes. In E. Dubinsky, A. H. Schoenfeld, & J. Kaput (Eds.), *Research in collegiate mathematics education.* (pp. 139-168). Providence, RI: American Mathematics Society.
Moore, K. C., Paoletti, T., Stevens, I. E., & Hobson, N. L. F. (2016). Graphing habits: I just don't like that. In T. Fukawa-Connelly, N. E. Infante, M. Wawro, & S. Brown, (Eds.), *Proceedings of the 19th Meeting of the MAA Special Interest Group on Research in Undergraduate Mathematics Education. Pittsburgh PA: RUME*. (pp. 16-30). Pittsburgh, Pennsylvania.
National Research Council (2014). STEM integration in K-12 education: Status, prospects, and an agenda for research. In M. Honey, G. Pearson, & H. Schweingruber (Eds.), *Committee on Integrated STEM Education; National Academy of Engineering*. Washington, DC: The National Academies Press.
Pinheiro, J., Bates, D., DebRoy, S., & Sarkar, D. R Core Team (2018). _nlme: Linear and nonlinear mixed effects models. R package version 3.1-137, URL: https://CRAN.R-project.org/package=nlme
Sengupta, P., Kinnebrew, J. S., Basu, S., Biswas, G., & Clark, D. (2013). Integrating computational thinking with K-12 science education using agent-based computation: A theoretical framework. *Education and Information Technologies*, *18*(2), 351-380.
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.
STEM Task Force Report. (2014). *Innovate: A blueprint for science, technology, engineering, and mathematics in California public education*. Dublin, California: Californians Dedicated to Education Foundation.
Stevens, I. E., & Moore, K. C. (2016). The ferris wheel and justifications of curvature. In M. B. Wood, E. E. Turner, M. Civil, & J. A. Eli, (Eds.), *North American chapter of the international group for the psychology of mathematics education*. (pp. 644-651). Tucson, AZ: The University of Arizona.
Stohlmann, M., Moore, T. J., McClelland, J., & Roehrig, G. H. (2011). Impressions of a middle grades STEM integration program: Educators share lessons learned from the implementation of a middle grades STEM curriculum model. *Middle School Journal*, *43*(1), 32-40.
Team, R. C. (2014). A language and environment for statistical computing. *R Foundation for Statistical Computing*, Vienna, Austria.

Thompson, P. W. (1993). Quantitative reasoning, complexity, and additive structures. *Educational Studies in Mathematics*, *25*(3), 165-208.

Tytler, R., Williams, G., Hobbs, L., & Anderson, J. (2019). Challenges and opportunities for a STEM interdisciplinary agenda. In Doig B., Williams J., Swanson D., Borromeo Ferri R., Drake P. (Eds.), *Interdisciplinary Mathematics Education* (pp. 51-81). ICME-13 Monographs. Springer, Cham.

Vitousek, P. M., Mooney, H. A., Lubchenco, J., & Melillo, J. M. (1997). Human domination of earth's ecosystems. *Science*, *277*(5325), 494-499.

Wang, H. H., Moore, T. J., Roehrig, G. H., & Park, M. S. (2011). STEM integration: Teacher perceptions and practice. *Journal of Pre-College Engineering Education Research*, *1*(2), 2-31.

Wickham, H. (2017). Tidyverse: Easily install and load 'Tidyverse' packages. R package version URL: https://CRAN.R-project.org/package=tidyverse.

Wilensky, U. (1999). *NetLogo* [Computer Program]: Center for connected learning and computer-based modeling. Evanston, IL: Northwestern University. Available at http://ccl.northwestern.edu/netlogo/

Wilensky, U. (2001, August). *Modeling nature's emergent patterns with multi-agent languages*. Paper presented at Eurologo 2001, Linz, Austria.

Wilensky, U., & Reisman, K. (2006). Thinking like a wolf, a sheep, or a firefly: Learning biology through constructing and testing computational theories—an embodied modeling approach. *Cognition and Instruction*, *24*(2), 171-209.

Zhu, M., Panorkou, N., Etikyala, S., Basu, D., Street-Conaway, T., Iranah, P… Samanthula, B. (2018). Steerable Environmental Simulations for Exploratory Learning. In *Proceedings of E-Learn: World Conference on E-Learning in Corporate, Government, Healthcare, and Higher Education* (pp. 83-92). Las Vegas, NV, United States: Association for the Advancement of Computing in Education (AACE). Retrieved from https://www.learntechlib.org/primary/p/184951/

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