BUILDING BRIDGES TO CLIMATE LITERACY THROUGH THE DEVELOPMENT OF SYSTEMS AND SPATIAL THINKING SKILLS

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ABSTRACT OF THE DISSERTATION

Building Bridges to Climate Literacy through the Development of Systems and Spatial Thinking Skills

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The population of our planet recently surpassed 7 billion inhabitants and is projected to rise to 9 billion by the year 2050. (UN Report, 2013)(UN Report, 2013)(UN Report, 2013) In order to sustain a population of this size we need to ensure that we maintain the quality of our natural environment deep into the future. How we decide to address the effects of our changing environment is contingent upon having a population that is science, geography, and climate literate. However, the challenges in achieving disciplinary literacy lie in deciphering and mastering the inherent complexities of the discipline. Not only does a learner need to comprehend content, but they also must apply the necessary science, geography, and climate skills and cross-cutting themes in their comprehension of the domain content. For example, to comprehend the climate system not only does an individual need to understand the content of climatology, but they also need the skills of systems thinking and spatial thinking. This three-study mixed methods dissertation explored the effectiveness of a conceptual representation intervention designed to scaffold high school learners as they develop systems and spatial thinking during a unit on the human climate system. Grounded in model-based reasoning and systems thinking research, the PMC-2E (phenomenon, mechanism, component, evidence, explanation) framework afforded students the opportunity to iterate over the course of a unit. They started with their generic ideas about the climate system, which developed into more sophisticated representations of the entire climate system as the unit progressed. My research questions focused on the effectiveness of this intervention in the (1) increased sophistication of students' system models; (2) the inclusion of subsystems in their systems models along with the identification of detailed causal connections of the subsystems to the entire system; and (3) the inclusion of spatial causal connections within their system models. Positive changes were found in all three studies which add to ongoing research in the areas of systems thinking and spatial thinking. These results also provide research-supported instructional tools to assist learners while learning complex material.

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1.1 Statement of Problem

The population of our planet recently surpassed 7 billion inhabitants and is projected to reach close to 10 billion by the year 2050 (UN Report, 2013). Our exponential growth rate has stretched and stressed our natural resources to the point of a questionable future. In order to sustain a population of this size we must carefully assess our global environment to ensure the quality of our air, water, and other resources are maintained deep into the future. Such assessment requires an understanding of complex scientific issues and topics. Climate change and evolution and are a couple of the difficult to understand topics requiring public understanding of both science and geography.

How we as a global society decide to address the needs associated with these environmental issues is contingent on having a population that is science and geography literate in general and climate literate more specifically. However, to be climate literate there are numerous skills a person must possess. Systems thinking and spatial thinking are only two of the many skills needed to effectively reason about the complexity of the human climate system. Such reasoning is required in order to understand and address the local, regional, and global impacts of climate change.

The prominent guiding documents in K-12 science education from the past 20 years (American Association for the Advancement of Science, 1993; National Council for Geographic Education, 2012; National Research Council, 1996; NGSS Lead States, 2013) recognize the necessity for developing skills in scientific practices and in recognizing important cross-cutting themes such as systems thinking and spatial thinking. The challenge lies in the translation of the goals of K-12 science into effective lessons to promote the development of skills such as systems thinking and spatial thinking in our learners. Past research has shown that students have difficulties when considering causality within systems (Hmelo-Silver & Pfeffer, 2004; Jacobson & Wilensky, 2006) and across spatial scales (Grotzer, 2012; Tretter, Jones, Andre, Negishi, & Minogue, 2006). The development of systems thinking provides learners with a framework for grappling with complexity of the climate system. The development of spatial reasoning provides learners with a framework for the identification of causal mechanisms that exist at various scales.(U.S. Global Change Research Program/Climate Change Science Program, 2009) Beside being critical for science, geography, and climate literacy, spatial reasoning and systems thinking were identified for this research project because of their timely importance in so many domains including business, industry, politics, medicine, and computer science to name a few. (Hegarty, Crookes, Dara-Abrams, & Shipley, 2010; Richmond, 1993; U.S. Global Change Research Program/Climate Change Science Program, 2009; Uttal & Cohen, 2012)

The purpose of this dissertation is to address research questions investigating the employment of a conceptual representation intervention to promote the development of systems thinking and spatial thinking when reasoning about causality in the human climate system. In this intervention, students initially considered the mechanisms causing phenomena from a generic viewpoint, and as more evidence became available over the course of a unit, their explanations about how the system operates over various spatial scales became more sophisticated. By sophistication, I am referring to pre-unit and post-unit gains in the complexity of their system models, including the number of subsystems, and explanations, and in the number of spatial causal connections made between spatial components and mechanisms of the human climate system.

The findings from the three studies making up this dissertation will contribute to the science education research community focusing on the development of systems thinking in general (Hmelo-Silver, Marathe, & Liu, 2007; Jordan, Sorenson, & Hmelo-Silver, 2014). Additionally they will contribute to the scant research on the development of spatial thinking by providing insights into how students reason about causality across various spatial scales. In addition to identifying ways to develop the necessary abilities of systems thinking and spatial literacy, another purpose of this research was to bridge teaching standards from frameworks to practice by identifying methods of making standards actionable. The identification of effective methodologies will ensure our students are developing the needed skills for their futures. The following sections of the introduction will provide additional background supporting the purpose of my research project.

1.1.1 Scientific and Geographic Literacy

Global challenges like those mentioned above require individuals to be both scientifically and geographically literate while employing the broad concepts, themes, and skills of these domains in their decision-making. This recognition that our society needs to be scientifically literate (National Research Council, 2007) has opened the door to the creation of domain specific literacy documents that spell out what every citizens needs to know about the particular domain, such as in atmospheric science and earth science. The challenges in achieving disciplinary literacy lie in deciphering and mastering the inherent complexities of the discipline. Not only does a learner need to comprehend content, but they also must apply the necessary science skills and cross-cutting concepts in their comprehension of the domain content. For example, the climate system is a complex mélange of interactions among many components in the Earth System.

The quest to develop scientific literacy in Earth System Science has led to the identification and promotion of essential literacy principles in ocean science (National Geographic Society, 2006), atmospheric science (University Corporation for Atmospheric Research, 2008), Earth science (Earth Science Literacy Initiative, 2010), climate science (U.S. Global Change Research Program/Climate Change Science Program, 2009), and most recently, energy (U.S. Global Change Research Program/Climate Change Science Program, 2011). These research-based documents developed by the scientific community provide classroom educators and those designing informal learning experiences with the big ideas essential for each domain. Recently, these big ideas along with the big ideas in the other scientific domains were brought together with science and engineering practices and cross-cutting concepts into one unified document to guide science instruction and learning in grades K-12, which if implemented in the spirit in which they were written, will lead students to be scientifically literate (National Research Council, 2012).

Those in the field of geography have also recognized the importance of big ideas and essential elements for all citizens to be geographically literate, and have crafted a set of standards that will prepare students for the global challenges and opportunities they face in the future (National Council for Geographic Education, 2012; NGSS Lead States, 2013). Similar to the rationale for science literate citizenship, the need for a geographic literate citizenship includes the same arguments, but in addition, the authors have identified that a geographically literate person can identify interactions, interconnections, and implications among the physical and human elements on the globe. They frame these components in both spatial and ecological perspectives, and thus a geographically literate person makes decisions related to global sustainability and human existence from an integrating these perspectives with geographic knowledge (National Council for Geographic Education, 2012).

1.1.2. Cross-Cutting Concepts and Themes in Science and Geography

Fundamental to scientific and geographic literacy are the inherent thinking skills of a scientist and geographer. Collectively called cross-cutting concepts, common themes, unifying concepts, or cross-cutting themes, they underlie and frame the content and practices of the experts in these fields as they seek the answers to their research questions. For example, ecologists combine both systems and spatial thinking when considering how matter and energy flow through ecosystems. They constrain their questions using boundaries within scale and systems, and use models to project their results beyond the initial boundaries. Climatologists use data and algorithms to create global models of the climate system, and then "downscale" their results to take into account regional climate inputs. Physical geographers ask questions about patterns observed at global and regional scales while considering the interactions, interconnections, and implications of the human and environmental systems that created these patterns. Reasoning with cross-cutting concepts and cross-cutting themes provides researchers with a way to expand and constrain their questions by provided pathways to understanding phenomena. However, it is through the development of expertise that scientists and geographers know how to reason with cross-cutting concepts and cross-cutting themes.

In a classroom, those same skills are cited as important and over–arching but are typically lost to the deluge of disciplinary content making up the identified course goals. Called by different names, over the past twenty years the major guiding documents for science education in the United States including *Science for all Americans* (American Association for the Advancement of Science, 1989), *Benchmarks for Science Literacy* (American Association for the Advancement of Science, 1993), *National Science Education Standards* (National Research Council, 1996), and currently the *Framework for K-12 Science Education* (National Research Council, 2012) have identified pervasive cross-cutting themes in science and engineering that serve as perspectives for learning content. However, it wasn't until the creation of the Framework for K-12 Science Education and its associated *Next Generation Science Standards* (*NGSS*) (NGSS Lead States, 2013) that these "cross-cutting concepts" gained prominence in the expectations set forth by the documents. The seven cross-cutting concepts identified in the *Framework* are: patterns; cause and effect mechanism and explanation; scale, proportion, and quantity; systems and system models; energy and matter, flows, cycles and conservation; structure and function; and stability and change. The Framework calls for explicit instruction on these cross-cutting concepts and marries all the cross-cutting concepts into the performance expectations found in the *NGSS*, whereas in the past, the guiding documents assumed that students would implicitly learn how to employ these cross-cutting concepts by way of the course content. The supporting documents of the *NGSS* provides the users with grade-level progressions to understand how these cross-cutting concepts can be integrated with the core ideas with increasing sophistication from grades K-12. Over time students gradually transition from a novice understanding of these cross-cutting concepts to one more closely aligned to an expert understanding how they are important to the various domains of science.

In the eighteen *National Geography Standards,* the core ideas along with the cross-cutting themes are deeply wedded to ensure students develop a geographic awareness that they can employ in any field – scientific, business, humanities, etc. The five themes identified in the standards are: space and scale; places; systems; human-environment interaction; and change into the content. The supporting examples of learning opportunities for each standard at each of the three grade levels (4, 8, and 12) clearly incorporate these cross-cutting themes into what the students should know and be able to do on completion of the learning experience.

The current guiding documents in these two domains are clear about the explicit incorporation of cross-cutting concepts and cross-cutting themes in science instruction and geography instruction; however, fidelity in translating standards into classroom practice has always been a challenge. The next section will briefly address these challenges. For the purpose of consistency in this study, the terms cross-cutting concepts and cross-cutting themes will collectively be identified as "themes" from this point forward, and when discussing systems thinking and spatial reasoning, they will be identified as "skills."

1.1.3. Supporting Climate Literacy

According to Climate Literacy: Essential Principles of Climate Sciences (U.S. Global Change Research Program/Climate Change Science Program, 2009), a climate literate populace is not only one that knows the fundamentals of weather and climate, but also is one that understands the climate system at various scales, both temporal and spatial; one that understands cause and effect in complex systems; one that can integrate both physical and human mechanisms; and one that understands the process of science as it asks questions and seeks answers about the climate system(U.S. Global Change Research Program/Climate Change Science Program, 2009). People are expected to integrate skills in identifying patterns, reason about complex systems at various spatial and temporal scales, understand cause and effect, and understand the movement of matter and energy among other fundamental skills of science and geography that are not typically stressed in K-12 science and geography education. If informed public decisions are to be made, those making the decisions and the general population must be able to use a variety of scientific and geographic reasoning skills like systems thinking and spatial reasoning.

1.1.4. Science & Geography Literacy Goals and Classroom Practice

While necessary for science and geography education, difficulties can arise when we try to turn scientific literacy and geographic literacy from goals into realities. Consideration must be given to how teachers teach and how students learn. Fortunately the research in science education, geography education, the learning sciences, and educational psychology have given way to the creation of learning progressions which combine research in identifying what students should know and be able to do in relationship to content and skills at various grade bands (National Council for Geographic Education, 2012; NGSS Lead States, 2013). These learning progressions were developed to guide teachers in their instruction and assessment decisions. Translating these standards into practice can be accomplished with appropriate professional development on how to interpret and implement the standards into their classroom instruction.

The fact the *NGSS* and *National Geography Standards* both explicitly integrate the core ideas with the themes of their domains, they send a message to teachers that their instruction should lead students to scientific and geographic literacy if the core ideas and themes are integrated while teaching (National Council for Geographic Education, 2012; NGSS Lead States, 2013). However, this integration of core ideas and themes is not necessarily evident for the students who require scaffolding in the themes as much as they need scaffolding in the core ideas. Therefore to meet the goals of scientific and geographic literacy for all, teachers must be provided with research-supported instructional methodologies that explicitly integrate the core ideas with the themes of the domains. Thus, the broader goal of this research study is to create actionable standards grounded in the research on how students learn.

1.1.5. The Development of Systems Thinking

Knowing how germane complex systems thinking skills are to understanding phenomena across many disciplines, researchers from many fields including the cognitive sciences and the learning sciences have been seeking to understand how individuals develop these skills for over two decades. This has led to many studies exploring various interventions designed to either elucidate the cognitive aspects of these skills (Goldstone & Wilensky, 2008; Hmelo-Silver et al., 2007; Hmelo-Silver & Pfeffer, 2004; Jacobson, 2001; Raia, 2012; Shepardson, Niyogi, Roychoudhury, & Hirsch, 2012), or to identify effective teaching methods to encourage the development of systems thinking (Ben-Zvi Assaraf & Orion, 2005; Goldstone & Sakamoto, 2003; Jordan et al., 2014; Kali, Orion, & Eylon, 2003; Levy & Wilensky, 2008; Raia, 2005, 2008).

The intervention employed in this project builds on the research of Hmelo-Silver et al. (2007) and L. Liu and Hmelo-Silver (2009) who employed a structure-behavior-function (SBF) conceptual representation to ascertain how novices and experts reason about complex systems such as the respiratory system and aquatic ecosystems. Novices have a tendency to focus on the structures of systems while overlooking mechanisms (behaviors) connecting system structures that lead to the function of the system. However, their framework and intervention changed the focus of the students from a structured view of the system to one that was driven by mechanisms. Although the SBF framework assisted learners in making causal connections among structures within a complex system, the structures were in the forefront of their consideration of the behaviors. The conceptual representation used in this dissertation instead focuses students on the mechanisms driving the phenomena while considering causality connecting components. Similar to the research of Jordan et al. (2014), I argue that students will gain a more sophisticated understanding of the complex system if the focus on the mechanisms which lead to the phenomena.

1.1.6. The Development of Spatial Thinking

Depending on the content domain, spatial literacy has different meanings. In this research project, the definition and foundational research comes from the field of geography. Geographers define spatial literacy as "constituting proficiency in terms of spatial knowledge, spatial ways of thinking and acting, and spatial capabilities" (National Research Council, 2006, p. 18). Someone with spatial knowledge effectively integrates spatial concepts within and across disciplines. Someone employing spatial ways of thinking and acting draws diagrams, analyzes diagrams, and seeks patterns and spatial relationships. Someone with spatial capabilities effectively uses and manipulates spatial tools and technologies to model the space in question. Furthermore, a spatially literate person has the following characteristics:

> • have the habit of mind of thinking spatially—they know where, when, how, and why to think spatially;
>
> • practice spatial thinking in an informed way—they have a broad and deep knowledge of spatial concepts and spatial representations, a command over spatial reasoning using a variety of spatial ways of thinking and acting, have well-developed spatial capabilities for using supporting tools and technologies; and
>
> • adopt a critical stance to spatial thinking—they can evaluate the quality of spatial data based on their source, likely accuracy, and reliability; they can use spatial data to construct, articulate, and defend a line of reasoning or point of view in solving problems and answering questions; and they can evaluate the validity of arguments based on spatial information. (National Research Council, 2006, p. 20)

How do these abilities develop? Like with any domain competency, the trajectory to expertise in spatial thinking develops over time through practice with contextualized examples and problems related to a domain. Over time, learners become proficient in the interpretation and analysis of spatial representations, thus increasing the potential that these skills will transfer to new problems in the original and new domains (Meentemeyer, 1989; National Research Council, 2006). However, there is little research in this area which has unpacked the specifics behind how spatial literacy develops with the exception of the research base that supports the gender, direct and indirect experiences, age, and culture differences in spatial abilities (Bednarz & Kemp, 2011; National Research Council, 2006).

The aspect of spatial literacy of interest for this research project is students' conceptions of the processes or mechanisms occurring at various *spatial scales* within complex natural systems, such as ecological systems or the climate system. Related to this area of spatial literacy, there have been a few studies (Gramling, Solis, Derbiszewska, & Grotzer, 2014; Grotzer, 2012; Hegarty et al., 2010; Jones & Taylor, 2009; Tretter et al., 2006) that have delved into students' perceptions of spatial scales; however as important as this research was in uncovering some key differences (effects of direct and in direct experiences, expert-novice, etc) in spatial abilities related to scale, these studies did not explore the ability of students to trace causality across various scales. According to the (National Research Council, 2006), spatial thinking skills are necessary when learning about complex systems, and therefore this is an area in which research is needed. This dissertation closes the research gap by testing the hypothesis that by focusing students on the mechanisms within a complex system during an instructional intervention, students will recognize the causality across spatial scales.

1.2 Overview of Three Studies

This dissertation includes three studies exploring various applications of the conceptual representation intervention called PMC-2E. (See Figure 1.1 and Figure 1.2) This section will describe the intervention and focus of each study. Grounded in a model-based reasoning framework as defined by Nersessian (2008a) who describes conceptual models as being "…imaginary systems designed to be structural, functional, or behavioral analogues of a target phenomena." (pp.12, 2008) These dynamic models aid learners in future learning by enabling generic mechanistic abstractions (to the students, i.e., ways in which currents move, convection, etc.) which can be used to reason about new phenomena. The PMC-2E conceptual representation begins with students addressing the phenomenon (P) by considering all possible mechanisms (M) connecting components (C) using their generic ideas. As a unit of study progresses, students gather evidence (E) that requires them to revise and elaborate on their initial ideas with explanations (E). Through the use of this conceptual representation, students' model-based reasoning skills develop as they think more deeply about the system under study. My overall research question seeks to understand the changes that occur in students' thinking about the human-climate system as a result of interacting with the intervention described above.

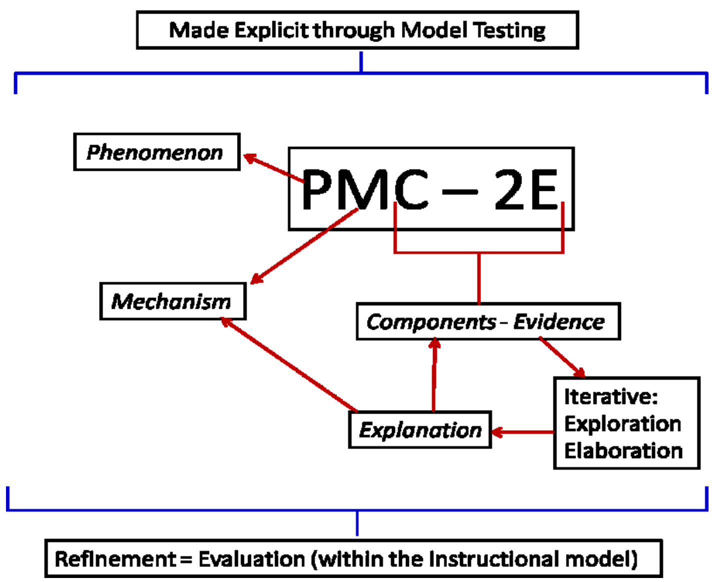


Figure 1.1: PMC-2E conceptual representation

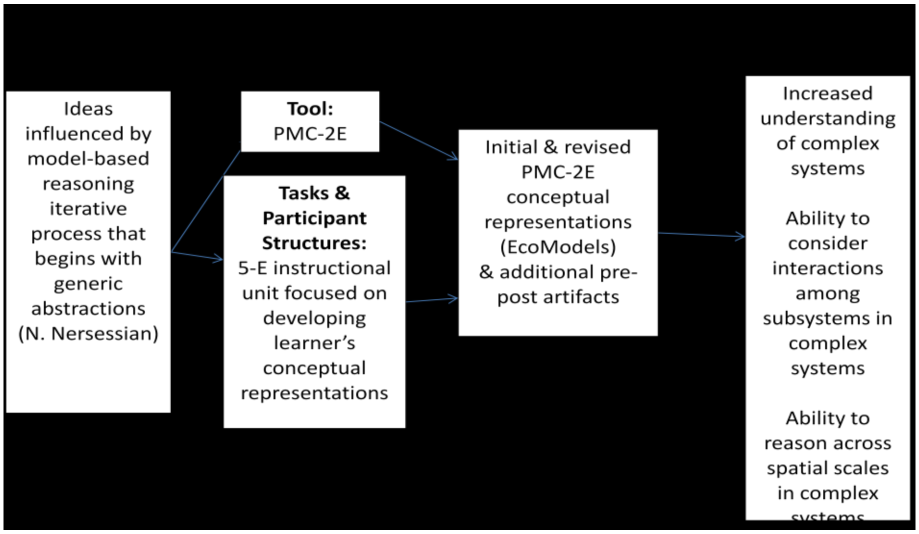


Figure 1.2: Dissertation Conjecture Map

In my first study, Chapter 2, I used a mixed-methods approach to quantify data from pre-unit to post-unit to determine whether or not students' (*n* = 23) thinking about the human climate system became more sophisticated through the use of the PMC-2E conceptual representation. By sophistication I am referring to pre-unit to post-unit changes in the types of relationships constructed within their system diagrams, the complexity of their systems diagrams, and the number of mechanisms and explanations included in their diagrams. Students began the unit by constructing an initial system model of the human climate system, made subsequent models as the unit progressed, and revised their initial model at the end of the unit. The significant results suggested that by focusing students on a conceptual representation centered on the mechanisms, their understanding of the human climate system does become more sophisticated. From pre-unit to post-unit they improved on the types of relationships, their system models became more complex, and they included a greater number of mechanisms.

Another challenge for students when developing an understanding of complex systems, is the consideration of the role of subsystems in the operation of the entire system. In the second study, Chapter 3, a mixed-methods approach was used to explore questions related to how the PMC-2E conceptual representation assists students in understanding the role of subsystems in the human climate system. Here, the treatment class (n = 23) and comparison (n = 21) classes both completed an explanation task before and after a unit on the human climate system, and these explanations were assessed for the number of subsystems as well as the quality of causal explanation linking the subsystem to the entire system. Additionally, the initial and final models created by the treatment class were assessed for the number and quality of the subsystems connected to the entire system. The positive results for the treatment class when compared to the comparison class, supports my hypothesis that by focusing students on the causal connections among the mechanisms assists them in identifying and connecting subsystems in their system models.

In my final study, Chapter 4, I explored the effectiveness of the PMC-2E conceptual representation on students' abilities to make spatial causal connections among the mechanisms in the human climate system. Students are challenged in making connections when the cause and effect are outside of their attentional frame (Grotzer, 2012). In the climate system, the mechanisms work at global, regional, and local spatial scales, posing another layer of complexity to understanding this complex system. This study also used a mixed-methods approach to analyzing pre-unit to post-unit changes in the treatment (n = 23) and comparison (n = 21) classes. Pre-unit and post-unit explanations created by the treatment and comparison classes were analyzed for the number and type of spatial causal connections made among the mechanisms. Additionally, pre-unit and post-unit models created by the treatment class were analyzed for the number of spatial causal connections made. The significant results for the treatment class only suggests that by focusing students on the mechanisms, the students also implicate the spatial causal reach and constraints of mechanisms when developing an understanding of the human climate system.

Findings from these three studies add to the research on how to assist learners in the development of systems and spatial thinking abilities. Furthermore, these findings may assist K-12 science education instructors and curriculum developers with a model for teaching about complex systems such as the human climate system and ecological systems by adding an instructional tool that not only scaffolds students as they learn about complex systems, but also provides frameworks for assessment. Finally, this work provides educators with a new lens in which to analyze student work in formative and summative assessments.

Chapter 2: Paving a Path to Conceptual Understanding of Complex Topics

Abstract

We are surrounded by complex issues, and rather than retreat from the issue or assess it simplistically, we should address them from the lens of complexity. For example, the climate change issue is complex and requires a systems-thinking perspective to fully grasp its reach. In the case of this system, there are many stakeholders and the biogeochemical system exists at many spatial and temporal scales, and has multiple interacting subsystems. Those with an ability to consider the climate system at various temporal and spatial scales as well as integrate multiple components of the climate system are the ones with the ability to solve issues as complex as climate change. But how does one develop this important skill? This mixed-methods research focused on the use of a conceptual representation to scaffold learners' system thinking while learning about the climate system. The PMC-2E conceptual representation is grounded in systems thinking and model-based reasoning research. Using this conceptual representation, students began to consider phenomena from a more abstract understanding based on prior knowledge, and as their understanding builds with new evidence about the components and mechanisms within the system, their explanations about the phenomena become more sophisticated. In this study, students used a digital platform to create and then manipulate models while learning about our human climate system. The inquiry-based unit provided ample opportunity for students to gather evidence related to the mechanisms working within the climate system. Three methods were used to assess the pre-unit and post-unit models for changes in quality and sophistication. Positive changes were found in all three areas: 1) the relationships students made within the climate system; 2) the overall structure of their models for the climate system developed greater

sophistication; and 3) the ability of the students to define their mechanisms with deeper evidence-based explanations. These promising results will not only benefit those instructing on complex topics, but will also assist us in better understanding of how individuals develop a systems-thinking perspective.

2.1 Introduction

Fundamental to science literacy is the ability to think systematically about phenomena within and across domains of science. Whether it is to understand the flow of nutrients in an ecosystem or the flow of energy in the climate system, systems thinking requires an individual to integrate their thoughts across multiple system components while considering the mechanisms that make the system work. The *Framework for K-12 Science Education* (National Research Council, 2012) recognized this need for systems thinking by including it as one of the seven cross-cutting concepts in science. "Defining the system under study—specifying its boundaries and making explicit a model of that system—provides tools for understanding and testing ideas that are applicable throughout science and engineering" (National Research Council, 2012, p. 84). Additionally, the *Next Generation Science Standards (NGSS)* (NGSS Lead States, 2013) informed by *The Framework* for K-12 Science Education, intertwines system and system models with core disciplinary ideas, and science and engineering practices throughout grades K-12. Although these important documents highlight the need for systems thinking, there remains a challenge in how to effectively integrate these ideas into frameworks for curricular design. In this study we used a conceptual representation called PMC-2E paired with modeling in the context of the dynamic climate system to help students grapple with the complexity of the climate system.

2.2 Literature Review: Challenges and the Development of Systems Thinking

The *Framework for K-12 Science Education* (National Research Council, 2012) recognized the importance of systems thinking and not only includes it as one of seven crosscutting concepts, but also mentions systems thinking within the scientific and engineering practices. Additionally, most core ideas introduced in Earth and environmental science classrooms have their foundation within a system or a cycle (National Research Council, 2012; NGSS Lead States, 2013). For example, the impacts and interactions among the different environmental spheres (geosphere, hydrosphere, atmosphere, and biosphere) reveal complex connections among all of the spheres. The cycling of water manifests itself in all of the spheres of the Earth system, as does the carbon cycle, and the climate system. However, systems are challenging to learn, and therefore classroom activities typically study isolated aspects of systems in laboratory activities without putting the entire systems back together (National Research Council, 1996).

2.2.1 Challenges in Systems Thinking

Knowing how germane systems thinking is to understanding phenomena across many disciplines, over the past few decades, researchers from many fields including the cognitive and learning sciences have been seeking to understand how individuals develop this skill. This has led to studies exploring various interventions designed to either elucidate the cognitive aspects of this skill (Hmelo-Silver et al., 2007; Hmelo-Silver & Pfeffer, 2004; Jacobson, 2001; Jacobson & Wilensky, 2006; Raia, 2005; Wilensky & Resnick, 1999) or to identify effective teaching methods to encourage the development of systems thinking (Ben-Zvi Assaraf & Orion, 2005; Kali et al., 2003; Raia, 2008). These studies and others have contributed to our understanding of how one develops system thinking abilities.

When compared to experts, it is clear that novices hold simplistic reasoning about systems thinking (Hmelo-Silver & Pfeffer, 2004; Jacobson, 2001). Jacobson in his exploratory study, created a complex system mental model framework after novices and experts responded to a number of problems related to complex organization of living systems. He identified that novices tended to hold a "clockwork" model of systems (centralized control; static structures), whereas experts tended to hold a "complex systems" model of systems (decentralized control; self-organization; emergence) (Jacobson, 2001). In the latter study, Hmelo-Silver and Pfeffer employed a structure-behavior-function (S = Structure, B = Behavior, F = Function) framework to analyze responses from middle school, preservice teachers, and aquarium experts related to aquatic systems. They found that novices tended to focus on the visible and static structures, whereas experts incorporated all three aspects into their models of the nature of aquatic systems (Hmelo-Silver & Pfeffer, 2004). This framework was subsequently applied by Hmelo-Silver et al. (2007), and was effective in identifying expert and novice differences in the understanding of the human respiratory system and an aquatic system. Similarly Raia (2005), in her exploratory study, found that the undergraduates held the static, linear-mono-causal approach to Earth processes when probed about complex phenomena in the Earth system. Finally, Levy and Wilensky (2008) found in their study of how middle school students dealt with complexity within social systems, that the students built "mid-levels" or subgroups to help them reason through systems phenomena. For example, the students either clustered the agents of the system in order to account for causality, or they divided the aggregates of the system to develop their arguments for causality.

2.2.2 Development of Systems Thinking

Knowing the challenges learners face when learning systems-related topics, interventions have been studied to assist learners in making ontological shifts from clockwork beliefs to complex systems beliefs. For example Raia (2008), who contended that understanding complex systems stems from understanding causality, coded student responses to Earth system problems focusing on four types of causality principles (efficient causality, material causality, formal causality, functional causality) based on Aristotelian concepts of causality. She concluded that when students understand causality in its differing forms, they incorporate a greater number of aspects of complex systems thinking such as emergence, self-organization, and downward causation into their models of complex phenomena. L. Liu and Hmelo-Silver (2009) applied the SBF conceptual representation (Hmelo-Silver & Pfeffer, 2004) in their intervention which compared two versions of a human respiratory system hypermedia program, a structure-focus version, and function-focused version. In their proof-of-concept study, they found that the function-focused version of hypermedia promoted deeper understanding than the structure-focused version in terms of non-salient phenomena occurring in the respiratory system. This research supports the notion that students fail in trying to grasp behavior of the underlying mechanisms.

Further, Ben-Zvi Assaraf and Orion (2005) investigated middle school students' systems thinking abilities using knowledge integration activities centered on the water cycle. These activities included concept maps, drawings, and summarizations of outdoor activities, all of which challenged the students to integrate what they learned about the water cycle. Their results showed that systems thinking can evolve over the course of a unit in stages where the next stage is dependent on the mastery of the previous stage. Thus students move from a fragmented and static view to a more dynamic view of the water cycle. Their work built on the prior work of Kali et al. (2003) who found that through the use of technology-based and inquiry-based knowledge integration activities and post-acquisition activities, students abilities to view the rock cycle as a system also improved from static to dynamic views. Here authors in both studies found that students recognize the simultaneously moving parts of the cycles in question after the intervention.

2.2.3 The Human-Climate System

Our climate system serves as an excellent example of a complex system in nature where multiple subsystems are interacting and negative and positive feedbacks prevail at various spatial and temporal scales. Understanding the system properties of the climate system has been deemed so important to climate literacy that it is listed as one of the core principles of climate literacy for all Americans: "Principle 4: Earth’s Weather and Climate Systems are the Result of Complex Interactions" (U.S. Global Change Research Program/Climate Change Science Program, 2009). For these reasons, and those outlined in the NGSS (NGSS Lead States, 2013), the climate system was selected as the science content focus for this study.

Several researchers have uncovered challenges related to understanding weather and climate concepts and have offered interventions to overcome these challenges. For example, Dove (1998) in her review of the literature identified that students have incorrect and/or oversimplified alternative conceptions about weather and climate concepts. Similarly, Henriques (2002) created a side-by-side comparison of scientific views versus student misconceptions of weather and climate concepts and claims that these misconceptions have not been addressed in the learning process. Both of these researchers suggest that a concerted effort is need to identify and then eradicate these misconceptions. Harrington (2008) argues that the pathway to overcoming the inherent misconceptions about emergent properties in the climate system (e.g. relationship between ocean circulation and mild European winters) held by students is through the use of critical thinking and argumentation. At a fundamental level, McCaffrey and Buhr (2008) suggest that through the use of teacher professional development and the identification of quality climate education resources, the challenges students have with climate concepts can be addressed. At a broader scale Dupigny-Giroux (2010) identified and defined six challenges for climate literacy which included learning, teaching and curricular needs. She also cited the role of life-experiences in shaping ones ideas about climate.

There have been a few studies directly related to overcoming these challenges. To address the flawed mental models students hold about the climate system Rebich and Gautier (2005) successfully tested the use of a mock trial setting which raised the undergraduate students epistemological awareness and motivation which in turn promoted conceptual change related to climate change topics. From their review of the literature on climate change education Shepardson et al. (2012) created a climate system framework and subsequent conceptual progression identifying three levels within their progression. Continuing their efforts in this area they created, administered and scored a climate system task taken by grade 7 students to uncover their ability to think about the climate system as a system (Shepardson, Roychoudhury, Hirsch, Niyogi, & Top, 2014). They found that students in their study conceptualize the climate system as unidirectional and linear and that they focused mostly on the atmospheric component of the system. Finally, Lombardi, Sinatra, and Nussbaum (2013) used climate change as a vehicle to successfully test their conceptual change intervention, which included the use of a critical evaluation tool to affect plausibility judgments related to different models for climate change.

Continuing the effort in developing methods to assist learners in understanding complex topics like the climate system, we therefore test a systems thinking conceptual representation as paired with climate system education to determine if students are better able to generate causal explanations. The theoretical foundation for this conceptual representation is presented next followed by an elaboration on the conceptual representation framework employed in this study.

2.3 Theoretical Framework

2.3.1 Generic Models and Conceptual Representations

The foundation of the framework in this study is built on research about the prior knowledge learners bring to instruction which includes their mental models as well as their conceptual representations. In their conceptual change study Griffith, Nersessian, and Goel (1996) argued that generic models are central to conceptual change, and that these generic models are built on the theory of constructive modeling and adaptive modeling. In this study we are applying their theory of constructive modeling which states that learners bring with them situation independent abstractions, or generic models.

In their example from the domain of physics, the authors of the study focused on the effort of one student who in trying to explain how a spring works, drew upon his mental model of a flexible rod to do so. The authors called this constructive modeling because the student engaged his generic mental model to iterate through the process of constructing an accurate model of the functioning of a spring, the target of his thought processes. They argue that the learner brings with them a set of generative principles inclusive of constraints that bridge domains and it is through the elicitation and manipulation of these generic models and constraints that constructive modeling in the new domain occurs. However, the constraints on the principles and models tend to be domain specific and therefore the learner must reinterpret these constraints as being generic before applying the generic models. They call this generic abstraction. In this study, we contend that students bring with them a productive generic mental model of weather, and it is through the generic abstraction of the constraints of their mental models they build their understanding of the climate system through the constructive and adaptive modeling process.

In our study students employ a visual modeling platform (i.e. a digital software program) to create their external visual representations of the climate system. Nersessian (2002) contends that external visual representations are part of an individual's cognitive system. "They aid significantly in organizing cognitive activity during reasoning, such as fixing attention on the salient aspects of a model, enabling retrieval and storage of salient information and exhibiting salient constraints, such as structural and causal constraints, in appropriate co-location. Further they facilitate construction of shared mental models within a community and transportation of scientific models out of the local milieu of their construction" (Nersessian, 2002, p.148-149). Nersessian (2008b) and Clement (2008) both reference the importance of model-based reasoning to the field of science, as models systematically guide a researcher in their endeavors.

Modeling as a practice in science and therefore science education is inclusive of externalizing ones mental models so that they can be manipulated, revised, and used as a basis for argumentation. Here learners use a digital modeling tool as a platform to externalize their mental models in the form of concept maps. External representations such as these allow learners to offload tough concepts which can be described as intrinsic cognitive load (de Jong, 2010). The dynamic nature of the scaffold used in this study affords them the ability to revise their models as evidence becomes available.

In addition to modeling, we employ a conceptual representation to embody the progression of learning taking place during the unit of study. Davis, Shribe, and Szolovits (1993) identify the roles representations have in assisting a learner in sense making, all of which are related to the foundation on which a learner can initially build their ideas. For example, representations can act as a mental substitution for the actual entity, it has ontological commitments, they are fragmented (but robust) theory, they are efficient, and they are personal to the individual making sense. Therefore, representations provide an organizational framework to begin to think about phenomena, or in the case of this study, our complex human-climate system.

Within the model evolution process students begin with a generic idea of a phenomena (Nersessian, 2002) or an anchoring conception (Clement, 2008). This conception begins the process where a conceptual model evolves over an instructional sequence or "learning pathway" in the development of an explanatory model of phenomena. In this study, we argue that the learner's external visual representations are platforms upon which the negotiation between their initial beliefs, new understandings, and reality play out. This negotiation is facilitated by the conceptual representation.

2.3.2 The PMC-2E Conceptual Representation

Research on the structure-behavior-function (SBF) conceptual representation (Hmelo-Silver et al., 2007; Hmelo-Silver & Pfeffer, 2004; L. Liu & Hmelo-Silver, 2009) informed the creation of the PMC-2E conceptual representation (Jordan et al., 2014). Our framework differs in that it is grounded in the model-based reasoning framework as described by Nersessian (2002, 2008b) who defines it as the scientific practice of "making inferences from and through model construction and manipulation" (Nersessian, 2008, p. 63). Jordan et al. (2014) posits that students' model the phenomenon (P) which includes components (C) from that phenomenon that can be linked to generic (i.e. not entirely linked to the context) mechanisms (M). In this research, students employed this model-based reasoning conceptual representation throughout a unit on the human climate system while focusing their model manipulations on mechanisms linking components. At the onset of the unit on the human climate system, the target model for this study, a student's generic abstraction (generic principles) may include a view of climate as being the weather they experience on a daily basis. This initial model sets the stage for engagement in the phenomena and the development of more sophisticated models. As students investigate various mechanisms their model expands as evidence (E) supports their explanations (E). As opposed to starting with previously learned components and their associated mechanisms when thinking about complex systems, the PMC-2E conceptual representation encourages students to think about generic mechanisms first in an effort to identify plausible causal agents. This we argue will encourage creativity in the scientific process of model building as noted in Jordan, Hmelo-Silver, Liu, and Gray (2013). (See Figure 1 below)

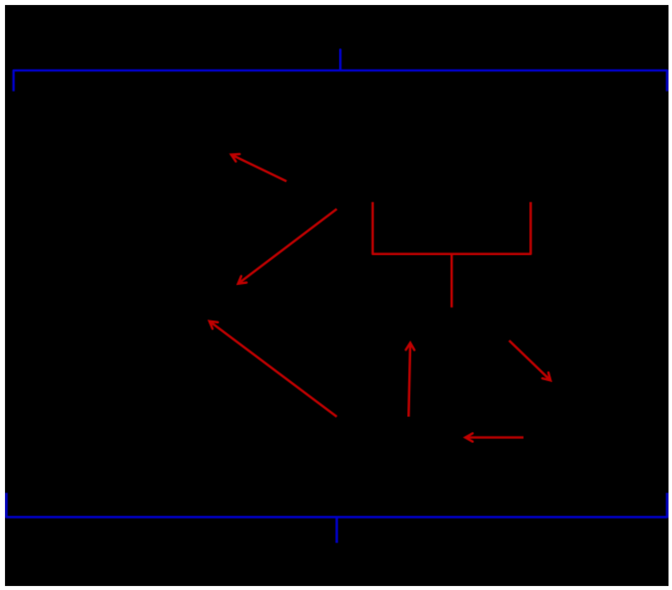


Figure 2.1: The PMC-2E conceptual representation.

2.3.3 The Present Research

As previously supported, conceptualizing complex systems with many components and subsystems interacting at various temporal and spatial scales poses a challenge to students. We suggest that it is with the support of framework such as the PMC-2E framework that encourages students to generate explanations about system level phenomena. In this study students ground their thinking about previously learned causal agents when they were introduced to the climate system. The PMC-2E conceptual representation allows them a space with a modeling tool to offload and change ideas while learning about the climate system. Students focused on what they already knew about mechanisms and used that prior knowledge as a stepping stone to identifying components (C). Over the course of an inquiry unit, students linked these to evidence and developed explanations (2E) about the phenomenon in an iterative process.

Given the challenges of systems thinking in general and systems thinking related to the human climate system more specifically, this study investigates a conceptual representation framework as an intervention to scaffold students through complex science topics. It combined the PMC-2E conceptual representation and concept mapping to create a dynamic scaffold to assist learners with developing sophistication in their systems thinking. Similar to past research, in this study, scaffolding assists learners throughout their exploration of the climate system. However, in this context the scaffold is dynamic, and learners build complexity into their systems as the unit progresses. The dynamic scaffold advances with the students throughout the unit so that they can modify their models as more evidence becomes available. In this study "sophistication" is defined as an improvement in the quality of students' conceptual understanding of complex systems when compared with experts over the course of a unit on the climate system. By quality we are referring to the types of relationships students include in their models (e.g. appropriately connected and labeled components and complexity of their models and the integration of explanations to support their mechanisms and connected components).

Based on the above outline, our research questions are centered on what changes occur when students engage in instructional activities that employ the PMC-2E conceptual representation as a dynamic scaffold in development of complex systems thinking. More specifically we are asking:

RQ1: What changes occur in the quality of the students' models as determined by the types of relationships they construct among the components?

H1: It is assumed that by engaging in PMC-2E students identify and explain the relationships between components, as noted by the strength of connections among components in the models

RQ2: What changes occur in the complexity of structure in students' models?

H2: It is expected that as students engage in PMC-2E during the unit on the human-climate system the complexity in their climate models will increase, as noted by the arrangement of nodes and links in the models

RQ3: What changes occur in the number of incidences of mechanisms and explanations as scored with PMC-2E framework?

H3: It is also expected that while engaging in PMC-2E within the unit, the students will include a greater number of mechanisms and explanations in their climate models.

2.4 Methods

2.4.1 Participants and Setting

The sample for this study consisted of 23 (females = 15; males = 8) high school juniors and seniors (16-18 yrs of age) from one class of an advanced environmental science course in a suburban East Coast U.S. school. Classes meet three out of four days for a total of 3.5 hrs per four day cycle. Data were collected in the spring semester during a unit on global climate change, a unit in a year-long curriculum aligned with state standards for learning in science. The content of the unit was not augmented in any way from the prescribed content and methods for this school district. Instead, it was enhanced with the scaffold discussed below in the procedure. The school district adopted unit included many inquiry-based and content rich lessons related to state standards for learning in science which were retained for this study. For example, students explored the impact of solar radiation on different Earth surfaces through a laboratory experience and then subsequently referred to available global data to compare their laboratory results.

2.4.2 Study Design and Materials

The unit in this study consisted of six lessons (see Table 1) that followed the 5-E (engage, explore, explain, elaborate, evaluate) instructional model (Bybee et al., 2006), which spanned eleven days of instruction and included specific measures to scaffold systems thinking. Students were engaged in group and individual activities that tied each lesson into systems thinking terminology and frameworks. For example, students were first introduced to system terminology (mechanisms, components, sources, sinks, etc) during the weather and climate lesson and subsequently applied these terms to aspects of weather and climate. Each successive lesson linked climate subsystems to the greater climate system through investigative activities where evidence was gathered and analyzed. For example the lesson on surface albedo is related to energy budget subsystem, and the ocean acidification lesson is related to the carbon cycle subsystem of the climate system. All lessons were aligned with district and state standards for science learning and were typical for this school district which supports inquiry and investigative approaches to science teaching and learning.

Sequence of Lessons	**Lesson Objectives**	**Lesson Activities**
1. Is it weather or climate?	Apply correct definitions of weather and climate to the interpretation of datasets and	*Initial climate system EcoModels were created prior*

	define climate as being inclusive of multiple interacting subsystems such ocean and atmosphere, and solar energy and albedo	*to the lesson activities.* Personal weather stories – was it a weather or climate phenomena? Analysis of climographs Analysis of GLOBE poster satellite images
2. What are greenhouse gases?	Identify key greenhouse gases and the role they play in changing the Earth's climate.	Brainstorm why certain gases are considered greenhouse gasses. Analysis of spatial and temporal trends in greenhouse gases from IPCC data Analyze the carbon cycle for sources, sinks, etc from a systems perspective
3. What happens when we change the Earth's surface albedo?	Identify and apply the mechanisms by which Earth's surface albedo can change.	Review of aspects of the global energy budget Investigation to define the

		concept of albedo and the role it plays in the global energy budget *Albedo EcoModels were created and refined during the lesson.*
4. What are the impacts of a changing climate on marine organisms?	Develop a model that demonstrates the mechanism by which ocean acidification occurs and the impacts it has on marine organisms.	Use images to elicit ideas about constitutes a coral ecosystem Lab investigation related acids and carbonates Compare data collected to online data sources from coral ecosystems & global climates *Ocean acidification EcoModels were created and refined during the lesson.*
5. What can we learn from climate models?	Identify the explanatory and predictive capabilities of global climate models, and run	Identify types of models and uses of models

	and interpret data from a global and a regional climate model.	Explore a very basic model and a more complex model and compare attributes
6. Strategies to lessen the impacts of climate change: mitigation, adaptation, resilience	Develop a plan to lessen the impacts of climate change that includes the integration of mitigation, adaptation, and resilience.	Roundtable discussion from viewpoints of various stakeholders *Final revision to climate system EcoModel.*

Table 2.1: Lessons, objectives, and activities employed within the instructional unit in this study including the timing of the creation of the EcoModels assessed in this study.

To scaffold and capture the development of their ability to reason about systems, students used an online cognitive mapping tool called EcoModeler (Jordan et al., 2013) (see Figure 2). This tool was developed to assist students in creating external representations of the phenomena within the unit. Students were familiar with this tool because they used it in a previous lesson to model aspects of ecosystems, but did not use it to apply the PMC-2E framework within that lesson. In this study, students were provided with the phenomena (P), (how are humans impacting our climate system), and from their background knowledge, they identified possible mechanisms (M) and interacting components (C) functioning within the climate system, and then connected these components with the mechanisms at work. They had the opportunity to revise their models as evidence (E) was made available through the lessons of the unit, and when they did, they added explanations (E) of how the mechanisms interact within the climate system to their models either directly on the model or in the "notes" section provided on the template.

Students used their models to guide their explorations, gather evidence from laboratory investigations, and develop explanations for the causes of the phenomena. Students each created a total of four models. They created a model of their understanding of the human-climate system at the beginning of the unit as a pre-unit assessment and again at the end of the unit as a post-unit assessment. They also created and modified models during and after a lesson on the surface albedo (lesson #3), and during and after a lesson on ocean acidification (lesson #4). In the case of the pre-unit model students spent time crafting an EcoModel demonstrating their understanding of the human-climate system (P), and at the end of the unit, the students revised their initial models based on what they learned throughout the unit. In the case of the albedo (P) and ocean acidification (P) EcoModels, the students were given the phenomena, and were asked to create an EcoModel for each based on their understanding of the phenomena. At the end of each of the lessons, they made revisions to each model based on what they learned from the lesson. A total of ninety-two models were coded and analyzed.

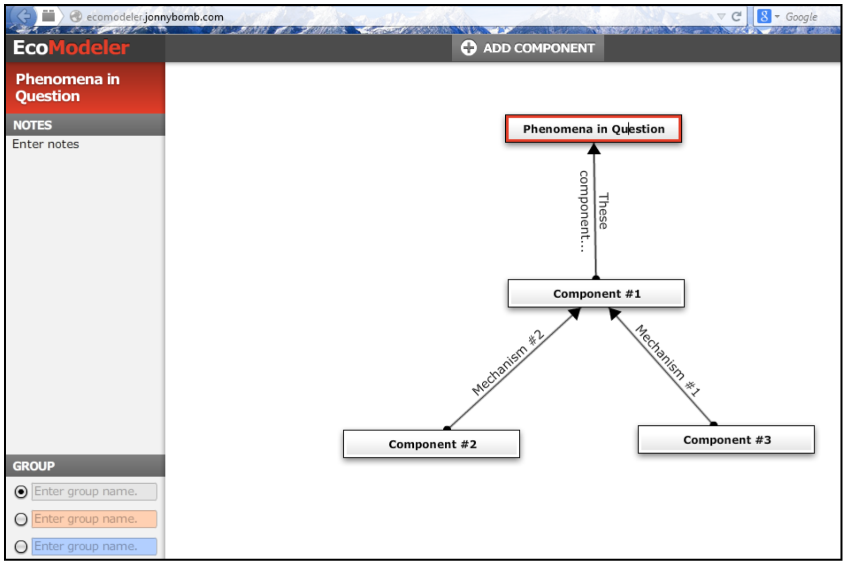


Figure 2.2: The EcoModeler online concept mapping tool

2.5 Procedures

This study employed a mixed-methods design where qualitative data were coded and "quantized" as described by Miles and Huberman (1994). At the end of the unit all of the conceptual representations were coded and scored using two concept map schemes (relational scoring and structural complexity), and they were also scored using a PMC-2E scheme. (See Table 2) In addition to the PMC-2E coding scheme used to identify mechanisms and explanations, the concept map coding schemes were used to inspect the connections and shapes of the models. Each scheme is described in detail below. These three coding methods allowed for the quantification of the content of the conceptual representations to reveal the development of students' systems thinking across the unit. Additionally, these methods were identified to triangulate the results and therefore complement each other where the results of one scheme be viewed in light of the results of the other two schemes. Inter-rater reliability analysis was performed by the author and a research climatologist for at least 20% of the cases in all three scoring methods. The resultant Kappa value for the relational scoring was found to be 1.00, $p < 0.001$, and for the structural scoring and the PMC-2E scoring it was found to be 0.79, $p < 0.001$. These scores indicate high reliability in the qualitative scoring (Cohen, 1960). All discrepancies were resolved through discussion.

Scoring Method	**Model Attributes**	**Research Question** *(…what changes occur in…)*
Relational	Strength of connections among components	the quality of the students' models as determined by the types of relationships they construct among the components
Structural	Arrangement of nodes and links	the complexity of structure in students' models
PMC-2E	Counts of components, mechanisms, and explanations (students were provided with phenomena and evidence)	the number of incidences of mechanisms as scored with PMC-2E framework

Table 2.2: Coding and Scoring Methods

2.5.1 Relational

McClure, Sonak, and Suen (1999) compared the coding reliability of six concept map scoring methods and found that the relational scoring method using a master map produced the most reliable scores in terms of the accuracy of the student's maps. In this method, scorers followed a decision tree where each proposition (two concepts with a connector) was given a value between zero and three depending on the strength and validity of the relationships among the propositions. We used the decision tree in Figure 3 to score all the conceptual representations. Students in this study were not provided a list of concepts to employ in their models, and therefore the relational scoring method was applied here without a master map to allow for student ingenuity and creativity. Gains in this scoring method show that students are making deeper connections within their propositions based on the accuracy and detail in their connected components and mechanisms.

[redacted]

Figure 2.3: Relational Scoring decision tree with examples. (McClure et al., 1999)

2.5.2 Structural

Complexity of a concept map as described by Novak and Gowin (1984) requires that a concept map be hierarchical and as new information is learned, the information is subsumed under the hierarchy. However, Ruiz-Primo and Shavelson (1996) approach concept mapping from an associationist network theory in which concept maps are networks where networks radiate from concepts using directional arrows, and multiple lines may radiate from concepts, and there may be links among subsets of concepts. Furthermore, Kinchin (2000) noted that a network concept map demonstrates "meaningful learning" which he defines as the opportunity for both the teacher and student to make explicit the interaction of new and existing knowledge, and concept mapping is a useful tool for doing so. It was this approach that informed the second coding scheme used in this study which scored the models based on their structural complexity. This coding scheme was adapted from a similar scheme first presented by Kinchin and Hay (2000) and then updated by Yin et al. (2005). Kinchin and Hay (2000) identified three key map types when assessing concept maps created by grade eight students: spoke, chain, and net, each of which is progressively more sophisticated than the previous map. Yin et al (2005) expanded on this list of three map types by including linear and circular types in their typology. To score for structural complexity in this study we expanded on the scoring outlined above to include a total of nine key map types: linear, circular, circular complex, hub and spokes, hub and spokes complex, tree, tree complex, and network complex. (See Figure 4) These additional map types were included in order to indentify nuances in student thinking about system complexity, and manifested itself as an extra loop, or branch not captured in the structural form not listed as complex. The maps scored on a scale of 1 to 9, based on the pattern they most closely matched. Gains in this scoring scheme shows students are connecting their propositions and developing more complex models of the phenomena.

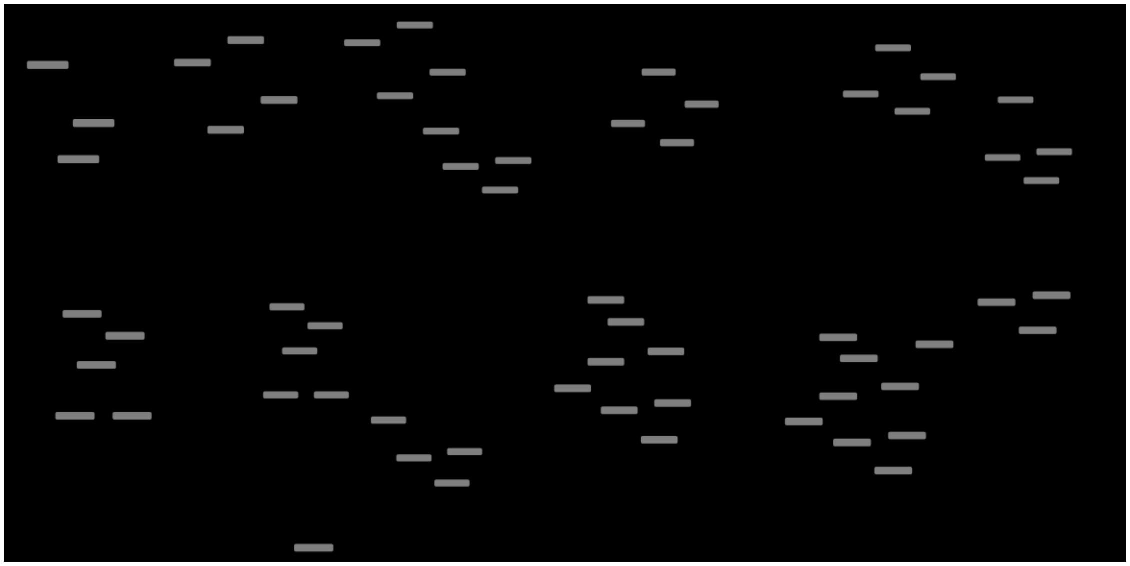


Figure 2.4: Structural Representations modified after Yin et al. (2005)

2.5.3 PMC-2E

We used an inductive approach (Patton, 2002) to develop a coding scheme for students' pre-unit and post-unit PMC-2E conceptual representations. In this study the phenomenon (P) in question was the functioning of the Earth's climate system, and was provided to the students. The students selected their own components (C), mechanisms (M), and explanations (E) when they created their representations. Evidence (E) was derived through the inquiry lessons, and was discussed as a class. After reviewing all of the representations a list was created for components, mechanisms, and explanations. (See Table 3) These lists served as the basis for the counts of components, mechanisms, and explanations in each of the student's pre and post unit representations. The inclusion of each component, mechanism, or explanation was counted as one instance, and model score was a total of all components, mechanisms, and explanations employed in the model. Gains in this scoring method demonstrate that as students gather evidence, they are moving from a generic conceptual representation of the phenomena to one that is more sophisticated.

PMC-2E	Sample data
Components (C)	terms such as ocean, land, atmosphere, water cycle, wind patterns
Mechanisms (M)	connected weather components as influencing the climate system, interactions of the carbon cycle influencing the climate system
Explanations (E)	explanations describing how the mechanisms connects the components such as "carbon enters the ocean from the atmosphere and affects ocean acidity"

Table 2.3: Examples of coded content

2.5.4 Pre-Unit to Post-Unit Differences & Assumptions Testing

As noted above, model *quality* was determined by the analysis and comparison of the relational coding of the pre-unit and post-unit models using the coding scheme by McClure et al. (1999). Model *complexity* was determined by the analysis and comparison of the structural complexity of pre-unit and post-unit models using the modified Yin et al. (2005) scoring scheme of nine different structural shapes. Finally, the pre-unit and post-unit models were scored based on the PMC-2E conceptual representation framework developed by the authors of this study.

For the relational data, analysis was performed using the Wilcoxon Signed Rank Test (Pallant, 2007; Patton, 2002) because the data were non-normally distributed (pre-unit skewness of 1.76 (SE = 0.48) and kurtosis of 3.24 (SE = 0.94) and post-unit skewness of 1.37 (SE = 0.48) and kurtosis of 2.21 (SE = 0.94)), and the Shapiro-Wilk test proved not to be significant ($p > .05$). The remaining data (structural complexity and PMC-2E) met the fundamental statistical assumptions of normality, linearity, and homogeneity necessary to run paired-sample *t*-tests (Field, 2013; Kachigan, 1986). An alpha level (p) of 0.05 was used for all statistical tests, and the effect-size was calculated using a *z*-score for the relational scoring, and the Cohen's *d* for the structural data and the PMC-2E data.

2.6 Results

2.6.1 Model Quality

Following the decision tree from McClure et al. (1999), each proposition (2 linked components) in all of the conceptual representations were scored. On average, the quality of student's conceptual representations increased from pre-unit (M = 16.96; SD = 9.84) to post-unit (M = 26.35; SD = 15.11). This difference, 9.39, was significant using the Wilcoxon Signed Ranks Test, $p < 0.002$, and represented a medium-large sized effect using a *z*-score of -3.087 and an n of 23. The pre-unit to post-unit change in model quality ranged between -1 to 28 points with 15 students increasing in the number of 2 pt and/or 3 pt relations in their models.

During the unit students created models as they participated in inquiry-based lessons on these topics. Assessing these models revealed a few patterns related to the conceptual understanding of the climate system in general, and systems thinking more specifically. For example, those students who incorporated both subsystems (albedo and ocean acidification) or one subsystem in their post-unit representations showed an average relational scoring gain of 12.07 (n = 14; SD = 10.17), and those who did not incorporate either subsystem in their representations on average only showed a gain of 5.22 (n = 9; SD = 4.32).

2.6.2 Model Complexity

Added to the structural complexity assessment by Yin, et al. (2005) were four additional levels of complexity which was found to be effective in identifying smaller shifts in conceptual understanding of the climate system. Subsequently each conceptual representation was scored for its complexity and given a score between 1 (linear) and 9 (network complex). On average, the complexity of student's conceptual representations increased from pre-unit (M = 6.35; SD = 2.06) to post-unit (M = 7.74; SE = 1.91). This difference, 1.39, was significant $t(22) = -3.47$, $p = 0.002$, and represented a medium-large sized effect, $d = 0.72$. See Figure 5 for an example of a pre-unit to post-unit shift.

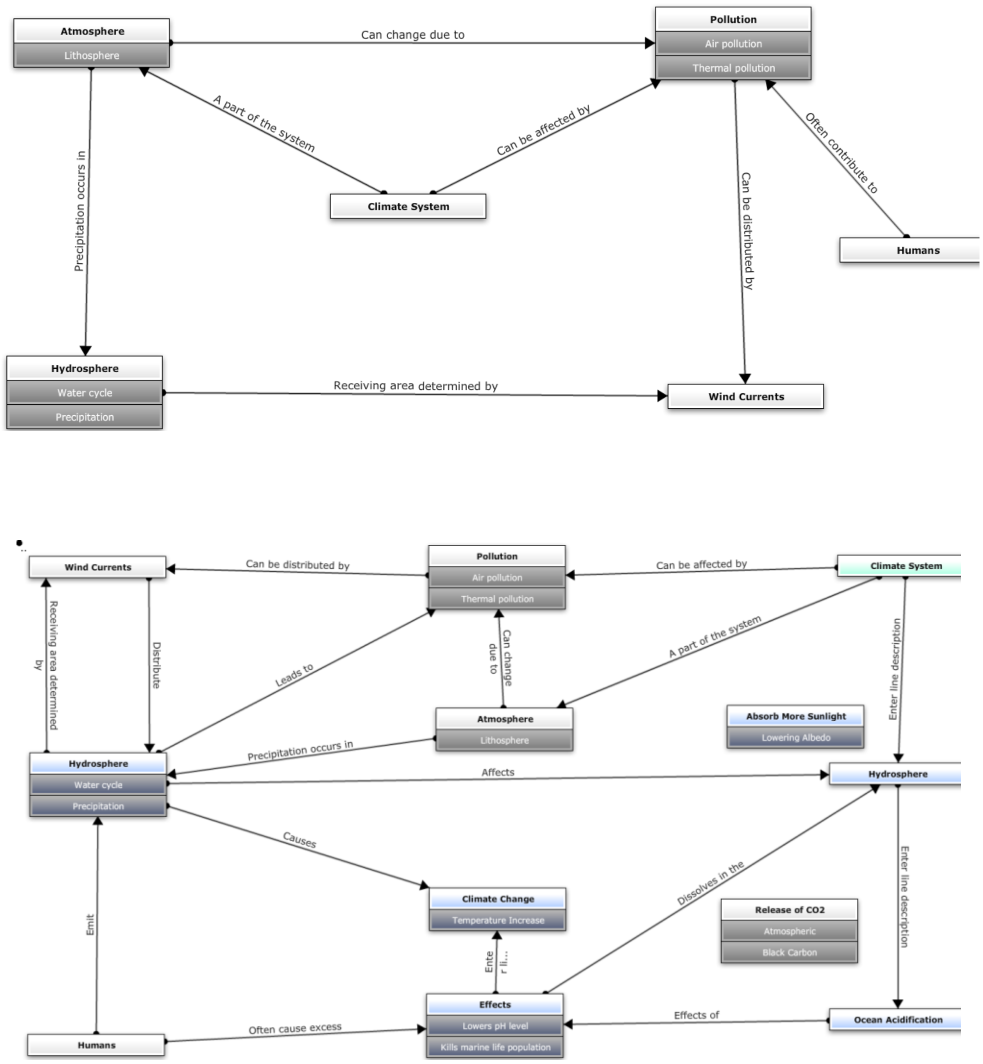


Figure 2.5: Sample pre-unit Ecomodel scored as circular complex in the top image, and post-unit EcoModel scored as network complex in the bottom image.

The EcoModeler tool allowed the students to add line comments to add explanations to their models, color to show groupings in their models, properties of the components, and additional notes to support their understanding of the phenomena, which along with the structure of their representations demonstrated complexity in their thinking when used in their representations (See Figure 6). The use of these modeling tools increased over the course of the unit, and was employed most extensively in the albedo lesson. For example, from pre-unit to post-unit, line comments were used by 4 additional students, properties were added by 7 additional students, color was added by 10 additional students, and notes were added by 6 additional students.

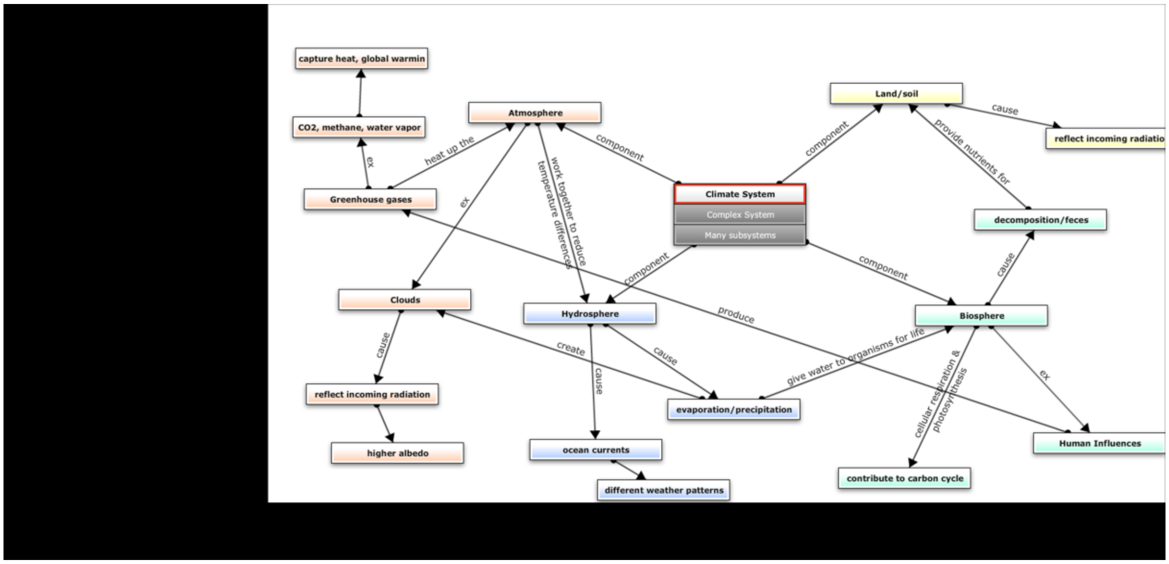


Figure 2.6: Student sample of a post-unit EcoModel included added color, line comments, properties, and notes.

2.6.3 Applied PMC-2E Framework

The results of the PMC-2E framework coding for the models are in Table 4 where the scores represent counts of components, mechanisms, and explanations. In each aspect of the scoring there was an increase that was significant ($p < 0.001$) and a large-sized effect (Field, 2013).

Pair	Pre-Unit *M* (*SD*)	Post-Unit *M* (*SD*)	*t* (*df*)	*p*	Cohen's *d*
Component	9.83 (3.77)	14.30 (5.15)	-8.072 (22)	<0.001	1.68
Mechanism	3.17 (1.83)	4.83 (2.46)	-4.830 (22)	<0.001	1.01
Explanation	6.17 (6.65)	11.70 (8.85)	-5.719 (22)	<0.001	1.19

Table 2.4: Changes in conceptual representations pre and post unit (n = 23).

The sophistication of student models as demonstrated through the coding of PMC-2E increased across all students, although not all students increased in all areas of their models. (See Figure 7 for sample) By providing students with the PMC-2E dynamic scaffold, 87.0% (20 of 23) of the students increased in their use of either mechanisms or explanations, whereas 69.7% (16 of 23) of the students increased in their employment of both mechanisms and explanations in their system models.

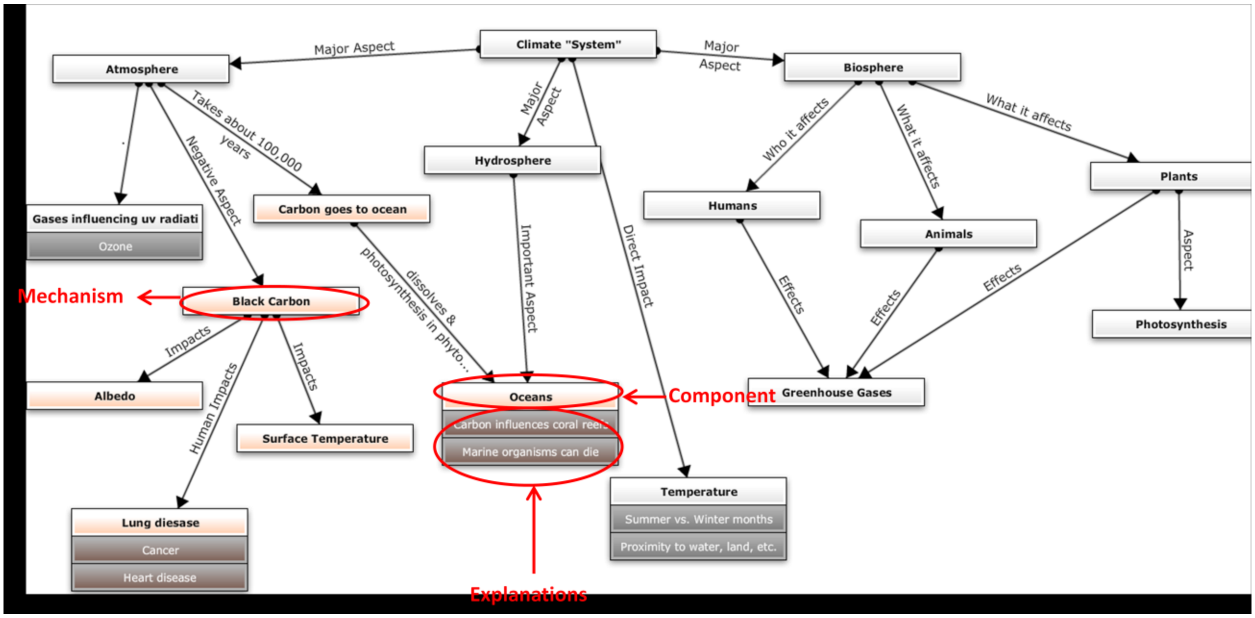


Figure 2.7: Sample post-unit EcoModel. From pre-unit to post-unit the components increased from 11 to 15, mechanisms increased from 3 to 7, and explanations increased from 5 to 23.

2.6.4 Combined Indicators of the Effectiveness of the Intervention

Each of the three scoring methods found significant results, with medium to large effect sizes. Therefore, our findings indicate that the use of PMC-2E conceptual representation does likely increase the sophistication of student explanations regarding components and connections in the climate system in a way that has practical significance to both educators and educational researchers. Figure 8 shows the means of all three scoring schemes combined. In total the students' could have increased their scores in five areas from pre-unit to post-unit: their relational score, their structural score, and within PMC-2E their component score, mechanism score, and explanation score. On average students increased in 3.91 (n = 23) scores of the five, where only one student had no improvement in any score because their conceptual representation did not change from pre-unit to post-unit.

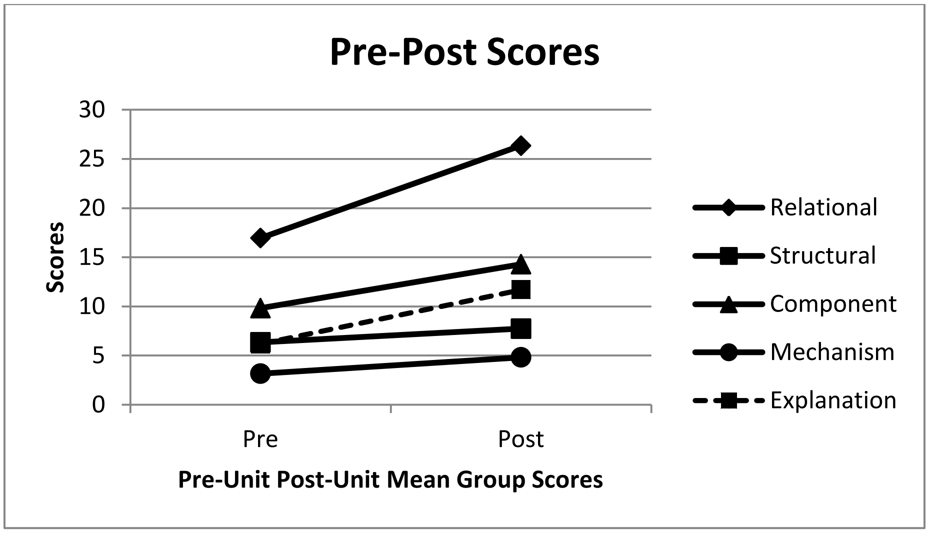


Figure 2.8: Means of the three scoring schemes (relational, structural, and PMC-2E which included components, mechanisms, and explanations) for pre-unit and post-unit. The phenomena and evidence were provided to the students and therefore not included here.

2.7 Discussion

Overall our results show that the students experienced changes in the quality and complexity of their climate models when supported by dynamic scaffold grounded in the PMC-2E conceptual representation. We hypothesized that by explicitly assisting the students in foregrounding the mechanisms of the phenomena, offloading and organizing their thoughts and directing students to identify explanations for the phenomena all within a space that allows for revisions assists the students over the hurdles of learning how to think scientifically. They do this by organizing their prior knowledge (generic models) about the climate system to better address specific problems within the climate system. The positive changes in the three combined indicators demonstrated that students developed more sophisticated climate models based on structures, mechanisms, explanations, and relationships.

Articulating the complexity of a system to include decentralized control, causality, and emergent properties is a challenge for novices who tend to focus on surface features of a system (Hmelo-Silver et al., 2007). In their expert-novice study on the development of complex systems thinking Hmelo-Silver et al. (2007) employed the structure-behavior-function (SBF) conceptual representation in their analysis and found that novices tended to focus on structures and not the mechanisms leading to causality within the system which experts attended to in their representations. Similar to their results, this study found that from pre-unit to post-unit more than half (n = 15) of the students labeled a greater number of their propositions with a relationship quality that was hierarchical, causal, or sequential thus showing an increase in the quality of their explanations. The reason for this increase may be because students using the PMC-2E conceptual representation framework were asked to make explicit the mechanisms by which parts of a system achieve a function.

Models of the climate system drawn by climate experts are extremely complex and include multiple subsystems interacting over space and time. The structural complexity of these models would be scored as network complex; however, their models would also include positive and negative feedback loops providing mechanisms that drive the climate in a direction toward warming and cooling. In this study, some students crafted network complex models of the climate systems, but it was not surprising that they did not include all of the specific details that would be found in a model developed by a climate expert. However, similar to how explanatory models in science evolve

(Clement, 2008), the dynamic nature of PMC-2E allowed the students to move towards greater structural complexity of the climate system models as they gathered more evidence to support their explanations. Furthermore, the EcoModeler platform allowed the students the ability to add notes and colors enhancing the complexity of their models by affording them additional space to describe, explain, support their human-climate system models.

2.7.1 Limitations and Future Directions

This study served as a basis to begin to understand how the PMC-2E scaffolds students thinking about complexity. In this regard, there are limitations to this effort. For instance, having a comparison group in a future study will assist in the analysis and assessment of effectiveness of PMC-2E. Additionally, three schemes were used to score the resultant models in this study, and although each provided insightful information, other scoring schemes may have provide other important insights to answer adjoining questions related to thinking about complex topics such as the climate system. For example, in the economics and systems dynamic research of Doyle, Radzicki, and Trees (2008) they assessed the effects of a systems intervention on the development of complex systems thinking in 46 subjects. They scored the causal diagram outputs of the subjects using two methods: detail complexity and dynamic complexity. They defined detail complexity as the amount of content (nodes and links) and dynamic complexity as an understanding of systems thinking features such as feedbacks and causality as well as the length of the causal path from the initial phenomena. Although dynamic complexity was not a focus in our research, given the importance of it in systems thinking, future research questions may benefit from employing a scoring protocol that includes this feature.

The results of this study also serve as a springboard for additional studies involving the PMC-2E conceptual representation framework in developing complexity in system thinking. For example, it was observed in this study that many of the students used the instruction on two subsystems (the roles of albedo and ocean acidification on the climate system) in their post-unit models; however, further research in this specific area is needed to capture the development of how students aggregate subsystems into broader systems. Levy and Wilensky (2008) found that when students were presented with complex social phenomena they tended to either break the complexity down into smaller groups, or assess the individuals in the entire complex phenomena and subsequently group them into groups with likenesses. Levy and Wilensky (2008) called this method that students employed while attempting to understand the dynamic nature of the system as "mid-level" construction. This focusing on breaking down aggregate models, or building up from agent-based models assists students in learning about emergent properties. Along this line of research and in summarizing her research, Raia (2012) recommended that students be permitted to manipulate both agent-based and aggregate system models to develop complex thinking in the geosciences. Future research comparing the use of both forms of system models using the PMC-2E conceptual representation as a scaffold has the potential to reveal the strengths in using both forms of system building.

2.8 Instructional Implications

Systems thinking and modeling are two of the seven identified crosscutting concepts of the Next Generation Science Standards (NGSS Lead States, 2013), and the PMC-2E conceptual representation is poised to be an effective instructional intervention to scaffold students while they develop these skills and blend them with the core ideas and practices of science. Within units on complex topics such as the climate system and ecological systems, explicit instruction on systems thinking and modeling can guide students as they reason with evidence to create deeper models of phenomena. Their systems grow more complex as this dynamic scaffold is utilized either by individual students or by collaborative groups of students and feedback is provided by the teacher.

Developed from the information included in the models created by the students in this study, Table 5 includes a set of characteristics found in student thinking about the human-climate system. The sophistication increases down the table as students consider the multitude of levels (spatial and temporal) and causality for what is dynamics found in the climate system. This information may assist an instructor in determining the prior conceptions student hold before beginning a unit on the human-climate system.

Sophistication of Student Explanations of the Human-Climate System	
Climate ***is*** Weather View (phenomena-component view)	This view is characterized by a limited understanding of the role of the components (sun, clouds, etc), and considers climate as daily weather or the average of their daily weather. They also believe that temperature and humidity vary by location, but do not consider the causal relationship (mechanisms) among the climate elements to create differences in the temperature and humidity at these locations (phenomena).

Climate ***as*** Weather View (phenomena-component view; temporal and spatial considerations are limited)	View is limited to the weather phenomenon that takes place at the local to regional scale, or on a daily or annual basis. The learner has difficulties conceiving of the temporal and spatial dimensions of the climate system. Their perception of climate change is within their temporal and spatial understanding of the dimensions of the climate system. Mechanisms in weather and climate are not identified.
General Global Climate System (phenomena-component view at local regional and global levels; mechanisms understood at local level, but a challenge at the global level)	Although this learner understands their local and regional climate, they may have difficulty understanding that the climate system is more than the basic processes taking place at the global scale. Regional interactions define the variability found in the climate system. They also see the climate system as something "big" and "out there" and thus are not concerned about how climate change may affect their local climate. They may also have difficulties in conceiving the temporal dimensions of the climate system.
Climate System is Complex	

	A view which identifies interactions among the climate components as they may affect parts of the entire system. However, there exists an individually selected central point upon which all other interactions are based. They can identify with the temporal and spatial dimensions of the climate system although it would be focused on their locus.
Complex Interactions underlie the Climate System Decentralized interactions of elements & described non-linearity's and randomness in actions	This view of the climate system that incorporates cause and effect across various temporal and spatial scales and understands the flow of energy in driving the system. They realize that because the climate system is a complex system, it is comprised of multiple subsystems interacting at various temporal and spatial scales. They understand how feedbacks can alter the stability of the system and cause it to change.

Table 2.5: Sophistication of explanations for the human-climate system where sophistication increases down the table

2.9 Conclusions

Results suggest that students' conceptions of the complex nature of the human-climate system improved after engaging in the PMC-2E conceptual representation as assessed in the system models they created. Students began with their generic models and throughout the unit, the conceptual representation afforded them the ability to foreground the mechanisms, organize and offload difficult concepts while they focused on generating explanations during each iteration of their models. As classroom science instruction adjusts to the blending of disciplinary core ideas, scientific and engineering practices, and cross-cutting concepts, teachers need assistance in ensuring student thinking is also blending these three areas germane to all fields of science. Our conceptual representation can provide this assistance as a way to monitor student progress.

Chapter 3: Connecting Subsystems to Conceptualize the Human Climate System

Abstract

Consideration of how our climate is changing requires an understanding of how our climate operates in time and space. It also requires and understanding of how the climate subsystems operate independently as well as connected to the entire system. How can we assist students as they grapple with understanding such complexity? This mixed-methods research employed a mental model conceptual representation and a digital platform that high school students used to develop system complexity during an inquiry unit on the human climate system. Grounded in model-based reasoning and systems thinking research, the PMC-2E (phenomena, mechanism, component, evidence, explanation) framework afforded students the opportunity to consider the complex phenomena from a generic level with basic components and mechanisms, and as the unit developed, they reconsidered the system with greater sophistication to include interacting subsystems. Pre-unit and post-unit performance was analyzed using three methods: the inclusion of subsystems in models and in explanations, and level of causal connections between the subsystems and the functioning of the entire system. Our encouraging results suggest that the PMC-2E conceptual representation is an effective framework to assist learners in building complexity into systems.

3.1 Introduction

We are surrounded by complex systems. Microscopic or macroscopic, biological, astronomical, social, or economical; understanding how these systems function at multiple levels is a challenge even for those committed to studying complex systems, let alone students. The consideration of systems thinking as an important life skill has been prominent in national science education standards since the 1990's (American

Association for the Advancement of Science, 1993; National Research Council, 1996; NGSS Lead States, 2013), and is also recognized as a necessary principle for science literacy in climate science (U.S. Global Change Research Program/Climate Change Science Program, 2009) and Earth system science (Earth Science Literacy Initiative, 2010), and oceanography (National Geographic Society, 2006), to name a few. The past fifteen years of learning science research has elucidated the issues in systems thinking, and has explored a number of interventions. However, a research gap exists in how students integrate subsystems into their systems thinking. To close this gap, the research we present here employed a conceptual representation intervention that scaffolded students in their consideration of the mechanisms linking climate subsystems with other climate subsystems and entire human-climate system.

3.2 Literature Review: Building and Decomposing Complex Systems from its Parts

The blended structure of the recently published *Next Generation Science Standards* (NGSS) (NGSS Lead States, 2013) requires the instructional integration of core disciplinary ideas, science and engineering practices, and crosscutting concepts so learners develop scientific habits of mind. Over the course of elementary school, middle school, and high science coursework, the crosscutting concepts (patterns, cause and effect, scale, proportion, and quantity, systems and system models, energy and matter: flows, cycles and conservation, structure and function, and stability and change) thread the core disciplinary ideas together.

Germane to the work in this study are the crosscutting concepts of *cause and effect* and *systems and system models*. Within the progression of gaining and applying cause and effect to scientific understanding, high school students are expected to

"…suggest cause and effect relationships to explain and predict behaviors in complex natural and designed systems. They also propose causal relationships by examining what is known about smaller scale mechanisms within the system. They recognize changes in systems may have various causes that may not have equal effects" (NGSS Lead States, 2013). In regard to system and system models, by the end of high school "students can investigate or analyze a system by defining its boundaries and initial conditions, as well as its inputs and outputs. They can use models (e.g., physical, mathematical, computational models) to simulate the flow of energy, matter, and interactions within and between systems at different scales. They can also use models and simulations to predict the behavior of a system, and recognize that these predictions have limited precision and reliability due to the assumptions and approximations inherent in the models. They can also design systems to do specific tasks" (NGSS Lead States, 2013). Although the grade level learning progressions in the NGSS support educators as they create lessons, cause and effect and systems thinking remain as challenging concepts for both the educators and learners. To assist in identifying effective instructional supports, our study focused on two aspects of the above: 1) seeking causal relationships among subsystems of a larger system; and 2) using models to simulate the movement of matter and energy, and interactions between and within subsystems and the entire system. (NGSS Lead States, 2013) The research base in how students integrate subsystems into their systems thinking about phenomena is limited, and therefore we look to the literature on student ability to recognize hidden mechanisms, and to recognize causality in complex phenomena to focus our study.

3.2. Recognizing the Hidden Mechanisms in Complex Phenomena

Over the past couple of decades researchers have identified that learners are challenged in connecting the hidden mechanisms to the functioning of entire complex systems. "Deeply complex systems" such as ecological systems or the climate system cannot be viewed as an entire system or by their individual components because the complex interactions create emergent phenomena even at the most microscopic levels (Lesh, 2006). When trying to explain macrolevel events emerging from microlevel or "invisible" components and mechanisms involving matter or complex phenomena, studies have shown that students face challenges. For example, in their study of students' conceptions of matter in chemical reactions, X. Liu and Lesniak (2006) found that through at least grade 8, students had difficultly discerning with accuracy the mechanisms behind chemical reactions where the entities were not visible. Similarly, Hmelo-Silver, Holton, and Kolodner (2000) in their design experiment with 6th graders learning about the respiratory system, noted that recognizing invisible entities and mechanisms working within a complex system are a challenge for learners to perceive because these entities and mechanisms tend to have varying spatial and temporal behaviors when interacting with the entire system. In their research on water related environmental literacy Covitt, Gunckel, and Anderson (2009) assessed the work of students in grades 3-12 and found that most students at the high school level have difficulty with invisible aspects of the water cycle and therefore did not account for water beneath the ground or the fact that water may contain invisible (molecular) substances.

In their literature review Ben-Zvi Assaraf and Orion (2005) identified eight characteristics of systems thinking that can pose a challenge to learners: "1. The ability to identify the components of a system and processes within the system; 2. The ability to identify relationships among the system's components; 3. The ability to organize the systems' components and processes within a framework of relationships; 4. The ability to make generalizations; 5. The ability to identify dynamic relationships within the system; 6. Understanding the hidden dimensions of the system; 7. The ability to understand the cyclic nature of systems; and 8. Thinking temporally: retrospection and prediction." (Ben-Zvi Assaraf & Orion, 2005) In order to identify ways to assist learners in developing the above skills necessary for complex systems thinking, their design research with 7^{th} grade students revealed that by the end of the unit on the hydrologic cycle some students added hidden components of the hydrologic cycle to their thinking. They attributed this growth to the knowledge integration scaffolding provided to students during the unit. It was hypothesized that those students who did not change in their conceptualizations of these hidden components did not demonstrate higher level thinking required for systems thinking.

3.2.2 Recognizing Causality in Complex Phenomena

Recognizing the existence of subsystems functioning in complex systems is only a component in the quest to understanding the function of complex systems. It is imperative that students also understand the causal connections within subsystems and to entire systems. Research on how students make causal connections guided our study. From her studies assessing student explanations of various science concepts, Grotzer (2012) found that students typically did not identify causal connections similar to those of scientists. Instead she identified a list of six causal patterns used in their explanations: simple linear, domino, cyclic, spiraling, mutual, and relational. Although this list is non-exhaustive, it provides researchers and educators with a starting point in unraveling students thinking in order to develop interventions to scaffold students' appraisal of complex phenomena. For example, children learn at a very young age that if they do something, an effect occurs. This simple-linear view of cause and effect works well for children until they encounter a more complex phenomena. In a classroom, slowly adding dimensions to a simple-linear cause and effect example in order to add complexity is one way of assisting learners to recognize other patterns of causality. She cautions that it is not important to specifically teach about these causal patterns as if they are the only ones, but instead identification of types of causal patterns should be emergent and organic and therefore may include others (Grotzer, 2012).

The issue with not recognizing hidden interactions among matter in general, and within systems more specifically, manifests itself when students are asked to identify causality leading to emergent phenomena. Ultimately we want students to be able to explain the processes occurring within systems at multiple levels, including those occurring among the subsystems. However, if students are reliant only on what they see in order to describe the effects of microscopic interactions, their explanations will remain simplistic (Grotzer, 2012). Depending on the particular phenomena, students adopt one of eight simplifying assumptions when addressing complex phenomena. When asked to ascribe causality to emergent phenomena generated from interacting subsystems, students identify obvious variables and mechanisms first, and if they are satisfied with their response, they will cease in looking any further for causal mechanisms (Grotzer, 2012; Lesh, 2006; Spiro, Feltovich, & Coulson, 1996). Furthermore, when effects of the causes are slow to emerge or are not obvious (i.e. change in average global temperatures over time), they tend to be overlooked as compared to when an effect is dramatic (i.e. natural disaster); the causes are uncovered rapidly and in the detail needed to completely understand the resultant phenomena.

How do students develop the ability to uncover the emergent causes of interacting subsystems in complex systems? Like Grotzer, Raia (2008) also analyzed student responses and found that students tended toward simplicity when asked to explain phenomena. However, she categorized causal patterns as taking one of four forms borrowed from Aristotle (efficient, material, formal, and functional). While using examples from research on plate tectonics, she describes the efficient form as similar to what we categorize as unidirectional cause and effect, a reductionist view of causality; the material form as having causal connections among different system levels; the formal form begins to introduce emergence properties among entities in different levels of a system; and the functional form is related to the dynamics of the entire system and how it maintains stability over time. She suggests that experts as opposed to novices recognize the functional form of causality in complex systems. She found most students tended towards efficient (mechanistic / reductionist) causes. For example, Raia refers to how students erroneously state that "minerals are the building blocks of rocks" while referring to the attraction and repulsion of atoms (cause) is what creates the crystal forms of minerals found in nature (effect). While there is need for this type of simplistic causal thinking, the field of Earth System Science as well as in other fields of science there is a greater need for students to develop deeper forms of causal thinking (Grotzer, 2012; Raia, 2008).

3.2.3 A Complex System with Interacting Subsystems: The Human Climate System

Serving as the content for this study, the human climate system is particularly challenging for students to grasp. The components interact at various scales (temporal and spatial) given the amount of time it takes for feedbacks to manifest themselves, and the fact that the effects can be felt at local, regional, and /or global scales. Furthermore, the human climate system is replete with subsystems which are typically studied individually, and then added to climate models individually or in small groups. For example, the carbon cycle is an important climate subsystem manifesting itself in the air, water, and land with fluxes in and out of each of these locations at different rates depending on where on Earth the carbon manifests itself. Not only is the carbon cycle difficult to understand by itself, but the difficulty is compounded within the context of the entire human climate system. However challenging it is to grasp the nuances systems thinking, the *Climate Literacy: The Essential Principles of Climate Science* (U.S. Global Change Research Program/Climate Change Science Program, 2009) clearly identifies system thinking in their principles as being necessary for an individual to be climate literate.

Recent research identified numerous naïve weather and climate conceptions held by students. For example, students in younger grades believe a deity is in control of aspects of our weather, and students in older grades believe that the winter is colder because the sun is further from the Earth at that time (Dove, 1998). In regards to the greenhouse effect, students believe it is the same as global warming, and that all living things will die because of it (Henriques, 2002). A classic view of atmospheric circulation includes the three-cell model, which is simplistic by nature given its inability to account for nuances such as the formation of extratropical cyclones. Students taught the three-cell model have difficulty in accounting for events not explained by this simple model (Harrington, 2008). Additionally, students believe that the hole in the ozone layer is the cause of global warming (McCaffrey & Buhr, 2008). In their review of the literature on climate misconceptions, Lombardi and Sinatra (2012) found that the conflation of weather and climate to be a persistent from elementary school through adults. These and the many other naïve conceptions held by students add to challenges of teaching the fundamentals of the climate system in general, and causal mechanisms inherent of this complex system more specifically (Choi, Niyogi, Shepardson, & Charusombat, 2001).

While naïve conceptions about various components of weather and climate have been identified, little research has been done to illuminate how students tie all of these components together and apply systems thinking and causality principles when learning about the climate system. However, Shepardson et al. (2012) synthesized the above literature on naïve conceptions and subsequently developed a climate system framework and a conceptual progression for learning about the climate system. In the context of this framework and progression, Shepardson et al. (2014) found that middle school students held linear and single cause and effect understandings of the climate system while the atmosphere as central to the function of the system.

Our research connects the pieces of the literature laid out in the above review. Specifically, we investigated the use of a conceptual representation intervention to assist students in recognizing hidden mechanisms and causality in complex phenomena such as the human climate system. An elaboration on our conceptual representation intervention and its theoretical framework are presented below.

3.3 Theoretical Framework

3.3.1 Models in Science

Modeling is key scientific practice employed as a methodology to uncover the underlying mechanisms producing phenomena (Clement, 1989; Dunbar, 1999; Giere, 2004; Nersessian, 2002, 2008a). Dunbar (1999) and Clement (1989) observed scientists in order to document how modeling figured into their research, and found that modeling, especially in the form of analogy, played a significant role in the work of the individual scientists as well as in collaborative settings. Although historians and philosophers of science agree on the prominence of models in reasoning about phenomena, we view modeling as a malleable starting point (Clement, 1989; Dunbar, 1999; Giere, 2004; Nersessian, 2002). Generic models in the form of abstractions are a place to begin, and through the iterative process, these abstractions align more closely with reality and the problem to be solved. This is a model-base reasoning approach, which we define following Nersessian (2008b), "….making inferences from and through model construction and manipulation."

3.3.2 Models in Science Education

Researchers have approached the challenge of assisting students in making deeper causal connections in complex phenomena and systems by engaging students in modeling. In their study of expert-novice interpretation of the functioning of an aquatic ecosystem and the respiratory system, Hmelo-Silver and Pfeffer (2004) and Hmelo-Silver et al. (2007) applied their Structure-Behavior-Function (SBF) conceptual representation to interpret how novices and experts view causality within complex systems. Novices viewed complexity through the interactions of the structures of the system whereas experts focused on the behaviors and functions that resulted from the interactions of the structures.

When reasoning about complex systems, students focus on the causality behind visible changes in a system. Additionally, they tend not to consider the causal connections when the system is in equilibrium since interactions tend to be invisible, and they tend to only consider simple linear cause and effect while neglecting the potential causal complexity among the mechanisms found in complex systems (Driver, Guesne, & Tiberghien, 1985; Perkins & Grotzer, 2000). Given this difficulty with causality, we contend that employing a mental model conceptual change framework will scaffold students as they develop sophisticated thinking about complex systems (Clement, 2008; Griffith et al., 1996; Nersessian, 2002). Students bring prior knowledge to instructional settings in the form of generic abstractions, and those models serve as their entry points on which they construct deeper knowledge. Griffith et al. (1996) argue that these "generic models" are a combination of constructive models as defined within cognitive-historical theory, and adaptive modeling as defined within computational theory. Here, we focus on the constructive modeling which recognizes that students bring situation independent abstractions about weather, or generic models to the instructional setting from which they begin the iteration process as learning progresses about the climate system. As an example, Griffith et al. (1996) refers to the "Clement protocol" (Clement, 1989) in which a student developed a model to assist him in understanding the workings of a spring, and by using this model to confirm his thinking, his confidence in the workings of the spring increased. In this case, the student's model of the target emerged over a number of iterations until all of the mechanisms of the target were accounted for in the model and in his response to the problem. From a scientific viewpoint, these models are part of the systematic reasoning process of a scientist as they investigate phenomena (Nersessian, 2008a).

3.3.3 Engaging Students with Scientific Modeling

In our study, students use models to make causal connections among subsystems in the climate system. Over time, these causal connections become more sophisticated than simple-linear connections if the particular connection warrants it. This model evolution and revision process is the focal point of modeling and conceptual change where the model has explanatory power and predictive capabilities; accurately accounting for the causal mechanisms of the system in question (Clement, 2008; Nersessian, 2002). By explanatory power, we refer to Lesh (2006) who states that the model must be able to elucidate salient and non-salient properties of the phenomena; be built upon situated and distributed knowledge, and adequately capture aspects of the physical world.

Following this framework, students were aided by an external representation platform which provided them with a space to revise their models as the unit progressed. Students used this visual modeling platform (an online digital software program) to create and revise their climate system models. According to Nersessian (2002) external representations assist students in organizing their conceptions, and in recognizing causal connections in their models. Furthermore, according to de Jong (2010) external representations reduce the intrinsic cognitive load inherent in difficult concepts.

3.3.4 Conceptual Representations

In addition, we used a conceptual representation to frame the learning context throughout the unit. A conceptual representation is flexible yet robust, building on prior knowledge of a learner, and because of these qualities, they are a starting point for a student to build models. They act as a proxy for the actual entity while students are making sense of the new phenomena (Davis et al., 1993), and provide constraints that direct the model-building process (Nersessian, 2008a). In this study, we posit that when students are learning about complex concepts such as the human climate system, they arrive at the instructional setting with a generic model, which develop to more closely approximate the real phenomena through the assistance of external cognitive representations.

3.3.5 The PMC-2E Conceptual Representation

In our study we employ an intervention called PMC-2E (Jordan et al., 2014). It's a conceptual representation that stems from the structure-behavior-function conceptual representation research (Hmelo-Silver et al., 2007; Hmelo-Silver & Pfeffer, 2004), and is grounded in model-based reasoning framework described by Nersessian as a scientific practice of "making inferences from and through model construction and manipulation" (Nersessian, 2008, p. 63). The PMC-2E conceptual representation framework contends that when students model phenomena (P), it initially includes components (C) and generic mechanisms (M), and as lessons progress in a unit, deeper causal connections are made through an iteration process of the gathering of evidence (E) that support their explanations (E) (Jordan et al., 2014). (See Figure 1 below)

The context of our study, in which the human climate system was the target, it was expected that students arrived to instruction with generic abstractions that more closely resemble weather concepts since the conflation of weather and climate is so prevalent (Choi et al., 2001). Our intent was to assist students as they bridge from viewing the human climate system as being a somewhat simple collection of weather variables, to a more complex system complete with interacting subsystems acting in various components of the Earth system.

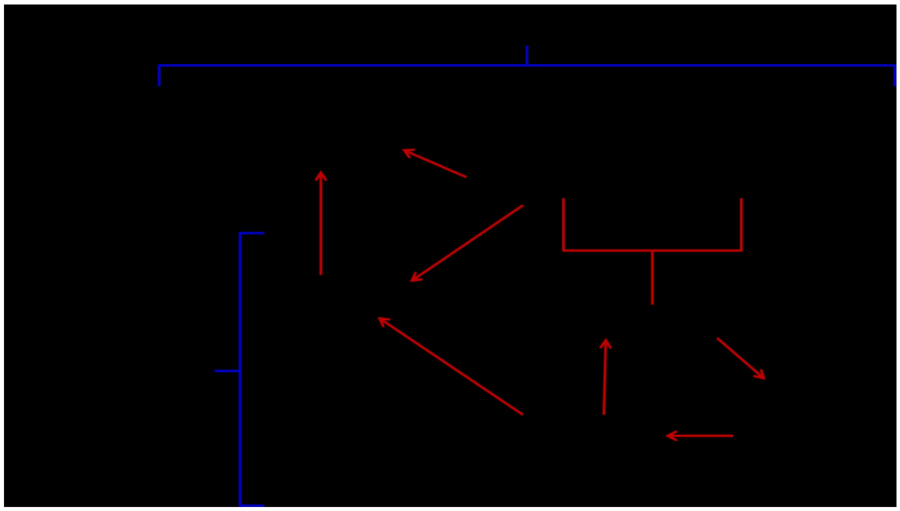


Figure 3.1: The PMC-2E conceptual representation. (Modified after Holzer, M. and Jordan, R.C., 2016)

There are numerous underlying mechanisms in the human climate system. Here we defined mechanism as "…entities and activities organized such that they are productive of regular changes from start or set-up to finish or termination conditions" (Machamer, Darden, & Craver, 2000). Using this definition as did Russ, Scherr, Hammer, and Mikeska (2008) and Clement (2008), we view mechanisms as having explanatory power linking causal connections to the phenomena. Hmelo-Silver and Pfeffer (2004) found that students are likely to focus on the structures of a system prior to considering the mechanisms of a system. By instead focusing on linkages among behaviors or mechanisms in a complex system, students' attention focused on causality among the mechanisms and thus gaining a deeper understanding of the complexities in the subsystems of the system. Doing so more closely approximates the theory building process of science when students revise their models (Nersessian, 2008a).

3.3.6 Research Questions

Our research recognizes all of the above mentioned challenges related to systems thinking, including the recognition of causality related to subsystems acting within a complex system. We suggest that by providing students with the PMC-2E conceptual representation as a scaffold, it will focus students on the mechanisms connecting components in a phenomenon. In this case, students will focus on the phenomena occurring in individual subsystems, and then connect the subsystems back to the entire complex system. Therefore, our questions focus on the changes in how students include subsystems in their model of the human climate system when they engage with the PMC-2E conceptual representation as a dynamic scaffold. Specifically we ask the following:

RQ1: What changes occur in the *number* of subsystems included in the treatment class's human climate system models and the strength of their causal connections between the subsystems and the entire system?

H1: It is expected that the number of subsystems will increase and the strength of their causal connections will increase.

RQ2: What changes occur in the depth of understanding of the human climate system?

H2: It is expected that the treatment students will increase in their understanding of the human-climate system.

3.4 Methods

3.4.1 Participants and Setting

This study took place in a suburban East Coast U.S. secondary school, and consisted of students, 16-18 years of age, in two sections of an advanced environmental science course. The study used a quasi-experimental design, where the treatment class (i.e., the class that used the dynamic PMC-2E scaffold) consisted of 23 students, 15 females and 8 males, and the comparison class (i.e., the class that completed the unit without using the scaffold) consisted of 21 students, 16 females and 5 males. The study took place over eleven days of the spring semester during a unit on the human climate system. The contents of the unit mirrored what was required of the school district approved curriculum for the course aligned to state standards for learning in science. The district curriculum and state standards for learning in science are inquiry-based, and therefore the lessons included in the unit were also inquiry-based. For example, students used a laboratory setting to test a hypothesis related to the Earth's surface albedo, and then compared their results to available global data related to surface albedo.

3.4.2 Study Design and Materials

The human climate system unit consisted of six lessons that employed the 5-E (engage, explore, explain, elaborate, and evaluate) instructional model (Bybee et al., 2006), and included topics ranging from generalities about systems mechanics to specifics about our climate system. The lessons are described in Table 1. They included group and individual activities that integrated systems thinking terminology and applications of these terms to climatology concepts. As the unit progressed, subsystem data (carbon cycle and energy transfer) were collected and analyzed by the students. All the lessons (including the dynamic PMC-2E scaffold) were aligned to state and district curriculums which encourage the facilitation of inquiry and data-rich science learning environments.

Lessons	Lesson Description & Activities
1. Is it weather or climate?	Students have difficulty discerning between weather and climate events, and therefore a foundation for the terminology needed to be set before starting the unit. Students share personal weather stories, and then learned how to identify which of the stories pertained to weather and which pertained to climate. This was followed with the analysis of satellite images of global climate data (e.g. insolation, surface temperature), and the construction and the analysis of climographs (temperature and precipitation graphs from around the world). *Activities were the same for both the comparison and treatment classes. However, before beginning the unit, students in the treatment class only were introduced to PMC-2E and created EcoModels of the human climate system.*
2. What are greenhouse gases?	In this lesson identified key greenhouse gases and the role they play in changing the Earth's climate, and how they change the climate. They analyzed the carbon cycle for important sources and sinks relative to the human climate system. Finally they analyzed spatial and temporal trends in greenhouse gases from

	IPCC data. *Activities were the same for the students in both the comparison and treatment classes.*
3. What happens when we change the Earth's surface albedo?	Students reviewed the mechanisms acting in the global energy budget and used insolation and temperature satellite images to identify and account for temporal and spatial variations in the energy budget. In a laboratory setting they investigated the concept of albedo and the role it plays in the global energy budget comparing their data to scientific data. *Activities were the same for both the comparison and treatment classes. However, students in the <u>treatment class only</u> created and refined albedo EcoModels during the lesson.*
4. What are the impacts of a changing climate on marine organisms?	This lesson focused on the impacts of climate change on ocean acidification and marine organisms. It incorporated analysis of a lab experience using acids and carbonates, data from coral reef ecosystems, and scientific articles on the topic. *Activities were the same for the students in both the comparison and treatment classes. However, students in the <u>treatment class only</u> created and refined ocean acidification EcoModels during the lesson.*
5. What can we learn	

from climate models?	Students were introduced to how Earth scientists use models, and for their explanatory and predictive capabilities. The explored various global climate models and of climate models and their outputs as a way to identify the spatial and temporal challenges of creating climate models. *Activities were the same for the students in both the comparison and treatment classes.*
6. Strategies to address and lessen the impacts of climate change: mitigation, adaptation, resilience	In this lesson students considered a three-tiered approach to combating the challenges of climate change – adaptation, mitigation, and resilience when taking on a role of a stakeholder in a roundtable discussion about climate change issues. *Activities were the same for the students in both the comparison and treatment classes. However, after completing the unit, students in the <u>treatment class only</u> refined their EcoModels of the human climate system.*

Table 3.1: Lessons used in the study, including when and where the intervention (*) was employed with the treatment class in the form of the construction of EcoModels.

Students in the treatment group used an online cognitive mapping tool called EcoModeler (Jordan et al., 2013) to develop their systems thinking. (See Figure 2) They used this dynamic scaffold four times during the climate system unit (see Table 1) to create models in the form of concept maps as external representations of their mental models. Students used EcoModeler in a previous unit on ecosystems, but did not use it in the context of PMC-2E. In this unit students were given the phenomena (P) for each of the four EcoModels they created. The phenomena for the pre-unit and post-unit EcoModels was the functioning of the human climate system, and during the unit, the phenomena for the EcoModels were black carbon/albedo (Sun-Earth energy budget subsystem) and ocean acidification (carbon cycle subsystem). Students began each model by adding their initial ideas about the phenomena in the form of mechanisms (M) and components (C). As the lessons progressed and evidence (E) became available, they modified their models to incorporate their changed conceptions about phenomena as well as explanations (E) for the mechanisms linking the components. The EcoModel platform provided the students with tools to enhance their models such as color coding and a notes section that many students took advantage of in order to clarify their models. For this study, the pre-unit (n = 23) and post-unit (n = 23) human climate system models from the treatment class were coded for the inclusion of subsystems and the level of causality attached to each subsystem. A total of forty-six models were coded and analyzed.

While the treatment class completed their models for the phenomena in question, the comparison class focused specifically on the content of the individual lessons having additional class time to do so. For example, in the lesson on the carbon cycle where students described a fast version of the cycle and a slow version of the cycle, a discussion ensued about the implications of a fast cycle where fossil fuel emissions are increasing the quantity within the fast cycle. To ensure that both classes had similar educational experiences, at the end of the unit the comparison class was provided access to EcoModeler to create models of the human climate system through the lens of PMC-2E.

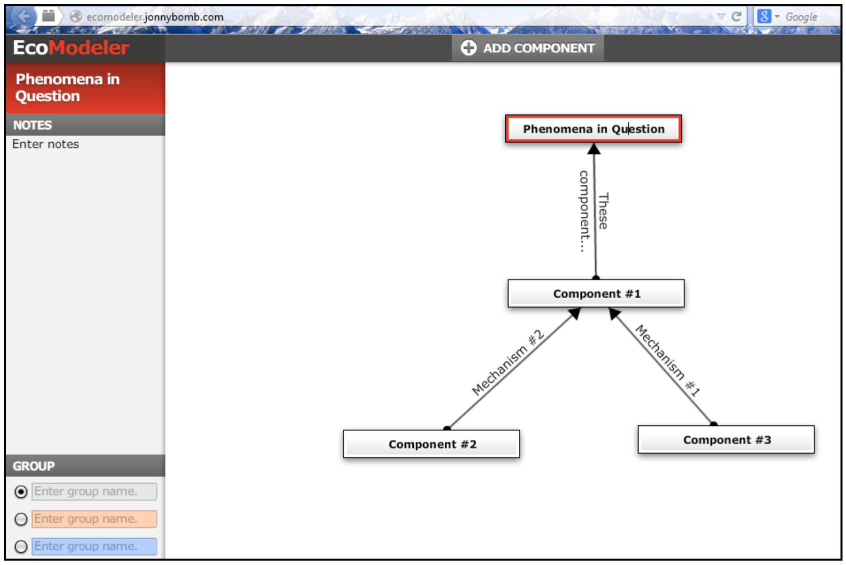


Figure 3.2: The EcoModeler online modeling tool

Prior to the start of the unit and again at the end of the unit, both the treatment and comparison classes answered an open-ended question about the climate system. The question was created by Shepardson et al. (2014) as part of their "Climate System Task" used to gather students' ideas about the climate system. Students were provided with a figure of the climate system and the following prompt: *The above diagram shows the components of a climate system. In your own words explain how the components influence climate.* We used this instrument to measure student's ability to incorporate subsystems and causal connections into their explanations of the human climate system prior to the unit and after completing the unit. Additionally, the pre-unit and post-unit explanations were scored for their climate understanding depth using a rubric with a scale between 1 (low depth) and 5 (high depth). The protocol for scoring and analyzing the data are described in the next section.

3.5 Procedures

3.5.1 Qualitative Analysis

In this study there were three sets of qualitative data from two instruments that were coded and quantified as outlined by Miles and Huberman (1994). Each coding scheme is described in Table 2 below. The pre-unit and post-unit EcoModels and the Climate System Task explanations were coded for the number of subsystems included as well as how well the students identified their causality within the human climate system. The Climate System Task explanations were also coded for the depth of their explanations in describing the human climate system. Using these three coding schemes (total number of subsystems, strength of causal connections, and depth of understanding) allowed us to triangulate the data in order to ascertain the effects of our intervention.

Task	**Key Ideas & Items Coded**	**Research Question** *(…what changes occur in…)*
EcoModels (*treatment only*) Climate System Task explanations (*treatment and comparison*)	Total Subsystems: Number of subsystems included in models and explanations	RQ1: the total number of subsystems included in the explanations for the climate system task
EcoModels (*treatment only*) Climate System Task	Causal Connections: Strength of causal connection among subsystems and the complex	RQ1: the strength of causal connections between the included subsystems and the entire system

explanations (*treatment and comparison*)	system in the models and explanations	
Climate System Task explanations (*treatment and comparison*)	Depth of Understanding: Score using a climate depth rubric	RQ2: depth of understanding of the climate system

Table 3.2: Summary of research items and research questions

Inter-rater reliability analysis was performed for at least 20% of the cases of the total number of subsystems and causal connections in the PMC-2E climate models, the total number of subsystems and causal connections in the Climate System Task explanations, and the depth of understanding scores. The resultant Kappa value for the total subsystems in the PMC-2E climate models was found to be 0.762, $p < 0.001$, for the total subsystems and causal connections in the explanation task was found to be 0.933, $p < 0.001$, and for the climate depth of understanding score was found to be 0.752, $p < 0.001$. These scores indicate a high reliability in the qualitative scoring (Cohen, 1960). All discrepancies were resolved through discussion.

3.5.2 Total Subsystems

The total numbers of subsystems were counted in the pre-unit and post-unit EcoModels (see Figure 3) created by the students in the treatment class, and the total numbers of subsystems were counted in the pre-unit and post-unit explanations created by the treatment and comparison students for the Climate System Task. The coding for both the models and explanations was generative in that the list of subsystems was garnered from the correct subsystems included in the models and explanations (e.g. biosphere interactions, hydrosphere interactions, carbon cycle). In total, 46 models were scored for the treatment class, and 88 explanations were scored (pre and post treatment $n = 46$; pre and post comparison $n = 42$) for both the treatment and comparison classes by the primary author and a research climatologist.

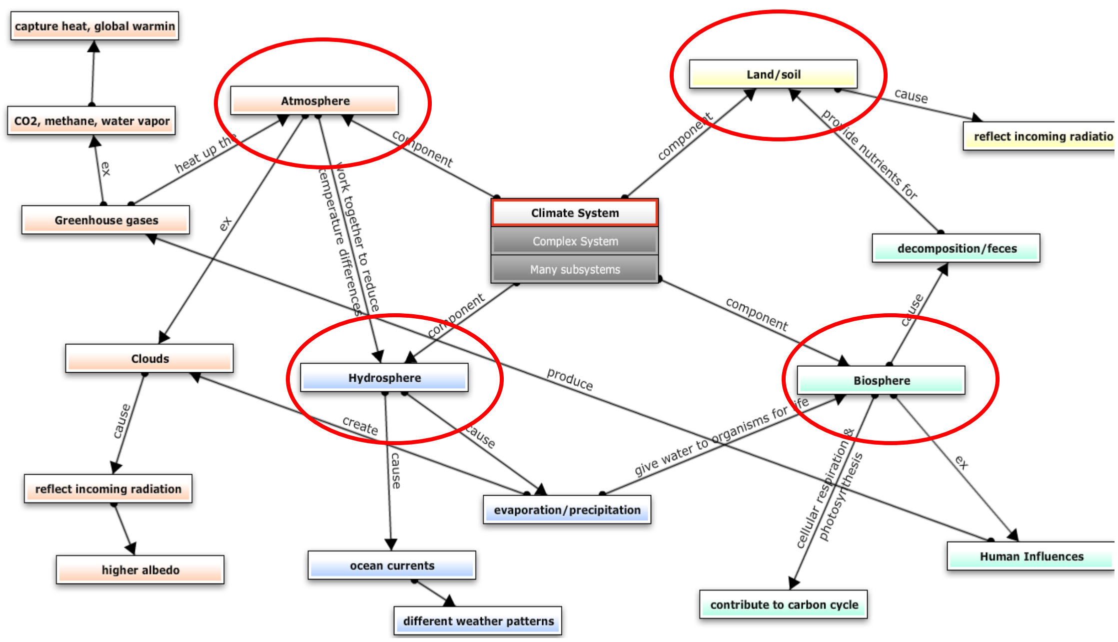


Figure 3.3: Examples of subsystems with complete causality found in a post-unit model created by a "treatment" student (e.g. biosphere, atmosphere, hydrosphere, and land/soil subsystems)

3.5.3 Causal Connections

Each subsystem included in the models and explanations was coded for a level of sophistication as showing "complete causality" or "incomplete causality." In the case of complete causality, the student identified a strong link to the human climate system, and in the case of incomplete causality, the student identified a connection to the human climate system, but did not show a depth of understanding of how the subsystem is connected to the human climate system or the effects of the subsystem on the human climate system. In total, 46 models were scored for the treatment class (n = 23 pre-unit and n = 23 post unit), and 88 explanations were scored (pre and post unit treatment n = 46; pre and post unit comparison n = 42) by the primary author and a research climatologist. Figure 3 above provides an example of a scored EcoModel, and Table 3 provides an example of scored content from the explanations.

Level of Causal Connection	**Samples from Data**
Incomplete Causality	*"...The water in the ocean evaporates and the water vapor is put into the clouds. When the clouds cannot hold anymore water, it rains. So, if you are near an ocean, you are more likely to experience rain."*
Complete Causality	*"... In reference to this picture I would also mention the carbon cycle. Plants take in CO_2 for photosynthesis and living organisms release CO_2 during respiration. Not only that, but the volcano and human emissions release CO_2 into the atmosphere, but there are other sinks for all this carbon such as in the ocean or as sediments. Having a lot of CO_2 in the air greatly impacts the climate because it is a greenhouse gas. It absorbs and traps*

	heat, raising the average global surface temp."

Table 3.3: Levels of sophistication found in explanations determined by incomplete and complete causality statements

3.5.4 Depth of Understanding

A key to understanding how the human climate system operates is to understand that there are numerous mechanisms and subsystems interacting at varying temporal and spatial scales. Therefore a Climate Depth of Understanding rubric was created using a generative process that included identifying patterns in the data and the sophistication of the students' explanations. PMC-2E conceptual representation also informed the characteristics used to describe each level of depth in the rubric. In total, 88 explanations were scored (pre and post treatment n = 46; pre and post comparison n = 42) by the primary author and a research climatologist. A score of "1" suggests that the student has a flawed and/or simplistic view of the climate system and does not think deeply about how the components in the figure interact with each other. A score of "5" suggests that the student is thinking about the interactions within the climate system as it exists within and beyond the diagram, and they include subsystems and feedbacks within their explanations. Table 4 describes the content of each step of the rubric, and provides examples from the data.

Score	Depth of Understanding & Characteristics	Examples from Data
1		

	Component View: Climate is something "out there" as simply another topic to study, and with no connection to the life of the respondent. No mechanisms are mentioned, and there may be some incorrect connections.	*"…Each component in this climate system influences the entire system because without one component the entire system would not work the same way."*
2	*Components Interact View:* Components interact, but the interactions mentioned are only a discussion of the labels on the diagram. The respondent views climate as within the diagram and does not mention mechanisms.	*"All of the components influence the climate because what they release or affect another component of the environment. The components in space, such as the solar insolation, affect components in the atmosphere, which affect components in the ocean. All of the components are related and without one another component wouldn't function the same way."*
3	*Mechanisms within the Diagram Interact:* The explanations describe the interactions within the diagram	*"Solar insolation provides the earth with light energy that can be transformed into thermal energy. Ice and clouds can reflect this light*

	and also identify mechanisms within the climate system. The respondent introduces and discusses one or more subsystems.	*(albedo). Other areas absorb this energy. Sea ice floats on the sea because of its low density in comparison to water. Water vapor evaporates under warm conditions and creates clouds that cause precipitation. Human influences release emissions into the air which absorb light energy and cause an increase in global temperature."*
4	*Mechanisms and Subsystems Interact:* The explanations discuss interactions as mechanisms which either warm or cool the climate (feedbacks). Unseen interactions and subsystems are explained.	*"Solar radiation enters the atmosphere. Some is reflected by the earth's albedo (clouds and snow/ice) while the rest heats the atmosphere. Heated water causes evaporation which then leads to the formation of clouds and precipitation. Furthermore, uneven heating of both the water and air causes circulation (currents and winds respectively. Human actions can upset this system by releasing greenhouse gases which absorb solar radiation and increase temperatures. They can also release aerosols which can reduce the Earth's albedo (black carbon)."*

5	*Our Complex Human Climate System:* Accurately describes the climate system mechanisms as leading to feedbacks, both seen and unseen interactions and subsystems are included	*"There are sources and sinks in this diagram that influence climate. The sources influence the system by putting things into the atmosphere, and the sinks influence climate because they take things like CO_2 out of the atmosphere. Also, there are several different places that can influence climate whether it is from the impact of solar energy or from precipitation over land compared to over the oceans. Carbon emissions also influences climate because it detracts from the clean air that is available. These carbon emissions can come from burning fossil fuels which contributes to negative impacts on land and over water."*

Table 3.4: Climate Depth of Understanding Rubric with increasing depth from #1 to #5

3.5.5 Quantitative Analysis: Pre-Unit to Post-Unit Differences & Assumptions Testing

As outlined above, the *total subsystems* were coded and scored as a count in pre and post unit models and explanations, the *causal connections* were coded and scored as a count in pre and post unit models and explanations, and the *depth of understanding* was scored using a rubric on pre and post unit explanations. Compiled scores for each question met the fundamental statistical assumptions of normality, linearity, and homogeneity necessary to run a paired-sample *t*-test for the total subsystems and causal connections found in the models, and repeated measures analysis of variance (ANOVA) for total subsystems, causal connections, and depth of understanding in the explanations. An alpha level (*p*) of 0.05 was used for all tests to gauge if there were statistical differences pre to post unit and between groups, and effect-size, Cohen's *d* for the paired-sample *t*-test statistics, and eta squared for the ANOVA statistics, was calculated to gauge if any statistically significant differences also has differences of practical significance (i.e., to both educators and research community) (Cohen, 1960).

3.6 Results

3.6.1 Combined Indicators of the Effectiveness of the Intervention

Results from our scoring methods found significant results, with medium to large effect sizes. Our findings suggest that the use of PMC-2E conceptual representation assisted students in recognizing subsystems and their causality within a system and it increased their depth of understanding of a complex topic such as the human climate system. Figure 4 provides a comparison of the means of all three scoring schemes for both the treatment and comparison classes where growth is evident in treatment class and not in the comparison class. Expanded results for each test are provided below.

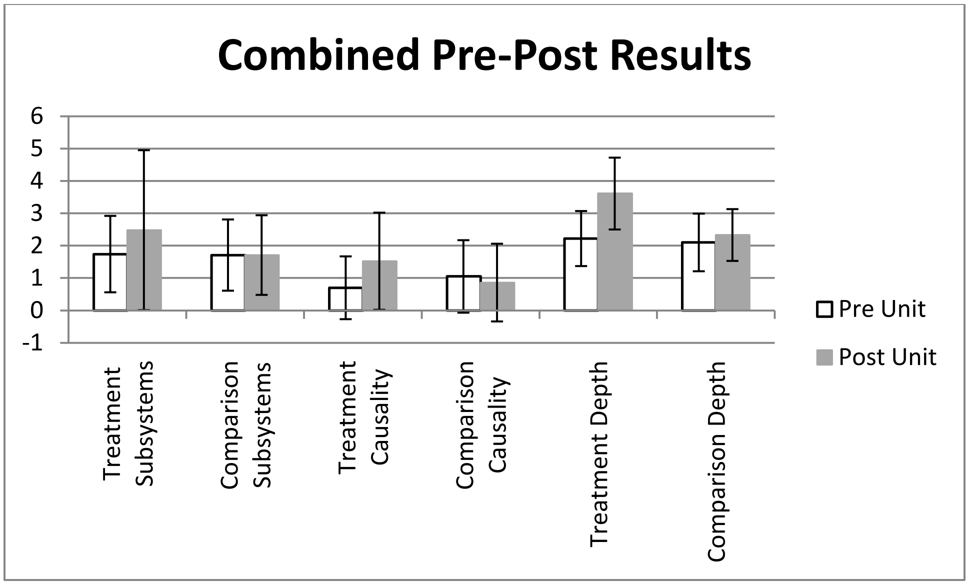


Figure 3.4: Means and standard deviations of the three scoring schemes (total subsystems, complete causality, and depth of understanding) from pre-unit to post-unit for the treatment and comparison classes.

3.6.2 Total Subsystems in Models and Explanations

The total number of subsystems included in the models created by the treatment class increased from pre-unit ($M = 2.91$; $SD = 1.20$) to post-unit ($M = 4.23$; $SD = 1.51$). This difference, 1.32 subsystems, was significant $t(22) = -5.883$, $p < 0.001$, and represents a large effect size as reflected in a Cohen's d score of 0.97. The total number of subsystems included in the explanations created by the treatment class increased from pre-unit ($M = 1.74$; $SD = 1.18$) to post-unit ($M = 2.48$; $SD = 2.47$), but for the comparison class remained the same from pre-unit ($M = 1.71$; $SD = 1.10$) to post-unit ($M = 1.71$; $SD = 1.23$).

To further examine these changes in the number of subsystems in the explanation task, we conducted a repeated measures analysis of variance (ANOVA) with class (treatment and comparison) as the between-subjects variable, and time (pre-unit and post-unit) as the within-subjects variable. The results show a non-significant interaction between class and time in the subsystem totals, with $F(2, 42) = 3.91$, $p = 0.056$. However with a relatively low p-value, a follow-up simple effects test can reveal statistically significant results (Field, 2013), which was the case with this study. The simple effects analysis on the repeated measures ANOVA results revealed a statistically significant increase from pre-unit to post-unit in the treatment class students' subsystem totals in their explanations, with $F(2, 21) = 8.19$, $p = .007$, $\eta^2 = 0.163$, which is a medium-large effect size. The treatment class's total subsystems score at post-unit were significantly greater than the comparison class's total subsystems score at the post test ($p = .007$); however there was no significant difference between classes at pre-unit, $p = 0.943$, and the comparison class's score remained unchanged at this low level (i.e., no significant differences) from pre-unit to post-unit with $p = 1.00$.

3.6.3 Complete Causality in Models and Explanations

Table 5 shows the means and standard deviations for the total subsystems with complete causality found in the Climate System Task explanations for both treatment (n = 23) and comparison (n = 21) classes by time period (pre-unit and post-unit) for the participants.

Class	***n***	**Pre-Unit**	**Post-Unit**
Treatment	23	0.70 (0.97)	1.52 (1.50)
Comparison	21	1.05 (1.12)	0.86 (1.20)

Table 3.5: Means and standard deviations (in parentheses) of the number of complete causality subsystems found in the Climate System Task explanation task at pre-unit and post-unit.

The total number of subsystems in which complete causality was identified in the models created by the treatment class increased from pre-unit (M = 1.17; SD = 1.11) to post-unit (M = 2.65; SD = 1.75). This difference, 1.48 subsystems with complete causality, was significant $t(22) = -6.10$, $p < 0.001$, and represents a large effect size as reflected in a Cohen's d score of 1.01.

To examine these changes in the number of subsystems with complete causality in the explanation task, we conducted a repeated measures analysis of variance (ANOVA) with class (treatment and comparison) as the between-subjects variable, and time (pre-unit and post-unit) as the within-subjects variable. The results show a significant interaction between class and time in the subsystem totals, with $F(2, 42) = 5.77$, $p = 0.02$, $\eta^2 = .121$, which is a large effect size.

3.6.4 Depth of Understanding in Explanations

Table 6 shows the means and standard deviations for the Depth of Understanding score based on the content of the pre-unit and post-unit explanations for both treatment (n = 23) and comparison (n = 21) classes by time period (pre-unit and post-unit) for the participants.

Class	***n***	**Pre-Unit**	**Post-Unit**
Treatment	23	2.22 (0.85)	3.61 (1.11)
Comparison	21	2.10 (0.89)	2.33 (0.80)

Table 3.6: Means and standard deviations (in parentheses) for Depth of Understanding rubric score based on the content of the pre-unit and post-unit explanations

To examine these changes in the rubric scores we conducted a repeated measures analysis of variance (ANOVA) with class (treatment and comparison) as the between-subjects variable, and time (pre-unit and post-unit) as the within-subjects variable. The results show a significant interaction between class and time in the subsystem totals, with $F(2, 42) = 15.61$, $p < .001$, $\eta^2 = 0.271$, which is a large effect size.

3.7 Discussion

The results of this study show that with a mechanism-based conceptual representation, PMC-2E, students recognize interacting subsystems within a complex system. Furthermore, they also recognize the causal connections of these subsystems to functioning of the entire system. When considering an entire complex system such as the human climate system the tendency for novices is to hold efficient or mechanistic view of the system with single causes and centralized control (Jacobson, 2001; Raia, 2005). A deeper understanding of a complex system requires an understanding of the causal connections among the subsystems creating the entire system. For example, changes in our global energy budget change our average global temperatures. However, to understand this connection one needs to understand how solar energy interacts with the various surfaces on Earth, as well as note where these surfaces are located to be able to connect changes in the Earth' energy budget to changes in temperature. Students connect solar energy to the heating of the Earth, but without refocusing their ideas, they will not connect solar energy to the intricacies of heating the Earth which includes aspects of Earth's energy budget such as absorption, reflection and scattering of light, nor will they connect it to the distribution of heat via wind and ocean circulation.

We hypothesized that when the students engaged in PMC-2E the number of subsystems and their causal connections would increase along with their depth of understanding of the human climate system. We found differences in how the treatment and comparison classes address subsystems in their explanations of the climate system such that the treatment class recognized and incorporated more subsystems into their explanations than did the comparison class. Furthermore, the treatment class recognized these subsystems as having causal connections on the functioning of the entire system. The comparison class maintained their focus on the salient aspects of the climate system found in the figure provided as a focus for their explanations, such as the ocean and volcanoes, and the atmosphere, without much mention of causal connections to the entire system. Whereas the treatment class students were more likely to incorporate subsystems and causal explanations of the linkages between subsystems and the climate system, such as in the relationship between carbon dioxide levels and the changing atmospheric temperatures, and changing ocean acidity. The depth of understanding of the human climate system results from pre-unit to post-unit results also support the efficacy of our scaffolded approach using the PMC-2E conceptual representation. The treatment class began by externalizing their generic abstractions of the climate system, which set the foundation for constructing the climate system over the course of the multi-lesson unit. As they revised their models they not only added to the depth in their initial models, but they also included causal connections as was evidenced by the detail in the comments on the connecting lines in their models.

Focusing students on casual connections of the behavior/mechanistic aspects of the human climate system and coupling it with model-based reasoning practices of science assisted students in not only developing attributes of complex systems thinking, but also developed their scientific habits of mind (Nersessian, 2008b; Russ, Coffey, Hammer, & Hutchison, 2009). Even though subsystems were placed in the forefront via explicit instruction, it was the iterative nature of the PMC-2E conceptual representation that provided the vehicle by which students extended the causal connections of the subsystems throughout the unit as demonstrated by the treatment results of this study. At the beginning of the unit students began with generic models, and as the unit progressed, PMC-2E allowed them the ability to foreground the mechanisms, and organize and offload complex concepts while iterating their models by gathering evidence to generate explanations. Through this process, this conceptual representation has demonstrated effectiveness for deeper learning about ecological systems (Jordan et al., 2014) in addition to the human climate system, and therefore it may also demonstrate effectiveness in learning about other complex systems by focusing attention on the causal connections among mechanisms in the system and scaffolding the development of model-based reasoning about the system using external supports. We believe it may also assist learners in identifying and employing the various causal patterns observed in nature, and thus move them away from the default simplified view of a complex system.

Our conceptual representation brought together elements of model-based reasoning which were effective in developing a more sophisticated view of human climate system which focused students on causal mechanisms. This methodical approach was modeled after problem solving steps used by scientists, and continued the research of Hmelo-Silver et al. (2007) and Jordan et al. (2014) in assisting learners in understanding complex topics. Continued research is needed to determine the effectiveness of this conceptual representation on student understanding of additional complex topics where hidden mechanisms exhibit causal connections in the phenomena. Additionally, research into why some students had difficulty with making causal connections within subsystems may elucidate the nuances in learning about complexity across grade levels and topics.

3.8. Instructional Implications

Although systems' thinking has resided in our national standards for over twenty years, the standards are only a set of expectations which do not necessarily provide instructional supports for developing systems thinking in our students (American Association for the Advancement of Science, 1993; National Research Council, 1996; NGSS Lead States, 2013). Past research has identified the challenges of systems thinking (Jacobson & Wilensky, 2006; Kali et al., 2003), and has offered effective interventions to assist students in developing this skill (Hmelo-Silver et al., 2007; Jordan et al., 2014). The research presented here adds to the list of effective interventions while focusing on a key challenge for students – identifying subsystems in complex systems, and understanding their causal connection to other subsystems and the entire complex system. For example, in their research findings, Gertzman and Kolodner (1996) addressed the challenges of implementing problem-based learning instructional models, and found that students need scaffolding to understand complex systems, and a way to help them is to break the problem down into parts and then reassemble it after the parts have been addressed. Combining PMC-2E conceptual representation with model-based learning empowers students to expand their thinking through an iterative process that begins with their generic mental models. Models have greater meaning when coupled with PMC-2E since mechanisms are moved to the forefront, while new evidence and explanations deepen causal connections. Educators can monitor student understanding in a formative manner in order to adjust instruction, and students can monitor their own learning as they build their models over the course of a unit.

The field of science in general and the field of Earth sciences in particular are now asking more complex questions that require complex methods to answer, and complexity in thought while interpreting results. In a science classroom, if we want our students to employ scientific practices as used in the various fields of science, there also needs to be a paradigm shift in the way science is taught. The *Framework for K-12 Science Education* (National Research Council, 2012) calls this into focus, and the resultant *Next Generation Science Standards* (NGSS Lead States, 2013) provides the ingredients for "blended" lessons and units which blend disciplinary core ideas, science and engineering practices, and crosscutting concepts. This raises the bar for instruction as it requires a shift in instructional practices to now include opportunities for students to construct meaning using scientific practices and recognizes crosscutting principles that transcend multiple scientific topics. Students need to interact with the phenomena while externalizing their models, and through model revisions over the course of time, their models more closely approximate the actual phenomena. Our conceptual representation, PMC-2E, provides science teachers and students with a thread to unravel and intertwine complicated topics such as complex systems like the human climate system. (See Table 7)

Teacher Enactment	**Student Enactment**
Students engage with <u>phenomenon</u> and provide initial thoughts on the <u>components</u>	Students create initial models displaying

and mechanisms acting to create the phenomena	generic components and mechanisms which connect to create the phenomena. These conceptual representations are constrained by what is initially known about the phenomenon.
Instruction about individual subsystems leads students to evidence that assist in crafting explanations behind the mechanisms driving the phenomena within the individual subsystems as well as the overarching phenomena	Students refine their models to include interacting subsystems as evidence becomes available
Above step is repeated until phenomena is accurately described using the evidence and explanations as a basis for the description	Students continue to refine their models which become more complex with each iteration

Table 3.7: Classroom enactment of PMC-2E conceptual representation

We offer an instructional approach that assists students in making those causal connections in complex systems. Beginning with the prior knowledge students bring to instruction in the form of generic models, an external representation is created. This external representation provides a place to start, and to construct their understanding of the system as they gather evidence and develop explanations. Eventually their models become more robust, have explanatory power, and can be used to make predictions. In the case of the human climate system, students start with their generic understandings about weather, and as the unit progresses, they gather evidence for the mechanisms found in the climate subsystems so as to enhance their initial models. As the unit progresses, their models of the climate system become more sophisticated as they use their modeling platform to offload the complicated aspects of the human climate systems so they can focus on the various types of causal connections among an assortment of mechanism during the model revision process. Teachers' use the formative generation of these models to assess and adjust instruction as needed.

3.9 Conclusions

Key to unraveling the complexities of complex systems such as the human climate system is the ability to seek out and apply underlying causal mechanisms such as those invisible at first glance. Subsystems exhibit their own spatial and temporal dynamic nature, and these subsystems affect the overall functions of the entire system. A systems thinker does not seek to simplify these interactions, but instead embraces the complexity. Resultant models of these complex systems have explanatory and predictive powers which allow scientists to further their field of study. For the novice, however, understanding a complex system can be overwhelming, and using an instructional scaffold such as PMC-2E can assist learners in constructing complex models they can use to explain and predict phenomena inside and outside a science classroom.

Chapter 4: Connecting Local, Regional, and Global Causality in the Human Climate System

Abstract

Our human climate system is a complex integration of multiple subsystems operating at various temporal and spatial scales. Addressing this topic in a middle school or high school classroom presents challenges given its complexities. The carbon cycle, a subsystem within climate, manifests itself at local, regional, and global scales. To assists learners with understanding the spatial reach of phenomena within the human climate system, we employed the PMC-2E conceptual representation as an instructional scaffold that has its foundation in systems thinking and model-based reasoning research. In this intervention, learners used a digital platform throughout a unit to help them conceptualize the human climate system and the spatial causal connections among the components of the system. Using pre-unit and post-unit assessments for treatment and comparison classes, we found positive changes in the number of spatial causal connections made by the treatment class. These results will not only assist us in better understanding how students perceive complex spatial topics such as those found in the climate system or environmental systems, but will also guide curriculum designers creating effective instructional materials for spatially dynamic topics such as the climate system.

4.1. Introduction

Scientific and geographic related phenomena occur at a variety of spatial scales. For example, in ecological systems, an impact event such as a toxic spill occurring at one location can have regional implications. Additionally in the climate system, many subsystems are recognized at a local or regional level, but can have global implications as is seen with the teleconnections of an El Niño Southern Oscillation event.

Both the *Next Generation Science Standards* (NGSS) (NGSS Lead States, 2013) and the *National Geography Education Standards* (NGES) (National Council for Geographic Education, 2012) state that spatial abilities are foundational to the fields of science and geography and recommend that all K-12 students gain these spatial abilities as they develop scientific and geographic literacy. For example, the NGSS recognizes seven crosscutting concepts germane to all sciences, of which, spatial abilities in the form of recognizing and utilizing the concept of scale can be found in all of them: (a) patterns; (b) cause and effect; (c) scale, proportion, and quantity; (d) systems and system models; (e) energy and matter; (f) structure and function' and (g) stability and change. Within the eighteen geography standards of the NGES, references to spatial abilities can be found in most all of them as well. Important to the research we present here are the specific standards that stress that students need to recognize the correct spatial scale within complex systems.

Given the importance of developing spatial abilities, it is surprising that there is little research on how students develop these spatial abilities especially as related to causes and effects within complex systems. The research presented here addresses this gap by exploring the following questions: how do students develop spatial abilities related to cause and effect within systems; and, what changes in classroom instructional might ensure learners gain these abilities?

4.2 Literature Review: Spatial Abilities and Causality in Complex Systems

4.2.1 Defining Spatial Terms

The terminology employed when discussing spatial skills in learning is sometimes conflated, and therefore clarification of these terms is necessary. Someone who is *spatially literate* is proficient in spatial thinking (National Research Council, 2006). *Spatial thinking* includes numerous spatial habits of mind, and spatial abilities. By spatial habits of mind we refer to the definition coined by Kim and Bednarz (2013) as "an internalized thinking process that uses spatial ways of thinking, such as the appreciation of spatial concepts and reasoning and the spatial representation of ideas (e.g., visualization)." *Spatial abilities* as defined by Golledge and Stimson (1997) are those abilities that one would possess to be spatially literate. Of the fifteen abilities proposed by these authors, our project was most focused on students developing the following, which collectively can be called *spatial relations*:

- The ability to recognize spatial patterns of phenomena at a variety of different scales
- The ability to interpret macro spatial relations such as world distributions of climates or vegetation and soils
- The ability to understand network structures
- The ability to uncover spatial associations within and between regions or cultures
- The ability to orient oneself with respect to local, relational, or global frames of reference
- The ability to compose, overlay, or decompose distributions, patterns, and arrangements of phenomena at different scales, densities, and dispersions

Scale, as typically described in the field of geography, has four components: *cartographic* or map scale (the ratio of measurements on a map versus on the ground); *observational* or geographic scale (the size under study by a geographic study); *measurement* scale or resolution (size of the data piece, such as pixel, grain size); and *operational* scale (extent at which phenomena operates within a system) . Our research is interested in how students come to learn about and utilize the *operational* scale of numerous phenomena occurring within complex environmental systems such as the human climate system. Combining the above definitions, we are exploring the development of spatial abilities related to connecting the operational scales of phenomena in the human climate system, a complex system.

The National Research Council (2012) calls attention to the operational scale of phenomena within their list of crosscutting concepts, highlighting the importance of developing this ability in learners throughout their K-12 science experiences. For example, in the progression of learning for the concept "Scale, Proportion, and Quantity," the authors assert that once students understand the numeracy behind scale of time and space they should be able to apply the appropriate scale to various phenomena as well as be able to go back and forth between scales of phenomena operating at various scales. This progression was adapted from the contents of Benchmarks for Science Literacy (American Association for the Advancement of Science, 1993) and more recently Atlas of Science Literacy: Project 2061 (American Association for the Advancement of Science & National Science Teachers Association, 2001), which when written were not supported by research. Our research assists in filling this void.

4.2.2 Local, Regional, Global: The Learning Challenges of "Scaling" in the Human Climate System

A basic skill of scientists in the fields of climatology and ecology is to consider the spatial extent or operational scale of phenomenon they question (Marceau, 1999; Meentemeyer, 1989; Wiens, 1989). Selecting an operational scale assists scientists in constraining the phenomenon in order to study it; however, in domains where complex systems are front-and-center, part of the challenge lies in the ability to envision how their results connect with other components or subsystems and across spatial scales. Scientists need to develop the ability to "zoom-in" and "zoom-out" of a selected operational scale to successfully investigate local, regional, or global phenomena within complex systems. But when complex systems within ecology or climatology are addressed in the classroom, connecting the correct operational scale to phenomena is typically neglected. Below we describe how students are typically challenged with both identifying the correct scale by which to study a particular phenomenon and the cause and effect related to that phenomenon.

At which scale?

In his essay, one of the key observations identified by Meentemeyer about the ideal spatial scale for study states that "sciences dealing mostly with phenomenon have more difficulty with time and space scales (e.g., geography, climatology, landscape ecology) because the size of the phenomenon decides the scale…."(Meentemeyer, 1989). During instruction, not correctly identifying the spatial scale(s) at which climate subsystems operate leads to the creation of misconceptions about the climate system. For example, students believe that small changes cannot lead to large effects such as with the impact of increasing greenhouse gases on our global temperatures. Additionally, they conflate the scale of the reservoirs and fluxes in the carbon cycle which then carries over into their understanding of the role of carbon in our climate system (McCaffrey & Buhr, 2008).

Another important consideration about scale is that scientists may opt to study a phenomenon that operates at either an absolute scale or a relative scale. The former has discrete boundaries, whereas the latter is more fluid and identified by the researcher based on their question and chosen methodologies. (Gibson, Ostrom, & Ahn, 2000; Marceau, 1999; Meentemeyer, 1989; Wiens, 1989). Multi-scale and cross-scale assessments are typically warranted to further understand the extent of a phenomenon. During instruction, single scale (ex: regional scale of black carbon emissions) examples are typically taught without application to additional scales. For example, when global climate models are employed to teach about changes in global temperatures over time, students are not taught about model resolution when analyzing the global data for local impacts. Adding the concepts of "upscaling" and "downscaling" to the list of concepts taught during instruction to assist learners in making sense of global climate models will help them understand the spatiotemporal extent of the temperature shifts they see in the models.

4.2.3 Conceptualizing Cause and Effect in Phenomena

A number of studies have characterized how students develop a perception of the size and scale of objects. Tretter et al. (2006) were interested in how students develop a sense of scale while referring to the work of Golledge and Stimson (1997) who stress that experience is what connects a person to the scale of objects and distances. In their study, students in grades 5, 7, 9, 12, and doctoral students answered a questionnaire asking for examples of objects related to a particular size, and they also participated in a card sort of objects of various sizes. They found that participants' conceptions of relative scale were more accurate than their absolute scale conceptions. Furthermore, the categories the participants used in the card sort were related to the size of an object they knew (landmark objects) and experiences with objects or while moving (i.e. cycling, driving) through space.

Like the accuracy of our perception of the size and scale of objects, we are also better at identifying causal relationships when the components are near to each other and near to us (Grotzer, 2012). Past research uncovering how we perceive action at an attentional or a physical distance focused mainly on the developmental progression of such abilities from infants to older children (Gramling et al., 2014; Grotzer, 2012; Kushnir & Gopnik, 2007; Sobel & Buchanan, 2009). Results suggest that infants, toddlers, and young children can accept cause and effect links between phenomena acting at physical distance, such as moving shadows, remote controls, and an intercom system. Furthermore, through interventions, they can identify mechanisms driving phenomena that exist with spatial gaps such between magnets and metals. However, when addressing phenomena where there is an attentional gap, even adults will look towards visible or nearby mechanisms for answers, or will side with efficiency and disregard the phenomena all together (Grotzer, 2012). For example, when considering the consequences of our changing climate, those in the middle latitudes are more challenged to accept that the climate is changing because the most dramatic evidence can be found at high latitudes (polar regions) and low latitudes (equatorial regions).

Coupling the challenge of identifying complex causality at a distance and grasping the correct scale of complex phenomena renders some topics, such as the human climate system, difficult for students to learn, This is especially true if students have not had personal experience with scale as suggested by Tretter et al. (2006), or causality

Grotzer (2012). We contend that using our instructional intervention will assist learners with these challenges in learning about causality within the human climate system where spatial contiguity is absent.

4.3 Theoretical Framework

4.3.1 Mechanism Approach to Causal Reasoning Embedded in a Mental Model Framework:

The above literature review points to experience as a starting point for identifying the causal relationships found in the action occurring at an attentional or physical distance. We use this argument to define our theoretical framework, which stems from two research areas: the mechanism approach to causal induction (Ahn & Kalish, 2000) and a mental model framework using constructive modeling as its foundation (Griffith et al., 1996; Nersessian, 2002). The mechanism approach to causal induction posits that learners go beyond cause and effect when addressing new phenomena and instead apply a generic mechanism to define the cause and effect. These generic mechanisms are at a different level than cause and effect or the phenomena. For example, Ahn and Kalish (2000) refer to how being sneezed upon (cause) will lead to becoming sick (effect); however, people believe there is a mechanism by which the sneeze causes sickness, perhaps through germ transmission, or another mechanism. This mechanism is at a different level from the cause or effect; the individual believes it has causal power thought to be the driver of the cause and effect. In addition to mechanisms, individuals often use "abduction" in causal reasoning; meaning the best hypothesis is chosen from numerous alternatives that best explains the evidence presented and existing knowledge. In the case of action at a distance, experience provides a learner with generic mechanisms they employ during abduction to achieve causal induction that links causes and effects. These generic mechanisms are a place to start in uncovering mechanisms at play in action at a distance such as those found within our complex human climate system.

We employ a mental model framework to define how an individual accounts for new phenomena. In the case of Griffith et al. (1996) they combine constructive and adaptive model approaches to conceptual change wherein students begin with general modes of reasoning including generic abstractions, and iterate as new evidence is made available that best models the target phenomenon under study. This iterative process assists students in connecting cause and effect when they are in two different attentional frames, such as increasing greenhouse gases and melting sea ice. During the problem solving process learners employ domain-specific abstractions understood at a level where they are considered generic. This process is similar to that which scientists employ when reasoning about phenomena (Nersessian, 2008b). Combining the mechanism approach and a mental-model framework we can capture the essence of how students formulate a model for complex phenomena. However, the models generated for the phenomena must have predictive and explanatory power while accurately accounting for the causal mechanisms connecting action at a distance (Clement, 2008; Nersessian, 2002). Taken together these form the conceptual representation we employed in our study. A conceptual representation frames the learning throughout the unit, and the flexible, yet substantial nature of a conceptual representation creates a starting point for learners to assist them in sense making of the new phenomena (Davis et al., 1993).

Finally, our intervention employed an external representation model-building space that aided students with their model revision process. Following Nersessian (2002), the use of external representations assists students in making causal connections while organizing their thoughts. With this online digital software program (ecomodeler.org), students created and revised their models throughout the unit. In addition to assisting students with the revision process, by creating external representations students were offloading concepts embedded with the complex topic of the human climate system. By doing so, they are reducing the intrinsic cognitive load typically found in difficult concepts such as those with spatial gaps (de Jong, 2010; Ginns, 2006).

4.3.2 The PMC-2E Conceptual Representation

The PMC-2E conceptual representation (Jordan et al., 2014) employed in our study has its roots in the research on structure-behavior-function (SBF) conceptual representation (Hmelo-Silver et al., 2007; Hmelo-Silver & Pfeffer, 2004; L. Liu & Hmelo-Silver, 2009). However, our conceptual representation differs from SBF because it is based on the model-based reasoning framework outlined by Nersessian (2002, 2008b) who refers to model building as a scientific practice by which inferences are drawn through the manipulation and construction of the models. In the case of PMC-2E students construct models around a phenomena (P) which begins with the identification of components (C) linked by generic mechanisms (M). In our study, the human climate system was the phenomena, and students were asked to identify components and link them via mechanisms. Initially students began with generic causal mechanisms, perhaps associated with weather, which is experienced on a daily basis. As the unit progressed, they revised their explanations (E) as additional evidence (E) became available while overcoming the spatial gaps of causes, effects, and associated mechanisms. In order for causal induction to occur when considering action at an attentional or physical distance, students must find the mechanism to be plausible (Griffiths & Tenenbaum, 2009), and by employing PMC-2E as a conceptual representation, the revision process assists students in identifying plausible mechanisms.

4.3.3 Research Questions

Our questions focus on the pre-unit to post-unit changes in the number of correct spatial causal connections students make when considering the mechanisms operating within the human climate system. More specifically:

RQ1: For the treatment class, what changes occur in the *number* of spatial causal connections in students' models?

H1: It is expected that the number of connections in their models will increase.

RQ2: For both the treatment and comparison classes, what changes occur in the *number* of spatial causal connections included in the explanations about the climate system?

H2: The number of connections will be greater for the treatment class.

RQ3: For both the treatment and comparison classes, what changes occur in the *types* of spatial causal connections included in the explanations for the climate system task?

H3: The types of connections will be same for both classes.

4.4 Methods

4.4.1 Participants, Setting, and Materials

The subjects for this study consisted of two classes (treatment $n = 23$; comparison $n = 21$) of high school juniors and seniors (16-18 years old) in an advanced environmental science class in a suburban U.S. East Coast high school. Data were collected during a unit on the human climate system that consisted of six lessons over eleven days. These lessons were not changed from what would be taught at this school, and therefore they were aligned with state and district standards for learning in science which support inquiry and investigative approaches to teaching and learning science. Students used data-rich exploratory methods to uncover aspects of the climate system such as modeling and experimenting. The only differences in the lesson structure between the treatment and the comparison classes were in the use of the PMC-2E intervention and the online modeling tool called EcoModeler (ecomodeler.org). See the next section and Table 1 for a further examination of the content of the unit and role of PMC-2E and the EcoModeler platform to scaffold the development of students' systems thinking.

4.4.2 Study Design and Materials

The six lessons of this unit followed the 5-E (engage, explore, explain, elaborate, evaluate) instructional model (Bybee et al., 2006), and took place over eleven days of instruction. In addition to required content related to the human climate system, measures were taken to encourage students to develop systems thinking through the use of individual and group activities that highlighted systems thinking terminology and frameworks. For example, students were introduced to systems terminology (e.g. sources, sinks, mechanisms, components) during a lesson that compared the difference between the terms weather and climate, and then applied these terms in their explanations. Additionally, as the unit progressed, different climate subsystems (radiation budget and carbon cycle) were introduced using active investigations that integrated the subsystems into the complex climate system with the focus on adding sophistication to students system thinking.

Lesson Sequence	Lesson Overview
1. Weather vs. Climate	Students compare and contrast the terms weather and climate by exploring personal stories of phenomena, climate satellite images, and global climate data. Systems thinking terminology was introduced and applied. *Treatment Class:* Before starting the lesson, students used the EcoModeler to create an initial model of the human climate system.
2. Greenhouse Gases	Students were introduced to the various greenhouse gases, and explored IPCC data on global spatial and temporal trends. Students also explored the carbon cycle as a component of the human climate system.
3. Solar Radiation & Surface Albedo	Students investigated the Earth's energy budget as a subsystem with a focus on the role of the Earth's albedo in regulated global climate. *Treatment Class:* In addition to the above these students created an EcoModel representing the effects of black carbon on the Earth's albedo.
4. Carbon Cycle and Oceans	Students investigated the carbon cycle as a subsystem and the role of ocean pH and the marine organisms along with the impact of changes in the carbon cycle on ocean pH and

	on marine organisms. *Treatment Class:* In addition to the above these students created an EcoModel representing the impacts of changes in ocean pH on marine organisms.
5. Climate Modeling	Students defined scientific modeling and then explored the inputs and outputs of different types of climate models of various spatial and temporal scales.
6. Strategies for adaptation, mitigation, and resilience	Students compared strategies for lessening the impacts of climate change and the used a round table discussion format to argue for and against different strategies. *Treatment Class:* In addition to the above these students made revisions to their initial EcoModel showing how their model of the human climate system changed based on what they learned over the course of the unit.

Table 4.1: Lesson sequence and brief overview for the unit on the human climate system (Lesson materials are available upon request from the primary author.)

4.4.3 EcoModeler and PMC-2E

The instrument selected to capture the students' conceptual representations of the human climate system was EcoModeler, which is cognitive mapping tool created by Jordan et al. (2014) (See Figure 1). The tool was created to assist students in developing systems thinking as they create and modify their system model external representations. Students in the study were familiar with this platform because they used it earlier in the school year to create a model of a local ecosystem. In this study EcoModeler is used by treatment class students to apply the PMC-2E framework over the course of the unit on the human climate system. Table 1 provides a sequence for the use of EcoModeler during the unit. The treatment class was provided with the phenomena (P) in each case, and subsequently created a system model with components (C) that were connected by mechanisms (M). Throughout the unit students gathered evidence (E) as they completed the lessons, and subsequently revised their models of the human climate system adding explanations (E) in the form of extra content on the EcoModels using line comments, or by adding extra sets of boxes with comments. Some students chose to provide further explanations in the "Notes" section of the modeling tool as part of their revisions.

During the unit each student (n = 23) created four EcoModels providing a total of ninety-two models for the entire class over the course of the unit. The initial EcoModel served as a pre-unit assessment, and final EcoModel served as the post-unit assessment. Both of these models served as data sources for this study. The overall functioning of the human climate system served as the phenomenon (P) for the pre-unit and post-unit EcoModels, the role of black carbon in the Earth's energy budget served as the phenomenon in the second EcoModel, and the role of the carbon cycle in ocean acidification served as the phenomenon in the third EcoModel.

While the treatment class completed their models for the phenomena in question, the comparison class focused specifically on the content of the individual lessons having additional class time to do so. For example, in the lesson on the carbon cycle where students described a fast version of the cycle and a slow version of the cycle, a discussion ensued about the implications of a fast cycle where fossil fuel emissions are increasing the quantity within the fast cycle. To ensure that both classes had similar educational experiences, at the end of the unit the comparison class was provided access to EcoModeler to create models of the human climate system through the lens of PMC-2E.

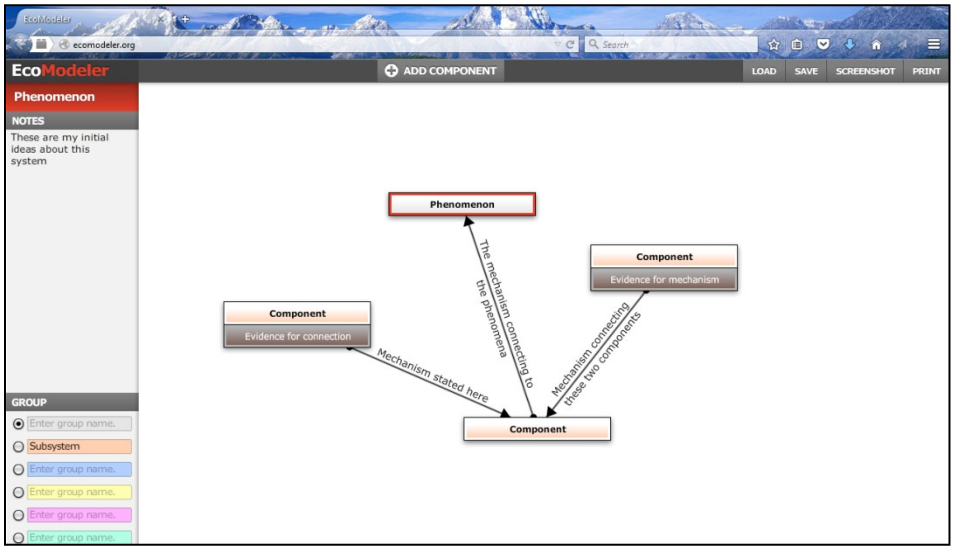


Figure 4.1: The EcoModeler online concept mapping tool (ecomodeler.org)

4.4.4 Climate System Task Instrument

To determine if the PMC-2E intervention was effective in raising the awareness of spatial causal connections in human climate system, additional instruments were employed. Students in the treatment and comparison classes completed a "climate system task" (CST) prior to starting the unit, and again at the end of the unit. The CST was created by Shepardson et al. (2014) to elicit student responses about the connections between components of the climate system. The CST consisted of a labeled figure of the climate system and the following prompts: "The above diagram shows the components of a climate system. 1) In your own words explain how the components influence climate. 2) Based on the above diagram of a climate system, explain in your own words how an increase in greenhouse gases would influence climate. 3) Based on the above diagram of a climate system, explain how global warming would influence climate." (Shepardson et al., 2014) The explanations were used to measure students' pre-unit and post-unit changes made in identifying causal connections at a variety of spatial scales.

4.4.5 Spatial Habits of Mind Instrument

Prior to starting the unit all students completed a Spatial Habits of Mind Inventory (SHOMI) (Kim & Bednarz, 2013). The authors of the SHOMI developed and validated this instrument to uncover the internalized spatial ways of thinking prior to and after a college course that employed Geographic Information System (GIS) technology to determine if the spatial habits of mind increased as students used the GIS software. The twenty-eight question Likert-scale inventory included groups of questions focusing on components of spatial thinking: pattern recognition, spatial description, visualization, spatial concept use, and spatial tool use (Kim & Bednarz, 2013). The data collected with this instrument were used as a measure of covariation with the explanation scores.

4.4.6 Personal Travel Experience

Finally, as a way to determine if personal experience in other locations besides where they currently live is related to conception of spatial causal connections, students were also asked to provide the number of towns they lived in, and the number states and countries they visited. These values were used as another measure of covariation with the explanation scores. The next section outlines the procedures used to analyze the data.

4.5 Procedures

In this mixed-methods study qualitative attributes of the CST explanations were coded and counted, and then analyzed with the quantitative data from the personal travel data and the SHOMI score (Miles & Huberman, 1994). The pre-unit and post-unit EcoModels were coded for spatial connections, and all pre-unit and post-unit CST responses were also coded for spatial connections. (See Table 2) Using these sets of scores along with travel data and the SHOMI scores allowed us to correlate the data to ascertain the effects of the PMC-2E intervention on assisting students in developing spatial abilities related to recognizing causality across spatial scales within the human climate system.

Task	**Key Ideas & Items Coded**	**Research Question** *(…what changes occur in…)*
EcoModels (*treatment only*)	Total number of spatial causal connections (local, regional, global) included in models	RQ1: the number of spatial causal connections included in the pre-unit and post-unit models?
Climate System Task responses (*treatment and comparison*)	Total number of spatial causal connections included in the explanations	RQ2: the number of spatial causal connections included in the explanations for the CST?
Climate System Task responses (*treatment and comparison*)	Types of spatial causal connections (local, regional, global) included in the explanations SHOMI score & travel experience used in analysis	RQ3: the number of *each type* of spatial causal connections included in the explanations for the CST?

of covariation

Table 4.2: Summary of research items and research questions

At least 20% of the responses were coded and analyzed both the PMC-2E climate models and the CST responses by the primary author and a research climatologist. The Kappa value to determine inter-rater reliability for the PMC-2E climate models was found to be 0.757, $p < 0.001$, and for the CST responses it was found to be 0.846, $p < 0.001$. These scores indicate high reliability in the qualitative scoring (Cohen, 1960). All discrepancies were resolved through discussion and necessary modifications to the coding schemes were made. The coding schemes are presented in the next sections.

4.5.1 Total Number of Spatial Causal Connections: PMC-2E

The total number of spatial causal connections in the pre-unit and post-unit climate models created using EcoModeler by the treatment class were counted and recorded. A spatial causal connection was identified if students included correct spatial components connected with a mechanism demonstrating they are considering spatial scale in the functioning of the component in the climate mechanism. Figure 2 is an example of a post-unit model where the student recognized that an uneven distribution of sunlight caused by the shape of the Earth leads to the production of wind to distribute this energy. He/she also recognized that Earth's climate varies depending on location, such as by latitude or altitude. He/she also recognized that human emissions (a regional cause) can be distributed in the atmosphere and also lead to ocean acidification. In total, 46 models were scored (pre-unit $n = 23$; post-unit $n = 23$).

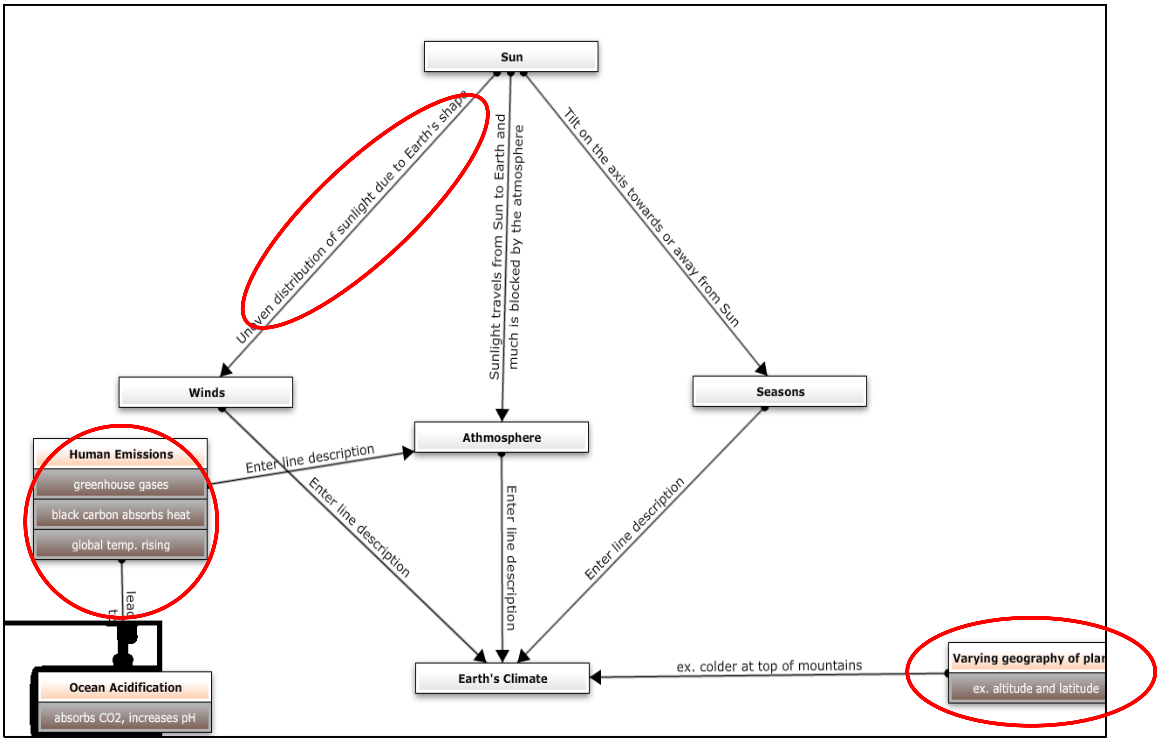


Figure 4.2: Sample post-unit EcoModel scored for spatial causal connections.

4.5.2 Types and Total Number of Spatial Causal Connections: Climate System Task

Understanding the operational scale of a phenomenon within a system is important to having an accurate model of a complex system that operates at multiple scales. To determine whether or not students' made a connection between a phenomenon and its correct operational scale, the types of connections the students made in their responses to the three CST questions were coded based on the spatial scales described in their responses. For example, if students made the connection that the release of greenhouse gases caused global temperatures to raise, it was coded as regional-global since the release of greenhouse gases occurs regionally, but it has a global impact. The possible connections included global-global, global-regional, global-local, regional-global, regional-regional, regional-local, local-global, local-regional, or local-local. Table 3 provides example of each code found in the data. The three question Climate System

Task was administered prior to and after the unit. A total of 138 responses were coded for the treatment class (*n* =23, 6 responses each), and 126 responses were coded for the comparison class (*n* = 21, 6 responses each).

Spatial Causal Connection Code	**Examples from Data**
Global-Global	*"The sun's solar insolation* (global) *warms the water and land* (global)*. This supports a current within the ocean* (global)*."*
Global-Regional	*"Global warming would influence climate because there would be less reflection within the sun's rays* (global) *and warmth would be circulating through the area* (regional)*."*
Global-Local	*"Agriculture would also change, as farmers* (local) *would have to adjust their crop schedules and methods depending on the new effects from global warming and the warming climate* (global)*."*
Regional-Global	*"An increase in greenhouse gases* (regional) *would warm up the area* (regional) *and influence the climate. Overall* (global)*, there would be an increase in temperatures and there would be more evaporation taking place."*
Regional-Regional	*"The clouds provide coverage* (regional) *and can cause humidity and fog* (regional)*. The precipitation* (regional)

	covers the ground with rain (regional). *The snow-tipped mountains* (regional) *provide runoff* (regional) *and the land and air interactions* (regional) *help reflect and emit warm and cold air* (regional).*"*
Regional-Local	*"The greenhouse gases* (regional) *mix with the air and this leads to rainfall that is tainted with unwanted chemicals. Also the air quality goes down and it is easier to get lung diseases or just be harder to breath* (local).*"*
Local-Global	*"Since human influences* (local) *such as carbon dioxide emissions go into the atmosphere* (global) *there is climate change meaning that the weather gets much warmer."*
Local-Regional	*"Particles and gases may be released into the atmosphere* (local) *affecting the chemical composition of the rainfall* (regional).*"*
Local-Local	*"Human influences* (local) *will cause air pollution and immediate warming of the air* (local).*"*

Table 4.3: Examples of spatial causal connections students made in the Climate System Task (CST) responses

4.5.3 Pre-Unit to Post-Unit Differences & Assumptions Testing

Compiled scores for each dataset met the fundamental statistical assumptions of normality, linearity, and homogeneity necessary to run a paired-sample *t*-test for the total spatial causal connections found in the EcoModels, and repeated measures analysis of variance (ANOVA) for total spatial causal connections. An alpha level (p) of 0.05 was used for both of these tests, and the effect-size was calculated using the Cohen's d for the paired-sample *t*-test statistics, and partial eta squared for the ANOVA statistics. However, a Bonferroni correction adjusting the alpha level (p) to 0.006 was made for the tests examining the significance in the number of types (ex. global-global, global-regional, etc) of spatial causal connections from pre-unit to post-unit. Repeated measure analysis of covariance (ANCOVA) was used with the SHOMI, and the places lived and travel data to identify the variance found in significant data of the previous tests. A simple effects test was used to reveal additional results with each class from pre-unit to post-unit.

4.5.4 Spatial Habits of Mind and Travel Data

In addition to the above coded and scored items, students completed the twenty-eight question Likert-scale spatial habits of mind instrument (SHOMI). For the SHOMI, each question was weighted between1-5 points with one point for the lowest agreement with the question, and 5 points with the highest agreement with the question. The highest possible score was 140 points, and the total score for each student was used in the analysis.

The students also provided data on the number of towns in which they lived, states in which they visited, and countries in which they visited. The counts provided for the number of towns in which each student lived, along with states and countries visited were also used in the analysis.

4.6 Results

4.6.1 Total Spatial Causal Connections in EcoModels and Explanations

Table 4 shows the pre- and post-unit means and standard deviations for the treatment and comparison classes. In response to research questions 1 and 2, the total number of spatial causal connections included in the EcoModels created by the treatment class increased from pre-unit ($M = 1.30$; $SD = 1.06$) to post unit ($M = 2.43$; $SD = 1.59$). This difference, 1.13 spatial causal connections, was significant ($t(22) = -5.348$, $p = 0.001$), and represents a large effect size as reflected in a Cohen's d score of 0.836.

The total number of spatial causal connections increased for both the treatment and the comparison classes. However, the increase in number of connections made by the treatment class was greater (Table 4). Further exploration of these statistics was conducted using repeated measures analysis of variance (ANOVA) with class (treatment and comparison) as the between subject variable, and time (pre-unit and post-unit) as the within subject variable. The results of both tests were significant. The between group results were $F(1, 42) = 5.70$, $p = 0.022$; medium to large effect size, and the within group results were $F(1, 42) = 20.82$, $p < 0.001$; large effect size. A simple effects test was significant for the treatment class ($F(1, 42) = 25.303$, $p < 0.001$, and large effect size) but not for the comparison class.

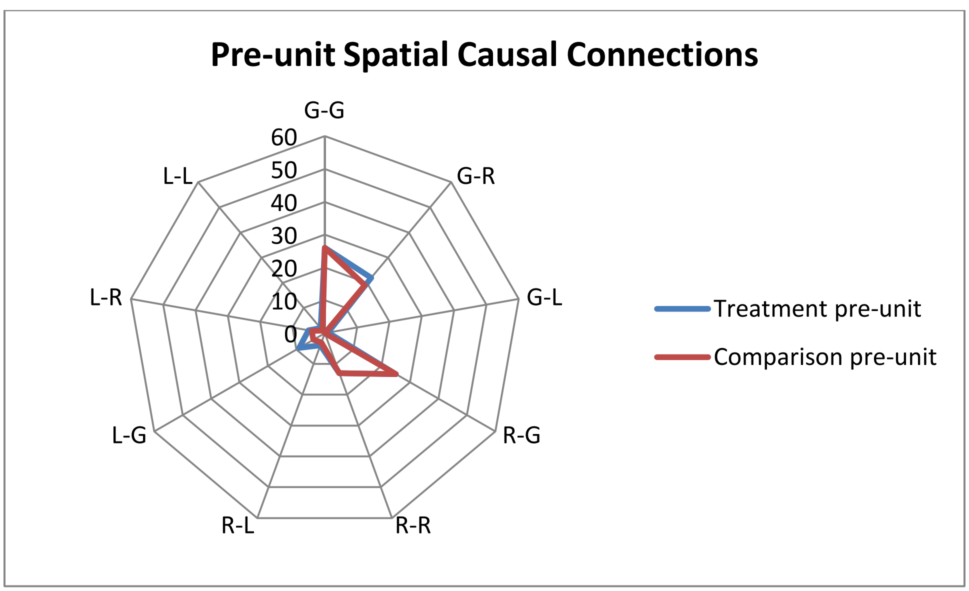
Class	**Pre-Unit**	**Post-Unit**
Treatment ($n = 23$)	4.65 (2.50)	6.78 (2.39)
Comparison ($n = 21$)	4.52 (1.75)	5.19 (1.78)

Table 4.4: Means and standard deviations (in parentheses) for the number of spatial causal connections found in the CST explanations at pre-unit and post-unit. Total connections for the Treatment class increased from 99 (pre-unit) to 157 (post-unit), and for the Comparison class increased from 94 (pre-unit) to 107 (post-unit).

The between groups ANCOVA results showed that a small amount of the difference could be accounted for in the travel experiences and spatial habits of mind (SHOMI) with the results for the treatment class remaining significant ($F(1, 42) = 6.45$, $p = 0.015$, medium-high effect size) from pre-unit to post-unit.

4.6.2 Types of Connections

Figure 3 presents the changes in total number of each type of spatial causal code made by each class, and Table 5 provides the pre-unit and post-unit means for all the types of connections possible.



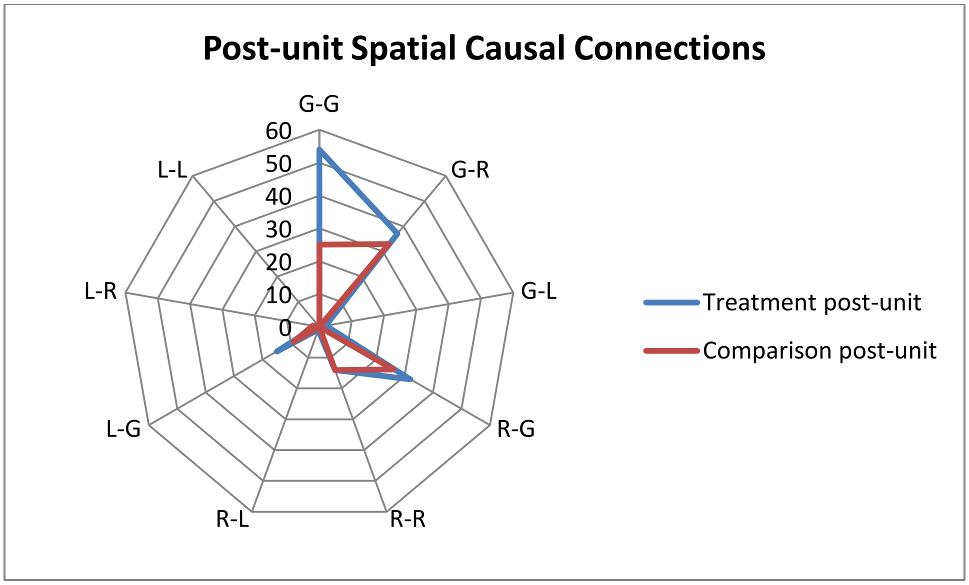


Figure 4.3: Changes in the number of spatial causal connections made by each class from pre-unit to post-unit where G = global, R = regional and L = local.

Spatial Causal Connection Code	**Treatment** (*n* = 23)		**Comparison** (*n* = 21)	
	Pre-unit	**Post-unit**	**Pre-unit**	**Post-unit**
Global-Global*	1.13 (0.87)	2.35 (0.65)	1.24 (0.89)	1.19 (0.93)
Global-Regional**	0.96 (0.64)	1.61 (0.99)	0.90 (0.77)	1.57 (1.03)
Global-Local	0.04 (0.21)	0.09 (0.29)	0.00 (0.00)	0.00 (0.00)
Regional-Global	1.09 (0.67)	1.39 (0.84)	1.19 (0.81)	1.24 (0.70)
Regional-Regional	0.57 (0.66)	0.61 (0.78)	0.62 (0.50)	0.67 (0.97)
Regional-Local	0.17 (0.39)	0.04 (0.21)	0.14 (0.36)	0.00 (0.00)
Local-Global	0.39 (0.66)	0.19 (0.51)	0.65 (0.57)	0.43 (0.68)
Local-Regional	0.22 (0.42)	0.04 (0.21)	0.19 (0.51)	0.10 (0.30)
Local-Local	0.09 (0.29)	0.00 (0.00)	0.05 (0.22)	0.00 (0.00)

Table 4.5: Means and standard deviations (in parentheses) of spatial causal codes in the CST responses.

*: The increase was significant from pre to post for the treatment group only.

**: Significant main effect for both groups.

The students in the treatment class tended toward making larger spatial scale connections (global and regional) as opposed to smaller scale spatial connections (local). To explore the data for each possible spatial causal connection further we conducted a repeated measures analysis of variance (ANOVA) for each spatial connection. A Bonferroni correction was made to the p-value which was set to 0.006 for each of these tests to account for the multiple comparisons. The results were only found to be significant in one between subjects case, global-global, with $F(1, 42) = 16.44$, $p < 0.001$, $\eta^2 = 0.281$, which is a large effect size. Additionally there was a significant increase from pre-unit to post-unit for both classes, $F(1, 42) = 14.062$, $p < 0.001$, $\eta^2 = 0.251$, which is a large effect size. To determine whether the number of places a student lived and traveled to along with their spatial habits of mind (SHOMI) impacted this score, we ran an ANCOVA on the global-global data. The results were significant, $F(1, 42) = 13.684$, $p < 0.001$, $\eta^2 = 0.265$, which is a large effect size demonstrating that these other indicators had only a very slight impact on the gains made from pre-unit to post-unit.

The global-regional spatial causal connection was significant in the main effects from pre-unit to post-unit in both the treatment and comparison classes, $F(1, 42) = 12.172$, $p = 0.001$, $\eta^2 = 0.225$, which is a medium-large effect size.

4.6 Discussion

The results of this study show that with a mechanism-based conceptual representation, PMC-2E, students recognize complex spatial causal connections when the actions are at an attentional or physical distance in the human climate system. The global nature of the climate system poses challenges to learners who experience local weather on a daily basis, and therefore using daily weather as an analog for global climate is an efficient tool for them to explain climate system phenomena (Grotzer, 2012). However, as important as personal experience is identifying the size and scale of objects (Tretter et al., 2006), personal experience with phenomena can place limits on the conceptualization of phenomena inside and outside personal experience. By doing so, they are only capturing their local weather and climate in their explanations, and in addition they do not perceive the implications of a trending climate record on the local area or the region. In addition, personal experience can place false boundaries and perceptions on locally experienced phenomena, such as air quality and pollution (Bickerstaff & Walker, 2001).

Furthermore, the mechanisms driving the phenomena locally do not necessarily work in the same fashion at the regional or global scale. For example, the mechanisms driving the carbon cycle in the local environment differ from those at a regional or global scale, and when these mechanisms cross boundaries, mechanisms within the carbon cycle contribute to the warming of our global climate. Our intervention provided students with a platform to consider mechanisms working at a variety of scales within the climate system, thus picking up where the limits of personal experience with spatial phenomena precludes them from making correct causal connections.

We hypothesized that when students engage in the PMC-2E the number and types of spatial causal connections would increase. Within the treatment class, the greatest increase in the number of spatial causal connections were made at the global and regional levels (global-global, regional-global, and regional-regional), whereas the number of spatial causal connections made in the comparison class stayed relatively the same from pre-unit to post-unit. Although both classes showed an increase in the global-regional connections over the course of the unit, only the treatment class saw an increase in the use of this connection across all three questions in the CST.

The visual and iterative nature of PMC-2E likely provided the students with an awareness of the spatial reach of the climate mechanisms by helping them to fill the spatial gaps between cause and effect with our climate system. This was seen in their responses to the CST questions which took the regional components modeled in the figure, and correctly extended and expanded on the spatial reach of the climate system mechanisms. Past research on how students view the environment has shown that students view themselves as divorced from the environment (Rickinson, Lundholm, & Hopwood, 2010; Shepardson, Wee, Priddy, & Harbor, 2007). This was evident in the CST responses in both the treatment and comparison classes since they typically viewed the human climate system as something "out there" (global or regional) and minimally connected themselves to the mechanisms controlling our climate system. This viewpoint has the potential to impact their future views of environmental issues at any scale, and would benefit from further research to ascertain the learning challenges and to identify effective interventions to overcome them.

The iterative nature of the mechanism approach to causal induction as outlined by Ahn and Kalish (2000) along with the iterative nature of the model-based reasoning approach as described by Nersessian (2002) focused students on mechanisms in general, but spatial mechanisms more specifically. The students began with generic ideas about the human climate systems, and then over the course of the unit they honed their systems thinking abilities and spatial abilities as evidence became available through the various lessons within the unit. PMC-2E conceptual representation and EcoModeler likely provided them with the ability to organize and offload difficult aspects of the climate system while considering other mechanisms and phenomena, and at the same time consider in greater detail the spatial connections of the mechanisms as they connected these mechanisms to their model of the human climate system.

In the past, this conceptual representation was effective when students were learning about interactions in commonly experienced ecological systems (Jordan et al., 2014) and other aspects of the human climate system (Holzer & Jordan, in preparation). The research presented here, however, shows that PMC-2E conceptual representation may also be effective in assisting learners with limited experience with spatially challenged complex system phenomena, such as understanding the spatial reach of human environmental impacts (Cash & Moser, 2000; Cumming, Cumming, & Redman, 2006). Further research surrounding PMC-2E conceptual representation is warranted.

4.7 Instructional Implications

The learning standards from the National Council for Geographic Education (2012) and the NGSS Lead States (2013) both emphasize the need for students to make spatial causal connections among complex content and within the mechanisms of the content. Because these standards place a greater emphasis on spatial abilities, there is a greater need to understand how students gain these abilities, especially those students with limited experiences that are spatially related. The PMC-2E conceptual representation provides instructors and students with a platform upon which spatial abilities can be built. Used in a formative manner in the classroom, students engage in a new phenomenon by first evoking their generic ideas that may explain the connections among the components and mechanisms under investigation. As the unit progresses, they modify their causal explanations as evidence becomes available. The instructor evaluates students' ideas and modifies lessons as needed in order to identify the challenges students are attempting to overcome. In the case of assisting students in their development of spatial abilities the models created using PMC-2E will elucidate the spatial scales that need further teaching. For example, if students are only considering the topic at a global scale, a lesson that seeks to close the spatial gap to connect students at a local scale to the global phenomena may be needed. By the end of the unit, the models created by the students will demonstrate growth in understanding of the spatial causal connections among all of the components of the topic.

4.8 Conclusions

Spatial abilities vary for numerous reasons, and novices lacking spatial abilities will be challenged in learning the key big ideas in geography and science. We presented an intervention that may have promising applications in an instructional setting because it provides a platform for students to offload aspects of spatially complex phenomena, while the students seek new evidence to support their explanations for how the mechanisms interact to create the phenomena. Ultimately, by using the PMC-2E conceptual representation, students can create models of the phenomena that have both explanatory and predictive power at the correct scale and in some cases at multiple scales where spatial boundaries are fluid. By assisting students in bridging spatial gaps in the mechanisms now, we are providing them with the experiences to bridge spatial gaps presented to them in the future.

Chapter 5: Conclusion

5.1 Introduction

The guiding documents for K-12 science and geography education clearly identify systems thinking and spatial thinking as skills necessary for science and geographic literacy (American Association for the Advancement of Science, 1993; National Council for Geographic Education, 2012; National Research Council, 1996, 2012; NGSS Lead States, 2013). Research on skill development and classroom interventions related to systems and spatial thinking has provided the science and geographic community with foundational understanding in these areas (Ben-Zvi Assaraf & Orion, 2005; Goldstone & Sakamoto, 2003; Goldstone & Wilensky, 2008; Hmelo-Silver et al., 2007; Hmelo-Silver & Pfeffer, 2004; Kali et al., 2003; Levy & Wilensky, 2008; Raia, 2008, 2012; Shepardson et al., 2012). However, research is needed to dig deeper into the development of these skills, and to identify research supported instructional strategies for educators. The findings from this dissertation add to the research and provided instructional strategies for educators.

5.2 Findings and Implications

Findings from these studies suggest that with the employment of the PMC-2E conceptual representation students' development of systems thinking became more sophisticated, they made causal connections of subsystems within the complex system, and they grew in their understanding of spatial nature of causality within the system. The PMC-2E conceptual representation encouraged students to foreground the mechanisms of the phenomenon, offload and organize their thoughts, and directed the students to identify explanations linking the mechanisms to the phenomena. They started with generic ideas about the human climate system, and within this intervention students used a model revision practice similar to that of scientists in order to address specific causal connections within the climate system (Clement, 2008; Nersessian, 2002). The positive findings in the first study, Chapter 2, demonstrated a growth in the sophistication of their systems thinking, possibly because they were focused on the mechanisms creating the phenomena. Past research on the systems thinking differences between experts and novices has shown that experts consider the behavior and functions of the system, while the structures were the entities making up the system (Hmelo-Silver et al., 2007; Hmelo-Silver & Pfeffer, 2004). By focusing students on the mechanisms (behaviors) instead of the structures we are encouraging students to think about complex systems in a more sophisticated way, similar to that of experts. The rubric provided in Chapter 2 could assist educators in analyzing student thinking in order to adjust instruction to include a greater emphasis on the mechanisms driving the phenomena.

In the case of the human climate system as well as in the case of ecological systems, subsystems play important roles in the functioning of the system, and a small impact in one subsystem may lead to large changes in the entire system. Research has shown that students are challenged in understanding how subsystems interact with entire complex systems (Jacobson & Wilensky, 2006; Kali et al., 2003). Additionally, research has shown that students are challenged in identifying mechanisms when they are hidden (Grotzer, 2012). The results of the second study in this dissertation suggests that by scaffolding students through the use of PMC-2E conceptual representation, they are more likely to recognize subsystems and how subsystems act as mechanisms impacting the functioning of the entire complex system. By offloading and organizing their thoughts throughout the unit, students have the ability to think more deeply about mechanisms such as a subsystem, and once they understand the functioning of the subsystem, they can tie it back to the entire complex system. Additional research is needed to ascertain how PMC-2E conceptual representation and cognitive load theory can be combined to study the role offloading plays when learning about complex topics. In the classroom, educators can employ the PMC-2E conceptual representation as an approach when teaching about complex topics as a way to encourage students to think more deeply about the mechanisms (including hidden mechanisms) driving the complexity.

Mechanisms at work within ecological systems and the human climate system act a various temporal spatial scales. This adds another layer of complexity to understanding the dynamics of a system, thus challenging the learner when trying to consider all these mechanisms at one time (Bickerstaff & Walker, 2001; Grotzer, 2012). The findings in Chapter 4 suggest that when students consider mechanisms in a complex system through the use of the PMC-2E conceptual representation, they also consider the scale at which the mechanism operates, and make spatial causal connections among the mechanisms. By focusing on a mechanism, students are focusing on it in its entirety, including its spatial reach, and understand that mechanisms can operate at either a local, regional, or global scale. They also understand that a mechanism that operates at one scale can manifest its causality at another scale. The platform provided the students to use to offload and organize their thoughts provided them with a visual display of their climate system from which they iterated over the course of the unit to make the correct causal connections. Interesting to note in the results was that students divorced themselves (local causal connections) from the phenomenon. This was evident from the lack of local causal connections the students made. This is in line with past research which showed the same

(Rickinson et al., 2010; Shepardson et al., 2007). Additional research is needed to ascertain why students are disconnected from systems that have causal connections that are local, regional, and global, and to identify effective interventions to connect students to these complex systems.

In these three studies, when the topics related to the human climate system were taught in conjunction with crosscutting concepts and science practices, the results were promising. In regards to instructional implications, these results suggest that instructors should make a concerted effort to create "blended" lessons which include scientific and engineering practices, melded with crosscutting concepts and disciplinary core ideas. For example, a carbon cycle lesson within a unit on the human climate system may have students collecting carbon cycle data demonstrating the movement of carbon throughout the Earth system over local, regional, and global spatial scales so that causal connections are made that connect them to the entire carbon cycle and therefore the human climate system.

Based on the findings of these three studies the effectiveness of the PMC-2E conceptual representation has been shown to develop sophistication in systems thinking, in the recognition of the causal nature of the subsystems within the complex system, and in recognizing spatial causal connections among the mechanisms within the human climate system. In addition to adding to the research base in these areas, these promising results that can also lead to effective instructional interventions that can develop science literacy, geography literacy, and climate literacy.

5.3 Future Research

Based on the findings of this work, two areas of study warrant further investigation: (a) how students connect complex (operate at various temporal and spatial scales) subsystems within complex systems; and (b) investigation into whether or not the PMC-2E assists students in transferring their systems thinking to other complex systems. Research in both of these areas would elucidate additional nuances in students' development of systems and spatial thinking.

As mentioned previously, the subsystems within complex systems, whether natural or human-made, operate at various temporal and spatial scales, and the research in this dissertation only explored the inclusion of subsystems in the human climate system as well as their causal connections. An additional study that explicitly focuses on the interactions of complex subsystems within a system including the identification of resultant feedbacks will provide the necessary understanding of how students develop complex reasoning about causality with a system. The results of this could lead to an instructional tool to assist learners with connecting complex mechanisms within a system.

Given how extremely important systems thinking is to how we live in, interact in, and make sense of our world, transferring this ability across topics is necessary. The knowledge transfer research in this area argues that although transfer is a challenge, scaffolds can assist learners in achieving transfer (Goldstone & Sakamoto, 2003; Goldstone & Wilensky, 2008; Jacobson, Kapur, So, & Lee, 2011; Jacobson & Wilensky, 2006; Raia, 2012). In the study by Goldstone and Sakamoto (2003) students learned about complex system principles through the use of computer models. The authors found higher rates of near transfer with computer models that were concrete as opposed to idealized; however, they found students who preferred the idealized models to be superficial in their transfer of systems principles. Although it is known that knowledge transfer is difficult, it is not impossible (Goldstone & Wilensky, 2008). Goldstone and Wilensky (2008), Raia (2008, 2012) and Levy and Wilensky (2008) argue that through the use of explicit teaching and the use of both aggregate and agent-based models, the possibility of far transfer is possible. Goldstone and Wilensky (2008) also argue that it is necessary for students to develop metacognitive practices as they navigate between the agent-based and aggregate models to further enhance their knowledge and use of the principles grounding complex systems. In addition to this past research, it is suggested that PMC-2E conceptual representation may also assist learners with transfer given the effectiveness of this mechanism-based intervention to help learners focus on how a system operates as opposed to the components that make it up. By focusing on the mechanisms they gain a generic understanding of how systems operate, which can then be transferred to additional complex systems.

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