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A CASE STUDY OF SCIENTIFIC MODELING IN FIFTH GRADE CLASSROOMS: TEACHER CONCEPTIONS, EPISTEMIC FRAMING AND STUDENTS' EXPLANATORY MODELS

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A CASE STUDY OF SCIENTIFIC MODELING IN FIFTH GRADE CLASSROOMS: TEACHER CONCEPTIONS, EPISTEMIC FRAMING AND STUDENTS' EXPLANATORY MODELS

BY

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DOCTOR OF PHILOSOPHY DISSERTATION

OF

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ABSTRACT

There is a call in science education for students to be in the business of "doing science," rather than "doing the lesson" (Jimenez-Aleixandre et al., 2000). Developing explanatory models is one important strategy for sensemaking in science. Teachers' knowledge plays a critical role in how classroom interactions are framed and how students perceive and go about their work. If we want students to be the knowers and doers of science, then we need to understand more about the relationship between teachers' knowledge of strategies like scientific modeling and how classroom interactions can be framed to support students as they develop epistemic foundations in science. A multiple-case study with cross-case analysis was conducted in three fifth grade classrooms. Surveys, interviews, classroom observations, and student work were used to examine how the teachers' conceptions of scientific modeling related to the epistemic framing of classroom interactions and the development of students' explanatory models. Data were analyzed in terms of the Epistemologies in Practice (EIP) framework (Berland et al., 2016). Findings show that all three teachers had sophisticated conceptions of the explanatory nature of scientific models and that classroom interactions involving the mechanistic features of models were framed in a way that positioned students to "do science" or make sense of the phenomenon for themselves. For aspects of scientific modeling in which the teachers' conceptions were more naive, classroom interactions tended to be framed in ways that were more consistent with "doing the lesson" or asking students to arrive at a predetermined "correct" version of the model. Implications for professional learning, curriculum, and policy are discussed.

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To all of the teachers and students with whom I have had the pleasure to work over the years - thank you for all you have taught me.

DEDICATION

This dissertation is dedicated to my family.

To my Dad, wanting to make you proud saw me though many long hours of writing. Thank you for always being in my corner and showing me unwavering love and support.

To my husband, Tim, thank you for believing in me and taking care of me during this journey and in life.

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To my oldest and dearest teacher friend, Emily, look at us now!

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CHAPTER 1

Introduction

Facing a future of increasingly complex problems, our children will be charged with developing innovative solutions to new and evolving challenges (National Research Council [NRC], 2011). We cannot possibly define the problems for them or hand them predetermined solutions. Rather we must prepare our children to successfully navigate these yet unknown situations by considering what kinds of thinking they will need to be able to do (Kuhn, 1999).

Scientific modeling is one critical dimension of how to make sense of complex phenomena (Gilbert 2004; Windschitl et al., 2008, 2018). Scientific models are not simply replicas or representations of objects or phenomena, they are tools used to hypothesize and test predictions. Models enable scientists to develop explanations for how or why a system works the way it does and predict new outcomes based on a mechanistic understanding of the system (Gilbert, 2004; Nersessian, 2008).

Developers of recent science education policy in the United States, in the form of the Next Generation Science Standards (NGSS), recognize the need for students to engage in the work of developing an understanding of complex phenomena, rather than being presented with a body of facts and knowledge presumed to be fixed and unchanging (NGSS Lead States, 2013). In recognition of this shift from asking students to learn about science to engaging in the work of science for themselves, the NGSS has not only incorporated the practice of *developing and using models* as one of eight core scientific practices, but also as a crosscutting concept (*systems and system models*) (National Research Council, 2011; NGSS Lead States 2013).

For teachers to engage their students in this sensemaking work, they too must be supported to develop a deep understanding of the scientific practices such as modeling. These sensemaking practices promote the deeper and lasting understanding needed to explain a variety of phenomena (Gilbert & Justi, 2003, 2016). However, many teachers, especially elementary school teachers, have not been given opportunities to learn about or engage in scientific modeling or related approaches to teaching modeling. Consequently, modeling is underutilized as an approach to thinking and sensemaking at the elementary level (Akerson, et al., 2009; Berland, et al., 2016; Oh & Oh, 2011). The idea that NGSS practices like *developing and using models* can be used to help students participate in a shared experience to construct meaning about real world phenomena is what motivated the current study.

Purpose of the Study

The purpose of this multiple-case study with cross-case analysis was to learn more about how three fifth grade teachers, who aimed to enact the NGSS, understood for themselves the nature and purpose of scientific models. Further, this study examined how developing and using models as a sensemaking strategy was enacted among the teachers and their students in classroom practice during a lesson in which they examined the phenomenon of how the air heats up. A qualitative case study design was chosen to provide a window into the experiences of these three teachers and their students in their community endeavor to develop explanatory models.

As the NGSS calls on educators to shift the focus of science education from “learning about” to “figuring out”, teachers have increasingly been incorporating science practices into their classroom practice (Banilower et al., 2013; Osborne, 2014).

However, what has consistently been missing in these efforts are instructional models that are coherent from the student's point of view; in other words, instruction that poses a problem or puzzling phenomenon and invites students to inquire about, investigate, and figure out for themselves a viable solution or justified explanation. As part of figuring out how science works, students should be involved in making decisions about what they are doing, why they are doing it, and how they will go about their work (Schwarz et al., 2017; Reiser et al., 2017).

The shift in instructional coherence is more fundamental than simply integrating the three core dimensions of the NGSS (science practices, core ideas and crosscutting concepts) into science activities (NGSS Lead States, 2013). Instead, it means centering students' epistemic beliefs about science knowledge and how that knowledge is constructed in classroom practice. This instructional practice represents a shift away from asking students to "do the lesson" and toward involving them in "doing science" (Jimenez-Aleixandre et al., 2000; Russ 2014). This is important so that students understand and value the epistemic nature of scientific claims; that they are to be justified and evaluated in terms of evidence (Kuhn, 1999, 2017). When students come to see themselves as the knowers and doers of science, they will be equipped to distinguish between scientific arguments and arguments of other kinds and able to evaluate those scientific arguments in scientific terms. Sandoval (2014) argues it is not that scientific arguments are the only or best way to understand the world but rather that, "the best way to evaluate when and how science might be appropriate to one's everyday concerns is to understand what science is and how it works" (p. 384).

There are differences, of course, between the work of scientists and the work of science in school (Berland et al., 2016; Russ 2014). Students bring a wealth of experience to draw on, but they have not yet acquired the depth of background knowledge and experience that professional scientists have. In addition, the goals of science must be transformed to also meet the needs of, and be situated within, a classroom community (Berland, et al., 2016). Teachers play a critical role in mediating how students engage in and develop their ideas and approaches to science. Further, there is a relationship between teachers' knowledge and their practice (Avraamidou & Zembal-Saul, 2010; Oh & Oh, 2011). Teachers, however, at the elementary level in particular, have not historically received adequate preparation to teach science. This is especially true for teaching science in a way that not only engages students in constructing knowledge from first-hand experience, but also attends to the epistemic beliefs that students have about what counts as science knowledge in the first place (Arias et al., 2016; Banilower et al., 2013; Osborne 2014).

In this context, there is a gap between research that explores students' epistemic ideas about professional science and research that explores how students develop scientific ideas. What is missing is research on how students' beliefs about science guide and inform the decisions they make as they go about the work of constructing knowledge and making science meaningful (Miller et al., 2018; Russ 2018; Sandoval 2005, 2014).

Teachers' knowledge and epistemic beliefs about science influence how they organize their instruction (Avraamidou & Zembal-Saul, 2010; Berland et al., 2016). Therefore, there is a need to understand more about how the interactions among teachers and students contribute to students' epistemic ideas as they construct a scientific understanding of the world. Further, since understanding how and why the natural world works the way it does, or developing explanatory models, is a primary goal of science, it ought to be one of the primary strategies for sensemaking in science education. Scholars have studied the ways in which modeling is used in classrooms (Schwarz et al., 2009; Windschitl et al., 2008, 2018). While growing, there is a need for a more comprehensive body of work on how a modeling-based instructional approach is articulated to support the development of students' epistemic ideas and scientific understanding. Consequently, this study was designed to contribute to an understanding of how scientific modeling is enacted in classrooms by examining the relationships among teacher conceptions of scientific models, epistemic framing of classroom interactions, and students' explanatory models in three fifth grade classrooms.

Significance of the Study

This study is significant because in order to help students become the doers and knowers of science, we must understand how their epistemic ideas (or ideas about what counts as knowledge, and how it is constructed) influence the ways in which they make meaning of science for themselves (Berland et al., 2016; Miller et al., 2018; Sandoval, 2005, 2014). Further, we cannot uncouple how students develop their approaches and beliefs about constructing knowledge from the epistemic ideas and messages that their teachers hold and impart (Ke & Schwarz, 2021; Miller et al., 2018; Russ 2018). Findings from this study provide insight into the epistemic framing of classroom interactions during modeling instruction in science by teachers and students. This understanding can help administrators and professional developers provide the kinds of support teachers need and deserve to help students develop an epistemology for science. Developing an epistemology for science means that students understand and value the way scientific claims are justified and evaluated in terms of evidence (Kuhn, 1999; Russ 2014). In turn, students will be equipped with the skills they need to determine when and how science can help them develop innovative solutions to the new and complex challenges they will face.

Research Questions

Two main research questions, and related sub-questions, guided this study of the ways in which scientific modeling was enacted in fifth grade classrooms:

Research Question 1: How was the NGSS practice of developing and using models enacted in three fifth grade classrooms?

A. How did three fifth grade teachers conceptualize scientific models?

B. How did epistemic framing guide classroom interactions involving scientific modeling in three fifth grade classrooms?

C. To what extent did fifth grade students develop effective explanatory models?

Research Question 2: How were the experiences involving scientific modeling similar and different across three fifth grade classrooms?

Definitions of Key Terms

“Classroom interaction”- Verbal or gestural communication, inclusive of classroom materials and artifacts, between or among any combination of teachers and students during a lesson (Berland et al., 2016).

"Conception"- An idea or understanding of an aspect of scientific modeling (Treagust et al., 2002).

"Epistemic frame"- A set of concepts and perspectives about what knowledge is, and how it is constructed that help an individual make sense of and organize their experience (Goffman, 1974; Redish, 2004).

"Epistemology"- The nature or study of people's beliefs about what knowledge is, how it is constructed, and when and how it should be changed (Berland et al., 2016; Chinn & Malhotra, 2002; Kuhn, 1993, 1999; Redish, 2004; Sandoval, 2014).

"Explanatory/Scientific model"- A (written, graphic, computational, physical and/or verbal) representation of a system and its components that demonstrates the mechanistic interaction of the components in order to hypothesize and/or predict new outcomes about how the system works (Gilbert & Justi, 2016; Nersessian, 2008).

"Modeling-Based Teaching (MBT)"- an instructional approach that integrates the ways models are developed and used in science with the role they play in science education (Gilbert & Justi, 2016; Seel, 2003; Windschitl et al., 2008, 2018).

"Modeling practice"- The work of creating, using, revising, evaluating and communicating a variety of representations in order to explain and test ideas about how phenomena in the natural world work (Gilbert, 2004).

"Modeling practices"- The actions of: creating or developing a mechanistic representation of a system; using a representation created by others; making changes to or revising a representation based on evidence; and critiquing or evaluating a representation of a system in terms of available evidence (Gilbert, 2004).

“Naive”- referring to ideas that are less aligned with conceptions of scientific models and modeling as they are used by scientists for making sense of a phenomenon (Treagust et al., 2002).

“Occurrence”- A spoken, gestured or drawn interaction among students or between the teacher and students that represented one or more of the descriptions from the coding guide for modeling practices adapted from Gilbert (2004) or the coding guide for Epistemologies in Practice (EIP) adapted from Berland et al., (2016).

“Sensemaking”- Situating encounters with the world in their appropriate cultural contexts in order to know what they are about (Bruner, 1977).

“Sophisticated”- referring to ideas that are more aligned with the conceptions of scientific models and modeling as they are used by scientists for making sense of a phenomenon (Treagust et al., 2002).

Overview of Research Design

This qualitative multiple-case study with cross-case analysis (Yin, 2018) examined how scientific modeling was enacted in three fifth grade classrooms. I applied case study methodology because I wanted to understand the real-world phenomenon of classroom interactions among teachers and students in context with all its complexities and nuances. It was precisely this complexity from which I drew insight. Upon identifying within-case patterns about the relationship among teachers’ conceptions of scientific models, epistemic framing of classroom interactions and students’ explanatory models, I was able to synthesize similarity and divergence in my findings across cases, draw analytical inferences (as opposed to statistical inferences) and situate those inferences in existing literature.

Methods and Procedures

Participants

Three fifth grade teachers, along with their students, participated in the case study. The unit of analysis was the classroom, inclusive of the teacher, students, materials, artifacts and their interactions. The teachers were recruited from among 18 fifth grade teachers who responded to the Students' Understanding of Modeling in Science (SUMS) survey (Treagust et al., 2002). The survey asked about the teachers' conceptions of scientific models and one additional question was added to help recruit teachers for the case study. The additional question asked about teachers' levels of use of scientific modeling based on the Concerns Based Adoption Model (CBAM) (Hall, et al., 2006).

Data Sources

Several data sources were used to gather information for the study. First, The SUMS survey (Treagust et al., 2002) was used to gather information about each case study teacher's conceptions of scientific models. In addition, I used a semi-structured interview protocol (Yin, 2018) to conduct an 18-30 minute interview with each of the three case study teachers. The interview questions were developed by Everett and colleagues (2009) and were grounded in theoretical aspects of modeling described in the literature (Everett et al., 2009; Grosslight et al., 1991; Upmeier zu Belzen and Kruger, 2010). Also, for each case study classroom, I observed and recorded video totaling between two and four class sessions, depending on how long each teacher's teaching sessions were. The instructional goal for the lesson I observed was for students to develop a model of how energy is transferred to the air. Finally, I collected the diagrammatic and/or written explanatory models that students developed in their notebooks during the lesson.

Analysis

A variety of multiple-case and cross-case study methods were used to analyze data to address the research questions. Data from the SUMS and the interviews were compiled into a descriptive profile of conceptions of modeling for each case study teacher. Interview data were coded using ELAN (2018) according to the aspects of Upmeier zu Belzen & Krugerthe's (2010) framework for understanding models.

I also conducted two rounds of coding of the classroom observation video using ELAN (2018). First, I coded data from the recordings of classroom observations for occurrences of modeling practices – *developing (creating), using, evaluating,* and *revising* (Gilbert, 2004). Second, I identified occurrences, or instances where one of the epistemic considerations from the Epistemologies in Practice (EIP) framework was prominent (Berland et al., 2016). These EIP considerations included *nature (or mechanism), generality, justification (or evidence),* and *audience*. I then ran queries in ELAN (2018) to identify occurrences in which the two frameworks co-occurred. Finally, I analyzed student diagrams and written explanations using a rubric adapted from a template that was developed to assess students' model-based explanations across three categories: *components*, *interactions,* and *explanation*, (Penuel, 2018).

For the cross-case analysis, first I compared the responses to the SUMS survey and interview data across each of the three case study teachers and identified overlaps and divergences in their responses. Then, to gain insight into the epistemic framing of classroom interactions, I looked across all three cases for similarities and divergences from the within-case patterns that I had observed. I also compared the percentages of occurrences of each of the four modeling practices across each classroom and the percentages of occurrences of the Epistemologies in Practice (EIP) considerations (Berland et al., 2016) across classrooms to identify any patterns that emerged across cases. Finally, to examine any patterns or divergences across the students' explanatory models, I compared the percentage of student work products that demonstrated varying levels of overall effectiveness using the model-based explanations rubric (Penuel, 2018). I also looked at student work across the cases for similarities and differences between the sub scores within the three categories: *components*, *interactions*, and *explanation*.

Several steps were taken throughout this study to ensure trustworthiness. Methodological triangulation was used to ensure that my findings were informed by multiple sources (Stake, 1995). Inter-rater reliability was established for the coding guides used to analyze classroom observation video. Through member-checking, teachers were invited to offer critical observations, interpretations, and other feedback that provided clarity on their cases and pieces of writing where their actions or words were featured. I also kept researcher notes that helped me attend to reflexivity. I continually questioned my assumptions and took care to interpret the data honestly and within the bounds of the cases, the data sources and analysis methods (Yin, 2018).

Organization of Dissertation

This dissertation is organized into five chapters. Chapter 1 discusses the problem and provides an overview of the research including the purpose and significance of the study, as well as a general overview of the methods and procedures used in the study. Chapter 2 is a review of the literature pertaining to the theoretical frameworks of the study, as well as relevant research in the areas of epistemic thinking in science and modeling-based teaching. Chapter 3 provides a detailed description of the methodology used in the study. Chapter 4 presents the individual case studies of the three teacher participants and a cross-case analysis. Chapter 5 presents a discussion of the findings, limitations, implications and recommendations for further research.

CHAPTER 2

Review Of The Literature

This chapter begins with an overview of the history of science education policies that informed this study. Then I discuss the theoretical perspectives in which this study was grounded; namely, constructivism, social learning theory, and epistemological perspectives. Finally, I will review relevant literature in two key areas including epistemic thinking in science education, and modeling-based teaching.

Introduction

Engaging students in meaningful opportunities to make sense of the natural and designed world is an important goal of science education, yet too little progress has been made in providing students with authentic opportunities to learn science (NRC, 2011). In order to solve the complex problems facing society, students must come to see themselves as the knowers and doers of science and have the confidence that they are capable thinkers and problem solvers.

Historically, science has been viewed as a body of facts to be learned and has been conveyed from teacher to student predominantly through lecture and didactic instruction (Windschitl, Thompson, & Braaten, 2008). For many students, science has been disconnected from their lives, uninteresting and seen as difficult and unattainable (van Driel, Beijaard, & Verloop, 2001).

While more inductive, experiential and project-based approaches to science education have been called for by educators and education reformers periodically since the 1880s, progress has been slow (Meltzer & Otero, 2015). Contemporary efforts to revitalize and reframe science education in the US can be traced back to

1957 when Russia was the first to launch an artificial satellite into space. The launching of Sputnik 1 ushered in the space age and renewed interest, funding and investment in science and science education. By 1982 however, most K-12 funding from the National Science Foundation had been cut (Meltzer & Otero, 2015). In 1983, the US Department of Education's 1983 report titled *A Nation at Risk* raised the alarm once again that American schools were failing (US National Commission on Excellence in Education, 1983). Although the report has since been criticized for its weak and inappropriate use of statistics, and misleading conclusions about the state of our nation's education and its influence on the economy, it has nonetheless had a significant influence on education reform that continues today (Berliner & Biddle, 1995). Among the calls to action in *A Nation at Risk* were for more science education and an emphasis on "rigorous and measurable standards" (US National Commission on Excellence in Education, 1983, p. 21).

The call for standards-based reform in the context of science education led to the publication of two reports published by AAAS, or the American Association for the Advancement of Science. The first was *Science for all Americans: Project 2061 report on literacy goals in science, mathematics, and technology* (AAAS, 1989) and the second was *Project 2061: Benchmarks of Science Literacy* and their related frameworks (AAAS, 1993). The AAAS reports were the first modern large-scale call for students to engage in inquiry, or to participate in the construction of science knowledge through the active participation in the practical work of science. Shortly thereafter, the National Research Council [NRC] (1996) published the *National Science Education Standards (NSES)*. These standards also called for students to engage in *hands-on* and *minds-on* science learning, building on the AAAS conceptualization of inquiry. In addition to expecting students to do science in order to learn science, the NSES also pointed to the need for more attention to science education in elementary school (NRC, 1996).

The National Science Foundation (NSF) led an effort to address these expectations by funding a number of large-scale reform projects including projects whose aim was to develop high quality instructional materials (Banilower, et al., 2007). Some of these NSF funded projects fell under a category called Local Systemic Change (LSC). The LSC theory of action was to combine high quality instructional materials with professional development for all participating teachers in grades K-8 in order to improve instruction and ultimately student knowledge, attitudes and skills (Banilower et al., 2007).

Results from these ambitious reform efforts showed encouraging but limited success. LSC project participation had a positive and significant impact on teachers' attitudes towards standards-based instruction, perceptions of preparedness for both science content and science teaching pedagogy, use of high-quality instructional materials, and time spent on science. The limitations, however, included wide variation in project quality, and the fact that the projects generally fell short of their goal of reaching all teachers (Banilower et al., 2007).

The limited impact of reform efforts has been largely characterized by top-down approaches to change and the lack of support for teacher development. Oftentimes, when new policies are released, too little attention is paid to teachers' attitudes towards and knowledge of the new expectations (Duffee & Aikenhead,1992).

Teachers have a significant impact on curriculum implementation and change. Without careful attention to supporting teacher knowledge and practice, implementation of new policy may fall short of its goals and classroom practice will change very little (Bybee, 2013; Cuban, 1992; Duffee & Aikenhead, 1992). Research on the LCS reform efforts also found that when an effort was made to engage students in hands-on science activities, there was still too little attention paid to sensemaking, and that while students were more interested in science, they were not necessarily learning more as a result of these activities (Banilower et al., 2007; Windschitl, et al., 2008).

Reflecting on the successes and challenges of previous standards and reform efforts in science, science education researchers came together to produce *A Framework for K-12 Science Education: Practices, crosscutting concepts, and core ideas* (National Research Council [NRC], 2011). This framework lays out core concepts as they articulate through K-12, and it also includes an explicit emphasis on the practice and thinking involved in an authentic and constructivist approach to learning science. There is also considerable attention paid to the importance of science for young children and an emphasis on equity of opportunity and cultural responsiveness for all children in science education (NRC, 2011).

The NRC framework (2011) also laid the foundation for our most recent national science education standards, the Next Generation Science Standards or NGSS (NGSS Lead States, 2013). The NGSS lay out the K-12 expectations of the knowledge, skills and approaches to thinking that students will need to help them explain phenomena in science and solve problems in engineering (NGSS Lead States, 2013).

The expectations laid out in the NGSS reflect a long history of aims that sought to instill disciplinary approaches to science learning into science education policy(Chinn & Malhotra, 2002; Dewey, 1916, Kind & Osborne, 2017). Hill (2008) pointed out that in contemporary society, skills that are highly valued are those that expect individuals to think critically and creatively, evaluate and critique new ideas, and draw on a range of disciplinary knowledge. Kind and Osborne (2017) argued for a conception of scientific reasoning that included the construction of models. They proposed that critical to the construction of models in science are three epistemic constructs used to justify conclusions: the value of a model as a cognitive tool, the explanatory coherence of a scientific model, and the limitations to the representational accuracy of a model. If these constructs are part of the disciplinary approach to sensemaking in science, then they ought to be part of our work in science education. Kind and Osborne (2017) state, however, that there is a “substantial gap between the goals of science education and the classroom reality” (p. 9).

To address the gap between the goal of prioritizing disciplinary knowledge in science education and the reality of classroom practice, specifically as it relates scientific modeling, this study examined the relationship among teacher conceptions of scientific models, epistemic framing of classroom interactions, and the extent to which students were able to develop effective explanatory models in three fifth grade science classrooms. This study sought to offer insight into the ways in which classroom experience was framed. This was done by examining interactions among teachers and students, as well as by considering the ways disciplinary tools for sensemaking were mediated, and how knowledge was constructed in three classroom communities.

Theoretical Frameworks

The constructivist, social learning and epistemological perspectives that informed this study are discussed in the following sections.

Constructivism

John Dewey (1938) wrote extensively about the role of experience in education. Experiences are our interactions with others, and the world and ideas around us. Dewey cautioned however, that not all experience is educative. Experience becomes educative only when it is accompanied by reflection. Further, Dewey posited that there must be *continuity of experience* for experience to be educative. According to Dewey, this means that we can consider the meaning of our present experience by connecting it to meaning we have made from our past experience. Our present experience must also prepare us to make connections to future experience.

Dewey's concept of *continuity of experience* has important implications for formal education. As educators and curriculum designers, we must be sure that first and foremost learning opportunities are grounded in experience. This experience must be personal and meaningful to students and based on their own experiences in the world around them. When learning experiences are thoughtfully designed to be personal and relevant to students, the work at hand becomes purposeful. Students are then better able to make connections to prior experience and prepared to make meaningful connections with their future experience. These connections, or *continuity* *of experience,* are what make experience educative and facilitate sensemaking in curricular contexts (Dewey, 1938).

Direct engagement with the world motivates students to want to find out more. It is also why phenomena are a central tenet of *A Framework for K-12 Science Education* (NRC, 2011) and the NGSS (Lead States, 2013). Posing real world problems or presenting complex and puzzling phenomena gives students something meaningful to ask questions about and lends purpose to the work of investigating and researching to find out more. This promotes *continuity of experience* because students are taking an active role in making decisions about how one experience connects or leads to the next.

Experience, of course, does not happen in isolation. It happens in our communities through interactions with other individuals and the world (Dewey, 1916, 1938). Communication is inherently social, and often facilitates our experiences. Dewey (1916) informed us that, "communication is a process of sharing experience until it becomes a common possession" (p. 11). We gain experience through communication.

As shared experience and communication are important components of a classroom community, they are also important to the work of science (Dewey, 1916; Nersessian, 2008; Russ, 2014). The NGSS practices are tools that help make *continuity of experience* a shared experience. For example, constructing explanations, engaging in argument from evidence, and developing models are each practices designed to facilitate communication and the sharing of ideas within a community that is trying to figure something out (Lead States, 2103). There is meaning made in the shared experience. I sought to understand more about how teachers and students went about the work of developing models to construct meaning from their shared experience with others in their community.

Social Theories of Learning

Like Dewey, Jerome Bruner (1977) believed that experience was important for learning and that social interactions were an integral part of experience. He argued further that social interaction was fundamental to intellectual development. Bruner (1977, 2008) posited that social interaction was the foundation of cognition, or the ways in which we mentally process information and construct knowledge. While cognition happens in the mind of the individual, it is the community within which an individual is situated that assigns significance to this knowledge. In other words, meaning is culturally situated and culturally dependent (Bruner, 1977, 2008).

According to Bruner, culture refers to the ways in which a shared, perceived reality is represented within a community. These “ways of life” are organized, constructed and communicated in terms of symbolism. Cultural practices- the ways of doing, thinking and talking- within a community are represented by cultural tools or symbols in order to share, conserve, and elaborate knowledge within the community and to pass it on to future generations (Bruner, 2008). Bruner proposed that communities share and create knowledge through multiple representational systems. First, are enacted representations, or action-oriented representations of ideas. Then, there are iconic representations, or image-based representations. Third, are symbolic or language-based representations. Although they are not mutually exclusive, there is a developmental progression to an individual's use of these representations (Bruner, 1977).

The scientific community, as an example, has particular ways of constructing and representing knowledge that include practices like modeling. Modeling in itself includes a set of practices and values about what counts as knowledge and what kinds of knowledge are meaningful (Gilbert, 2004). These meaningful ideas may be represented or symbolized through physical models, graphic representations, mathematical models, collegial conversations and professional papers (Gilbert & Juisti, 2016; Nersessian, 2008).

In science education, as in science, we are interested in developing a shared understanding of how our world works and as a community we have cultural practices and tools that help us to create meaning and to establish and communicate our ideas. The ways in which a community constructs and communicates meaning were a central interest in my study of scientific modeling in fifth grade classrooms.

Lev Vygotsky’s (1978) work, like Bruner’s, situated social interactions as fundamental to development, or the ability to engage in increasingly abstract and complex reasoning. Vygotsky argued that the social nature of development preceded individual development. In his *Zone of Proximal Development* (ZPD) Vygotsky provided a model for how moving from one developmental stage to the next is both possible with and dependent upon interactions with a *more knowledgeable other*, or someone who is at a higher level of development and skilled at guiding others in creating meaning from experience. Vygotsky posited that children are capable of performing tasks that require higher cognitive functioning when they work collaboratively, before they are able to perform those tasks on their own. Cognition and development appear first as social processes through mediated interaction with others and with cultural tools, and then are internalized and become independent processes.

The enacted, iconic and symbolic representations posed by Bruner (1977) are some of the cultural tools that can be mediated with a teacher or *more knowledgeable other* to help students construct knowledge together through experience within their classroom communities (Vygotsky, 1978). Vygotsky rejected Piaget's argument that development followed a fixed progression of stages largely based on age and that children ages 7-11 could not reason abstractly beyond the concrete operational stage (Piaget et al., 2000). It was Vygotsky's (1978) position that it was precisely the mediated interaction with teachers, peers and cultural tools that enabled a child to move from one developmental stage to another. Several recent scholars have found for instance, that with mediation and scaffolding from a skilled teacher, even young students (grades K-5) can develop sophisticated mechanistic accounts of scientific phenomenon through modeling (Manz, 2012; Penner et al., 1997; Louca & Zacharia, 2015; Schwarz et al., 2009).

Collins et al., (1991) applied Vygotsky's ZPD model to their concept of *cognitive apprenticeship*. In traditional trade-based apprenticeships, the skills needed for a particular trade are passed from expert to novice through a hands-on approach that includes modeling, scaffolding and coaching until the novice acquires the skills to perform the tasks of the trade independently. Collins et al., proposed a similar approach to helping students acquire disciplinary knowledge and skills in a school setting, but they recognized that the cognitive tasks involved in school subjects are largely done mentally and are therefore invisible. To make these discipline-specific cognitive tasks visible, cognitive apprenticeships invite the teacher, and peers, to model their own thinking for one another while asking questions of each other to make important ideas and processes visible to the classroom community. In this way, cognitive apprenticeship is a model for helping students move from one developmental stage to another through collaborative practices.

This is the kind of work going on when students are making sense of a phenomenon and trying to figure out how and why systems work the way they do in a science classroom. Papathomas & Kuhn (2017) found that a cognitive apprenticeship with a skilled teacher positively impacted middle school students' argumentation skills. As such, the present study sought to develop an understanding of the nature of mediated classroom interactions among teachers and students. More specifically, this study focused on the nature of this work at the upper elementary school level while teachers and their students engaged in the work of scientific modeling.

Framing

Goffman (1974) posited that meaning, or understanding of experience, is made with others and that this shared understanding is the basis for shared assumptions about reality. As such, Goffman used the term 'framing' to describe the social organization of experience. Frames are a set of concepts and perspectives that help an individual make sense of and organize their experience; in turn, these frames can guide the actions of individuals and groups. Goffman characterizes framing as a person's answer to the question, "What is going on here?" (p. 25). The answer to this question has particular relevance to this study, which sought to answer that very question about three classroom communities engaged in scientific modeling.

Epistemic Framing

Ideas about knowledge and knowledge construction, or epistemology, are of great importance to educators. Epistemology refers to people's beliefs about what knowledge is, how knowledge is constructed, and when and how knowledge should be changed (Berland et al., 2016; Chinn & Malhotra, 2002; Kuhn, 1993, 1999; Redish, 2004; Sandoval, 2014). A person's epistemology is not necessarily explicit or conscious (Chinn & Malhotra, 2002). Teachers and students may unknowingly hold beliefs about what counts as knowledge, and whose knowledge counts that influence the framing of classroom interactions.

Important to the study of epistemologies in classrooms is the idea that epistemic beliefs are situational, that is they can be context dependent (Redish, 2004). In particular, Redish characterized *functional epistemology* as the structures that influence how an individual will construct knowledge in a particular situation. Further, Redish explained *epistemic frames* as the expectations teachers and students have about, "How will I build new knowledge here? And "What counts as knowledge here?" (p. 33). Framing is a dynamic process of social interaction that is continually negotiated among teachers and students (Berland & Hammer, 2012). Kuhn (1999) also pointed out, "different minds can arrive at genuinely different and legitimate understandings of the same evidence" (p. 20).

Important to the framing examined in my case study is Redish's (2004) description of how a classroom situation can be framed epistemically as *knowledge* *from authority* or *knowledge as fabricated stuff* (p. 34). *Knowledge from authority* conveys an expectation that what counts as knowledge comes from, and is evaluated, by the teacher, whereas *knowledge as fabricated stuff* conveys an expectation that what counts as knowledge is determined and evaluated by the classroom community, as they pursue sensemaking as a collective endeavor.

Epistemic Thinking in Science Education

Scientific epistemology describes the nature of scientific knowledge, how that knowledge is constructed and how value is placed on the truth of that knowledge. It is paramount that we support students to develop epistemological ideas that "scientific knowledge is constructed by people, not simply discovered out in the world" (Sandoval, 2005, p. 639). Scientific claims or assertions are justified and evaluated in terms of evidence. Justification and evaluation are valued and expected in science and further, lead to more or less certainty in the knowledge that's been constructed by the scientific community (Kuhn, 1993, 1999). The practice of science and its epistemic foundations reinforce one another (Kuhn et al., 2017).

Sandoval (2005, 2014) argues that research on epistemology in science education has historically focused on either discovering students' ideas about the epistemologies of professional science, or on how students develop scientific ideas through their work in the science classroom. What continues to be missing is research into how students' epistemic beliefs about science guide the ways in which they make meaning in their classroom science practice (Sandoval 2014, Miller et al., 2018). Sandoval calls the classroom application of epistemic beliefs *practical epistemologies* and suggests more research is needed into making students' epistemic ideas visible.

We need to understand the ideas students have about their own knowledge production in regard to their work in science classrooms (Sandoval, 2005).

A few studies have begun to examine the gap described by Sandoval (2014). One case study followed a teacher teaching a grades 3/4 split classroom for one year as she worked to improve her students' abilities to construct and evaluate arguments with a particular focus on how they used evidence. Students did improve their argumentation skills and the authors implicated the teacher's sustained focus throughout the year on classroom norms that framed the role of persuasion as integral to the classroom work. The authors also called out how the teacher framed the students as accountable to one another within the classroom community and how that led to a shared epistemic framing of the role of claims and evidence among students (Ryu & Sandoval, 2012).

In a second study (Kuhn et al., 2017), a group of high school biology students who participated in an extended problem-based argumentation activity showed not only more effective use of science practices, but superior epistemological understanding regarding the evaluation of claims in relation to evidence, on a delayed assessment given five weeks after the activity, when they were compared to a group who participated in the typical biology curriculum.

A third study (Kawasaki & Sandoval, 2019) examined the case of one teacher's effort to redesign a unit to be more coherent from the students- point of view, in order that the students had more control over how and why they should proceed through the lessons in the unit. The researchers found that in instances where the teacher used framing that positioned the students as the decision makers, students took on a more active role in their knowledge construction. On the other hand, when the goals of the teacher's framing were unclear, students took on a more passive role more typically seen in didactic teaching approaches.

Berland et al., (2016) offer a framework for examining how epistemic ideas and framing are at work in classrooms when students are trying to make sense of phenomena. The framework characterizes students' epistemological understanding of the work at hand and makes visible the *meaningful use* of science practices. In their Epistemologies in Practice (EIP) framework, the authors offer four epistemic considerations that can be applied to knowledge products in the classroom. A knowledge product is any instance or example of shared knowledge in the classroom that is made public (e.g., verbal interaction or utterance, questions, written explanations, diagrammatic models etc.) (Berland et al., 2016).

The first EIP consideration is *Nature* (or Mechanism), which examines the degree to which a knowledge product articulates the causal mechanisms that can explain hypothesized processes involved in a particular system. In other words, does a knowledge product *describe* what is going on in a system or does it explain *how* or *why* the system works the way it does?

The second EIP consideration is *Generality,* which examines how the knowledge product relates specific science ideas or phenomena to more generalized scientific ideas or principles. This consideration helps us understand the degree to which students consider their knowledge products to be specific to one situation or more generalizable and helpful in explaining multiple phenomena.

The third EIP consideration is *Justification* (or Evidence), which examines the degree to which the information or evidence included in the knowledge product is determined by someone else (often the teacher or secondary source, e.g. textbook) or determined and justified by the students themselves.

The final EIP consideration is *Audience*, which examines whether the knowledge product is being created for the teacher to evaluate students' understanding or created for the students themselves as a productive tool for sensemaking and knowledge construction.

A few recent studies have applied the EIP framework to better understand teachers' and students' conceptions and use of modeling knowledge. First, Schwarz et al., (2014) examined multiple explanatory models from two fifth grade students whose teacher focused on teaching modeling during three units over the course of a year and a half. They found that models from both students showed growth in the EIP consideration of *mechanism*. Both students demonstrated increased abilities to incorporate the mechanistic features that showed how or why the phenomena worked.

Second, Vo et al., (2019) examined the ways that three fifth grade teachers conceived and practiced modeling practices and EIP considerations over three years. The authors found that all three teachers grew in sophistication of the conceptions and practice for some modeling practices and EIP considerations, although the growth varied across teachers.

A third study (Ke & Schwarz, 2021) examined the ways in which students in two fifth grade classes took up the epistemic messages that their teachers presented over the course of a unit focused on modeling. These researchers found that the uptake of epistemic messages by students varied across the two classrooms. Factors that appeared to contribute to this uptake were teachers' foregrounding, consistency, and unpacking of the epistemic messages in their lessons.

A response is mounting to answer Sandoval's (2005, 2014) call to investigate *practical epistemologies* so that we can better understand how students develop and apply epistemic ideas in science. My study adds to this small but growing collection of studies that used the EIP framework to better understand how teachers and students framed their work; in other words, how they decided what counted as knowledge in their classrooms.

Modeling-Based Teaching

Modeling-Based Teaching (MBT) is an instructional approach that integrates the ways models are developed and used in science with the role they play in science education (Gilbert & Justi, 2016; Seel, 2003; Windschitl et al., 2008, 2018). Gilbert and Justi (2016) specifically distinguish *modeling*-based teaching from *model*-based teaching in that the latter implies only using existing models for teaching and learning science, whereas the former necessitates that students are engaged in the process of developing, using, evaluating and revising their own models as a means to construct knowledge.

Historically, most of the research involving Modeling-Based Teaching [MBT] has been done with high school and college students (see Chittleborough, et al., 2005; Everett, et al., 2009; Furman et al., 2018; Grosslight et al., 1991; Jimenez-Liso et al., 2021; Justi & Gilbert, 2003; Malone et al., 2018; Treagust et al., 2002; Windschitl et al., 2008). Collectively, these studies have described students' understanding of the nature and purpose of scientific modeling as somewhat naive or novice in relation to how scientists use modeling to make sense of phenomena. For instance, Grosslight et al., (1991) found that a majority of both seventh and eleventh graders viewed models more as replicas used to describe an object or phenomenon, and less as representations of the underlying mechanisms that help explain the phenomena, which is how participating expert scientists characterized their use of models. Similarly, Chittleborough et al., (2005) found that many students in grade eight through their first year of university had naive concepts of models as representations, although to a lesser degree than Grosslight (1991). Importantly, Chittleborough et al., (2005) found that students' understanding of the nature and role of models in science and in teaching did improve as the grade levels progressed. This suggests that perhaps, with maturity and experience, students’ conceptions of modeling will progress along a continuum towards more expert or sophisticated conceptions.

As the science education community progresses toward a better understanding of how teachers and students conceptualize and apply scientific modeling in the classroom, two pertinent lines of questioning have emerged. First, if previous work suggests modeling is challenging for adolescents and college-age learners, to what extent might children in elementary school be able to engage in modeling as a sensemaking practice? Second, are limitations on how students currently use modeling in science classrooms related to the preparation and understanding that their teachers have for understanding and teaching scientific modeling?

To address the first question, an emerging group of scholars have applied and studied MBT with elementary school teachers and students. These researchers have found that children in elementary school are able to engage in the process of developing, using and revising models to help them develop explanations of phenomena (see Baumfalk, et al., 2018; Lehrer, & Schauble, 2012; Louca and Zacharia, 2015; Manz, 2012; Penner et al., 1997; Vo et al., 2015).

In addition, Zangori, Forbes & Schwarz (2015) found that third grade students who developed their own diagrammatic models of processes involved in the hydrologic cycle were better able to identify important components of the model and explain how the processes worked, compared to peers who were provided a template to complete. This suggests that younger students are able to select relevant elements to represent and then articulate complex concepts using their own models.

Several studies have also shown that while elementary students are able to develop and use models to construct explanations, the more that modeling becomes part of their classroom practice, the more sophisticated their models and their explanations become (Zangori & Forbes, 2015; Manz, 2012; Louca & Zacharia, 2015). In particular, Manz (2012) found that third grade students engaging in the practice of modeling over the course of a year initially treated the models they developed as artifacts conveying discrete knowledge and facts. Over time, however, they came to view their models as tools that could help them ask new questions, as well as predict and analyze changes to the system under study.

Students in elementary school, including kindergarteners, were more likely than older students to engage in spontaneous revisions of their model as they were constructing it, moving iteratively through the development and revision processes multiple times before an agreed upon model was tested under new conditions (Louca

& Zacharia, 2015). This demonstrates young children's conceptions of models as changeable rather than fixed entities that can and should be revised as new evidence emerges. This is a more expert than naive conception of models that research suggests can be demonstrated by even very young children (Grunkorn, zu Belzen, Kruger, 2014; McNeil et al., 2018; Oh & Oh, 2011; Treagust et al., 2002).

Penner, Giles, Lehrer, and Schauble (1997) found that students in grades one and two who engaged in modeling-based learning experiences were better able than their non-modeling peers to evaluate models in terms of how the system worked over the perceptual qualities of whether the model replicated the object that was being represented. Further, first and second grade students involved in the iterative process of modeling demonstrated an understanding of the nature and purpose of modeling that was more similar to students in grades four and five.

The science education community is building confidence that modeling as a sensemaking strategy is appropriate and productive for children throughout elementary school. One current limitation is that there are pockets of studies at various grade levels that focus on a handful of curricular contexts. More work is needed to build a body of literature that more cohesively describes the progression of modeling-based teaching and learning throughout the elementary school grades and across curricular contexts. By focusing on fifth grade teachers who are teaching concepts related to energy transfer in Earth's systems, the current study added to the connectivity of understanding on how scientific modeling is currently used in elementary schools across grade levels and across contexts.

A second line of questioning explored in the literature was how teacher conceptions of scientific models and modeling relate to students' still limited use of modeling as a sensemaking strategy. A review of the literature revealed that students were able to demonstrate more sophisticated understanding and use of scientific modeling when the researcher participated in the modeling intervention or professional development (see Penner et al., 1997), and when teachers were given direct and explicit support (Baumfalk, et al., 2018; Louca & Zacharia, 2015; Vo et al., 2015, 2019). In contrast, classrooms in which teachers did not have any specific support for modeling or MBT, both the teachers' and students' conceptions and epistemologies of the nature and purpose of modeling were notably more naive and novice (Grosslight et al., 1991; Treagust et al., 2002; Justi & VanDreil 2005a; Vo et al., 2015).

In particular, of all the grade spans, there is scant research on the development of elementary teachers' knowledge and practice of modelling-based teaching (MBT) (Everett et al., 2009; Vo et al., 2015, 2019). One research team has recently studied the relationship between teacher practice and student model-based explanations when a modeling-enhanced science curriculum was used with third graders studying hydrologic systems (Vo et al., 2015, 2019). This research team found that when teachers were supported with science curriculum enhanced with explicit opportunities to engage students in developing, using, evaluating and revising models, students' model-based explanations of the causal mechanisms of hydrologic processes improved. Importantly, the degree to which the teachers supported modeling practices and incorporated epistemic considerations of scientific modeling varied across classrooms, suggesting that support for teacher development of understanding scientific modeling practices and principles is a necessary area of further study (Baumfalk, et al., 2018; Vo, et al., 2015, 2019; Zangori, et al., 2017).

In one study, even though preservice elementary teachers had taken four science content courses, they had not yet developed a strong understanding of the types, uses, and characteristics of scientific models (Everett et al., 2009). Elsewhere, in an in-depth case study of five beginning high school teachers, Justi and Van Driel (2005a) found that teachers did not initially have comprehensive knowledge of models and modeling as it related to their teaching activities (see also Van Driel & Verloop, 1999).

Preservice and in-service teachers often do not have experience with scientific modeling, or the related pedagogical content knowledge (PCK) (Shulman, 1987) required to engage students in modeling as a sensemaking strategy (Gilbert & Justi, 2016; Justi & Van Driel, 2005a; Oh & Oh, 2011; Vo et al., 2015). These researchers have suggested teachers need experience and ongoing support with the practices and epistemic nature of scientific modeling in order to support their students in this work. As the small but growing body of literature on MBT in elementary schools contributes to our understanding, more research is needed to understand how teachers conceptualize scientific modeling, and how their practice can support students' model-based reasoning and explanations in a variety of curricular contexts.

If more attention is not paid to understanding how scientific modeling is enacted in elementary classrooms, policies such as the NGSS will continue to pose high expectations of teachers and students without administrators and professional development providers being equipped with the necessary understanding to provide the types of support that will help teachers actualize these goals. This study contributes to the science education community's understanding of what is currently happening and what might be possible in elementary school classrooms, while also providing insight into what supports might be necessary to help elementary school teachers and students engage in scientific modeling that promotes sensemaking.

Chapter Summary

In this chapter I first reviewed the major events and education policies that led to the context and need for this study. Of particular importance were the NGSS, which call for students to engage with complex phenomena and do the work of science to figure out how the world around them works (Lead States, 2013). I then reviewed the theoretical perspectives that informed this study, specifically the constructivist and social learning theories that situate meaning making as something that students and teachers do together (Bruner, 1977; Dewey, 1916, 1938; Vygotsky, 1978). I also discussed the role of framing, specifically epistemic framing, as important to understanding the classroom interactions observed in this study (Goffman, 1974; Reddish, 2004). Finally, I reviewed literature relevant to epistemic thinking in science education (Berland et al., 2016; Kuhn, 1993, 1999; Sandoval 2005, 2014) and modeling-based teaching, particularly in elementary school classrooms (Schwarz et al., 2009; Seel, 2003; Windschitl et al., 2018; Manz, 2012, Vo et al., 2015, 2019). In chapter three, I will discuss the methods used in this multi-case qualitative study about how modeling was enacted in three fifth grade classrooms.

CHAPTER 3

Methodology

This chapter outlines the methods used in this qualitative study. It presents the details of the research design, the role of the researcher, research context and participants, data sources and collection, the data analysis techniques used to address the research questions and a discussion of trustworthiness.

Research Design

This study applied a multiple-case design with cross-case analysis (Yin, 2018). Case study methodology is most appropriate when researchers seek to understand a real-world phenomenon that cannot be separated from its context. The phenomenon often includes many intersecting constructs of interest that cannot be teased apart (Yin, 2018). Phenomena related to teaching and learning provide just such situations. For instance, understanding how children are learning in a classroom cannot be separated from practices the teacher is using; likewise understanding how a teacher develops her practice cannot be isolated from her interactions with her students. In case study research, it is not necessary, in fact not recommended, to reduce the complexity of the phenomenon because it is precisely this complexity for which understanding is sought (Yin, 2018). Due to the complexity, however, it is critical that the case is clearly defined.

Case study methodology has been widely used to understand complex phenomena in education. Several studies have examined the implementation of scientific modeling in classrooms using single case designs focused on the teacher or on teaching practices as their unit of analysis (see Bismark, Arias, Davis & Plainscar, 2014; Christodoulu & Osborne, 2014; Justi & Van Driel 2005b). Other studies have used multiple-case designs with the teacher as the unit of analysis (see Akerson et al., 2009; Arias, Davis, Marino, Kademian & Palinscar, 2016). Still others employed a multiple-case design with cross-case analysis, again with the teacher as a unit of analysis (see Justi & Van Driel, 2005a; Vo et al., 2015).

For this study, the unit of analysis was the classroom, inclusive of the practices and interactions between teachers and their students as well as learning products produced collaboratively and individually. These classroom interactions and products were analyzed to understand more about classroom practices that targeted the Next Generation Science Standards (NGSS) practice of developing and using models, in order to answer the following two research questions and related sub-questions.

Research Question 1: How was the NGSS practice of developing and using models enacted in three fifth grade classrooms?

A. How did three fifth grade teachers conceptualize scientific models?

B. How did epistemic framing guide classroom interactions involving scientific modeling in three fifth grade classrooms?

C. To what extent did fifth grade students develop effective explanatory models?

Research Question 2: How were the experiences involving scientific modeling similar and different across three fifth grade classrooms?

Role of the Researcher

Throughout this study I paid careful attention to the ethical considerations of my role as the researcher. In qualitative research, it is important for the researcher to consider their role as a primary instrument of the study (Stake, 1995). The researcher plays an active role in negotiating what data get collected and how throughout the study, not just during its design. This is particularly true for studies using data sources such as interviews where there is a dynamic relationship between the researcher and participants. Similarly, in observational data collection the researcher is in the position of determining what gets paid attention to (Stake 1995; Yin, 2018).

As a member of the leadership team of a Research-Practice Partnership (RPP) in which the case study teachers participated, I was aware of how my relationship to the participants could influence the study and thus, took care to maintain this awareness and continually reassess my role and biases as the study progressed. At the time of the study, I had been in a professional relationship with each of the case study participants for several years and had facilitated professional learning sessions in which they were participants. Through my written solicitations and in conversations, I worked to be sure the teachers understood the goals of the research and that it was not in any way evaluative of them or their teaching practice. I also used a method of bracketing (Tufford & Newman, 2012), in which I kept reflective memos throughout data collection and data analysis to reflect on my position, biases and honesty of interpretation. Bracketing does not eliminate, but rather, helps the researcher acknowledge their role, assumptions and biases and take conscious steps to preserve the honesty and integrity of interpretations and findings.

While I maintained awareness of my potential influence as the researcher, my role in the RPP also positioned me to have a trusting relationship with the teachers. Prior to this study, I had a collegial rapport with each of the teachers and have supported each of them in improving their practice previously. This may have contributed to their comfort participating in the study.

Research Context and Participants

Context

The Research Practice Partnership (RPP)

This case study was conducted in the context of a mature Research Practice Partnership (RPP) between a mid-sized, northeastern state university's school of education and surrounding public school districts. The RPP has been addressing problems of practice in kindergarten through eighth grade science education since 1995. During the 2019-2020 school year, the RPP included 13 school districts and supported 844 teachers and 18,339 students.

Upon their state's adoption of the Next Generation Science Standards (NGSS Lead States, 2013) in 2013, the RPP worked toward building a comprehensive program to meet the NGSS expectations. The RPP adopted the FOSS Next Gen program (2019) in grades K-8. Each grade level implemented three courses per year, one in each of earth, life and physical science. These courses were designed to support teachers and students in developing understanding of the three dimensions of NGSS, which included practices, core ideas and crosscutting concepts. All teachers who were new to a given grade level received between three and six days (15-30 hours) of curriculum-based professional learning (PL) workshops before teaching new courses, depending on the grade level. This PL happened during the school day and occurred just prior to course implementation. This core PL focused on initial course implementation. District administrators committed to release time for all teachers to participate in the PL which was conducted by RPP leadership staff and a teacher leader from within the RPP, who was also released to facilitate the PL workshops. After completing the core PL sequence, teachers returned every other year for one day (5 hours) of advanced PL relative to the current course that they were teaching. In addition, RPP leadership staff and Teachers on Special Assignments (TOSAs) provided coaching and support, as well as PL and strategic planning for principals and central office leaders.

Curricular Context

The curricular unit of focus for this study was the FOSS Earth and Sun Next Generation Edition course (2019). FOSS is a published science curriculum intended for students in kindergarten through eighth grade science and it is widely adopted by schools throughout the United States. FOSS materials contain many features that are educative for teachers in terms of understanding the NGSS expectations. They provide students with opportunities for active learning and sensemaking. The program has supported teachers and students across the US to develop sustainable elementary and middle school science programs that are supportive of teacher and student learning.

Earth and Sun is a 13-week course that addresses the fifth grade NGSS. The course is divided into five investigations that last between two and four weeks each. The investigations were designed to engage students in exploring phenomena related to the Sun and Earth as parts of a planetary system, the properties of air and the atmosphere, energy transfer from Sun to Earth, and the cycling of water and energy throughout Earth's systems. Throughout the course, students considered how all of these phenomena interacted in order to understand weather and climate. Part of the FOSS instructional sequence included specific instruction designed to engage students in the NGSS practice of developing and using models embedded in their learning of the core ideas in science (FOSS, 2019).

My study was conducted while the students were working on the fourth investigation in the course which lasted for three to four weeks and focused on helping students figure out how Earth's atmosphere heats up. This investigation built on the previous investigation in which students examined the properties of air and the factors involved in creating weather. The fourth investigation engaged students in understanding concepts related to energy transfer in Earth's systems, and targeted among others, the NGSS practice of developing and using models as well as the NGSS crosscutting concepts of systems and system models, and energy and matter (FOSS, 2019). In particular, this study focused on Part Two of this investigation in which students developed models to explain how energy is transferred to the air after they investigated concepts related to the phenomenon. In each of the participating classrooms, this instructional sequence was spread out over two to four days of 45-80 minute sessions.

Sampling Procedures

The sampling frame for this study was all 62 fifth grade teachers from the same state in the northeastern United States whose districts participated in the RPP during the 2019-2020 school year. To learn more about teacher conceptions of modeling, all of the fifth grade teachers were invited to take the Students' Understanding of Models in Science (SUMS), a 27-item Likert-scale survey that characterized conceptions of scientific modeling (Treagust, Chittleborough, & Mamiala, 2002).

In order to identify three case study participants from the larger pool of 18 survey respondents, I added two additional survey items. The first additional item asked teachers to select one of five statements (see Table 1) that best described their experience with teaching the NGSS practice of developing and using models. The statements were based on levels of use from the Concerns Based Adoption Model (CBAM). CBAM posits that teachers go through several levels as they develop familiarity and the skills needed to successfully adopt an innovation or change (Hall, Dirksen, & George, 2006). This relates to the ongoing support for teacher development that is necessary for effective teaching to which the RPP paid close attention (see Loucks-Horsely et al., 2009). On the survey I developed statements specific to the NGSS practice of developing and using models that reflect levels of use descriptions in the CBAM. The second new item asked respondents if they would be interested in participating further in a study with their classroom as a case study participant.

Table 1

Descriptions of Teacher Experience with the NGSS Practice of Developing and Using Models Based on Levels of Use in the Concerns Based Adoption Model (Hall, Dirksen, & George, 2006)

Level	Description
1	I haven't had the opportunity to learn much about the NGSS practice of developing and using models yet, but might be interested as I learn more.
2	I know developing and using models is a part of the NGSS, and I'm beginning to consider how it might fit into my teaching practice. I'm interested to learn more about it.
3	I know developing and using models is a part of the NGSS. I'm learning about it as I go and I engage students in this work the best I can where it is called for and described in our science curriculum.
4	I know developing and using models is a part of the NGSS. I think it is a valuable part and appreciate the opportunities to target this work when it comes up in our science curriculum.
5	I think developing and using models is an important NGSS practice and I work on it with my students whenever I see the opportunity.

From the teacher survey responses, I identified teachers who selected level four or five on the levels of use question, as shown in the bottom two rows of Table1. These responses suggested that modeling was a prioritized practice in their classrooms. Therefore, this was a purposively selected sample (see Patton, 2002) because the participants stood to provide insight into what was possible when intentionally engaging students in the practice of developing and using models. There were four respondents who answered the levels of use item at level 4 or 5 and who also indicated interest in participating as a case study participant. One teacher was not able to complete the classroom visits due to scheduling. Consequently, three classrooms were selected, which was the targeted number of cases for this study.

The teachers from the three selected classrooms did not engage in any specific professional development (PL) in modeling beyond the 35 hours of PL that all teachers in the RPP received. During the 2019-2020 school year, all three of the selected teachers taught fifth grade in the same state in the Northeast United States. Two of the teachers taught in the same district, but at different schools, and one teacher taught in a different district at a third school.

Informed Consent and Confidentiality

Protecting the rights and confidentiality of all study participants was very important to me. Participation by teachers and students was voluntary and they had the right to withdraw participation at any time. All participants had a right to review their data and study findings. Pseudonyms were used for the teachers and student work was not identified. Teacher participants, and students' guardians completed consent forms prior to data collection (see Appendices A & B). Students also completed assent forms (see Appendix C). All of the forms included study details, participant and researcher roles and responsibilities, and participants' rights. All of the forms were approved and stamped by my university's Institutional Review Board (IRB). The completed consent and assent forms were locked in the researcher's office on the university campus. All data were stored on a password-protected computer.

Participants

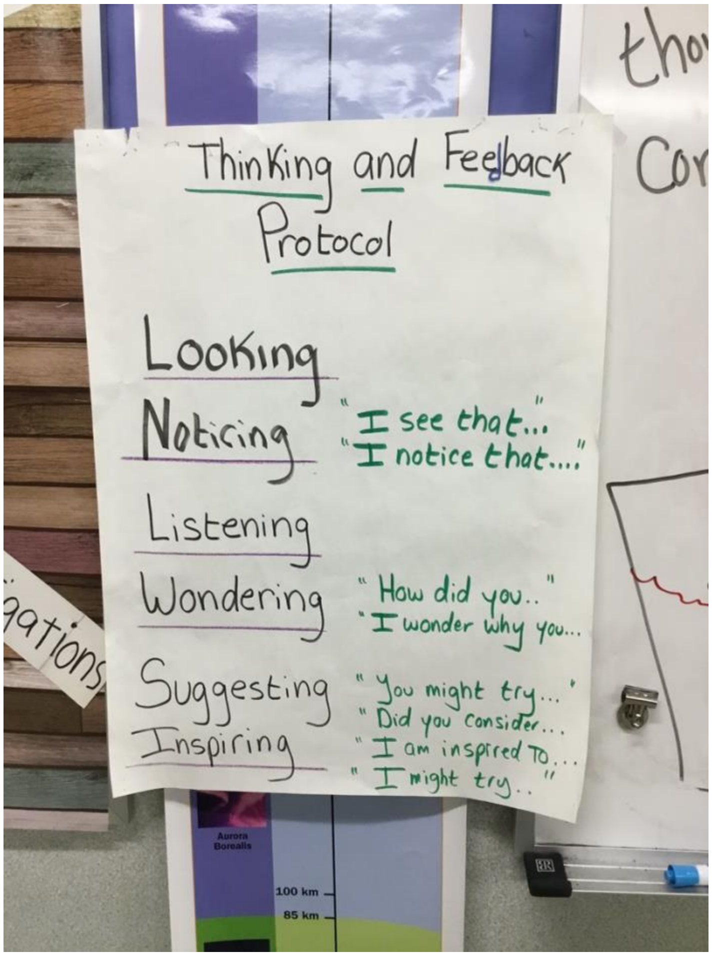
Natalie's Classroom

"Natalie" was an experienced teacher who had been teaching for over 20 years at a suburban middle school (grades 5-8). There were 366 students in her school at the time of this study. According to data published on the state's website, 89% of students at this school identified as white, 4.6% as two or more races, 3.3% as Hispanic, 1.4% as Asian, .05% as Black or African American and .08% as American Indian or Alaskan Native. The state reported that 18% of students at this school qualified for subsidized lunch.

At the time of the study, Natalie had been teaching fifth grade science for over 12 years. During the 2019-2020 school year, she taught only science and taught four sections of science each day. Her class periods were 50-55 minutes long. There were 22 students in the class that I observed during one science lesson that ran over the course of four days in December of 2019. Natalie's classroom (see Figure 1) was bright and inviting and her students were eager to work with one another. Her commitment to science learning was evident in student work displayed and stored around the room, as well as on bulletin boards that displayed tools for sensemaking and discourse. Natalie had participated in over 35 hours of PL with the RPP which included a five-hour session focused on modeling practices. When describing her experience with teaching modeling on the SUMS survey, Natalie selected the response *I think developing and using models is an important NGSS practice and I work on it with my students whenever I see the opportunity* (Level 5).

Figure 1

Support for Discourse and Feedback on the Wall of Natalie's Classroom



Denise's Classroom

At the time of the study, "Denise" had been a classroom teacher for about 15 years and had been teaching science for all of those years. She had taught fifth grade for over 12 years at the same suburban elementary school (K-5). There were 652 students in her school at the time of this study. According to data published on the state's website, 87.1% of students at this school identified as white, 5% as Hispanic, 5% as Asian, and 1% as Black or African American. The state reported that 5.7% of students at this school qualified for subsidized lunch.

During the 2019-2020 school year, Denise taught two sections of science and two sections of math each day. During my visits, Denise had a schedule of 50-60 minutes per session and there were 24 students in the class that I observed during one science lesson that ran over the course of four days. On the SUMS Survey, when presented with options to describe her level of experience with teaching modeling, Denise selected the statement *I know developing and using models is a part of the NGSS. I think it is a valuable part and appreciate the opportunities to target this work when it comes up in our science curriculum* (Level 4). Denise had completed over 35 hours of PL with the RPP and had also attended a five-hour workshop focused on modeling practices. It was clear that Denise was well organized and there were colorful and inspirational paintings around the classroom (see Figure 2).

Figure 2

Organization and Inspiration in Denise's Classroom

Lydia's Classroom

"Lydia" had been an elementary classroom teacher for over 20 years. She had been teaching fifth grade for over eight years at a suburban elementary school (K-5). There were 378 students in her school at the time of this study. According to data published on the state's website 78.9% of students identified as white, 12.4% as Hispanic, 4% as Asian, 2.1% as Black or African American, and 2.6% as two or more races. The state reported that 23.8% of students at this school qualified for subsidized lunch.

During the 2019-2020 school year, Lydia was teaching reading and science and had three sections of science each day. During my visits, Lydia had a block schedule of about 80 minutes per session and there were 22 students in the class that I observed during one science lesson that ran over the course of two days. Lydia's classroom (see Figure 3) was large and inviting and her students were eager to talk with me and welcome me into their community. When describing her experience with teaching modeling on the SUMS survey, Lydia selected the response *I think developing and using models is an important NGSS practice and I work on it with my students whenever I see the opportunity* (Level 5). Like Natalie and Denise, Lydia had participated in over 35 hours of PL in science including five hours focused on modeling practices.

Figure 3

Students Providing Feedback on Each Other's Models in Lydia's Classroom

Data Sources and Collection

SUMS Survey

The SUMS survey (see Table 2) characterizes conceptions of modeling into five factors, including *models as multiple representations*, *models as exact replicas*, *models as explanatory tools*, *uses of scientific models* and *changing nature of models* (Treagust et al., 2002). These factors are consistent with theoretical literature on aspects of scientific modeling (Grosslight et al., 1991; Oh & Oh, 201; Upmeier zu Belzen & Kruger, 2010). Each item was rated on a five-point Likert scale ranging from (1) strongly disagree, (2) disagree, (3) not sure, (4) agree to (5) strongly agree. For all factors except *models as exact replicas*, responses on the agree end of the scale represented a more sophisticated understanding of modeling. Responses on the agree end of the scale for *models as exact replicas* represented a more naive understanding of models. The internal consistency of each factor ranged from .71 to .84 using Cronbach's alpha, which are close to or exceeding the desirable .80 (see Devellis, 2012).

The SUMS instrument was developed with 228 public high school students in Australia. It has been used with high school students in Australia (Liu, 2006), Taiwan (Cheng, & Lin, 2015) and in the United States (Chittleborough et al., 2005; Gobert et al., 2011; Levy & Wilensky, 2009). SUMS has also been used with preservice science teachers (Everett et al., 2009). Wei, Liu and Jia (2014) used Item-Response Theory and Rasch modeling to further validate the SUMS with 629 high school students in China. They found that the SUMS adequately represented the five factors, but they recommended adding easier and harder items to the survey to strengthen each of the constructs. As was recommended by Wei and colleagues, to improve discrimination between agree and disagree items, I eliminated choice (3) [not sure] from the Likert scale in the current study.

In addition to the SUMS items, I asked a few demographic questions on the survey (e.g., years of teaching, number of science classes they were teaching, etc.). As discussed in the sampling procedures above, I also added two other questions. One question was about each teacher's level of use of modeling in their teaching practice and the other asked if they would be interested in being a case study participant. These two questions were used to identify case study participants. All responses were kept confidential and under password protection. The survey was administered online in

November of 2019 using SurveyMonkey, adhering to recommended principles of survey administration (Devellis, 2012) including readability, contrast, and matrix questioning structure.

Table 2

Students' Understanding of Modeling Survey (SUMS) (Treagust et al., 2002)

Factor	Item	Statement
Models as Multiple Representations	1	Many models may be used to express features of science phenomena by showing different perspectives to view an object.
	2	Many models represent different versions of the phenomenon.
	3	Models can show the relationship of ideas clearly.
	4	Many models are used to show how it depends on an individual's different ideas as to what things look like or how they work.
	5	Many models may be used to show different sides or shapes of an object.
	6	Many models show different parts of an object or show objects differently.
	7	Many models show how different information is used.
	8	A model has what is needed to show or explain a scientific phenomenon.
Models as Exact Replicas	9	A model should be an exact replica.
	10	A model needs to be close to the real thing.
	11	A model needs to be close to the real thing by being very exact, so nobody can disprove it.
	12	You should be able to tell what everything on a model represents.
	13	A model needs to be close to the real thing by being very exact in every way except for size.

	14	A model needs to be close to the real thing by giving the correct information and showing what the object/thing looks like.
	15	A model shows what the real thing does and what it looks like.
	16	Models must show a smaller scale size of something.
Models as Explanatory Tools	17	Models are used to physically or visually represent something.
	18	Models help create a picture in your mind of the scientific happening.
	19	Models are used to explain scientific phenomena.
	20	Models are used to show an idea.
	21	A model can be a diagram, picture, map, graph or photo.
Uses of Scientific Models	22	Models are used to help formulate ideas and theories about scientific events.
	23	Models are used to show how things work in scientific investigations.
	24	Models are used to make and test predictions about a scientific event.
Changing Nature of Models	25	A model can change if new theories or evidence prove otherwise.
	26	A model can change if there are new findings.
	27	A model can change if there are changes in data or belief.

Interview Protocol

I used a semi-structured interview protocol (Yin, 2018) with each of the three case study teachers. The interview questions (see Table 3) were developed by Everett and colleagues (2009) and were grounded in theoretical aspects of modeling described in the literature (Everett et al., 2009; Grosslight et al., 1991; Upmeier zu Belzen and Kruger, 2010). As Yin recommends, I asked follow-up questions based on participant responses to better understand teachers' conceptions of modeling. Each interview was between 18 and 30 minutes, video recorded and conducted a few weeks after the classroom observations.

Table 3

Interview Questions (adapted from Everett et al., 2009) Aligned to Theoretical Aspects of Modeling (Upmeier zu Belzen & Kruger, 2010)

Theoretical Aspect of Modeling (Upmeier zu Belzen & Kruger, 2010)	Interview Questions (adapted from Everett et al., 2009)
Nature of models	What is a scientific model?
	How close does a model have to be to the thing itself?
Multiple Models	Can a scientist have more than one model for the same thing? Why or why not?
Purpose of Models	What is the purpose of a scientific model?
Testing Models/ Changing Models	Would a scientist ever change a model? If so, why? If not, why not?

Classroom Observations

For each case study classroom, I observed and recorded video between two and four class sessions, depending on how long each teacher's teaching sessions were. The instructional goal for the lesson I observed was for students to develop a model of how energy is transferred to the air. I set up and recorded additional iPad videos during the observations to capture multiple contexts within the classroom and documented my thinking in research memos immediately following each session (Patton, 2002). Classroom observations were conducted in December of 2019. Teachers and students had been working together on this unit for almost 12 weeks and were 75% of the way through the course. This is important because the teachers' curricular goals were to engage students in co-constructing knowledge with their peers, and with teacher support, about the phenomenon of heating air. This goal required trust between students and their teacher (Loucks-Horsley et al., 2009). Therefore, it was important that the classroom observations were made almost four months into the school year, at a time when it was assumed that a trusting rapport had been established between the teachers and their students.

Student Notebook Knowledge Products

As part of classroom instruction, students collaborated in small groups of 3-4 students to develop a model of how the Earth's atmosphere heats up, or more specifically, how energy is transferred to the air. As part of the lesson, students were asked to create a diagrammatic model of this phenomenon and a corresponding written explanation. See examples in Figures 4, 5 and 6.

Figure 4

Example One of a Student Learning Product

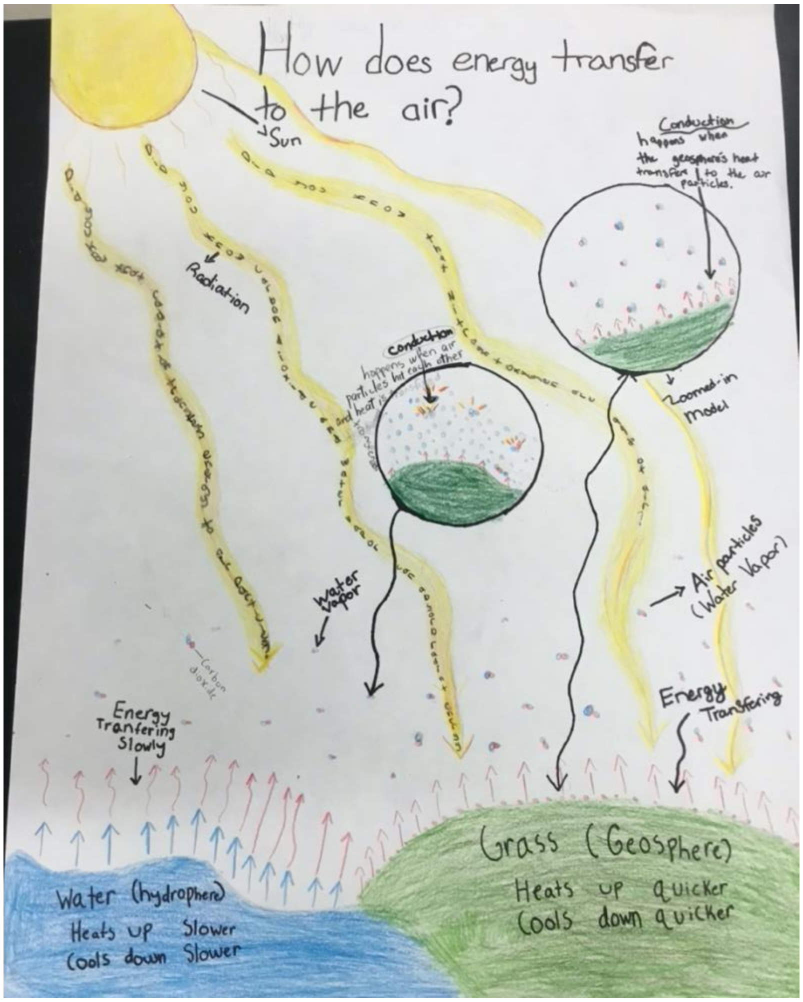


Figure 5

Example Two of a Student Learning Product

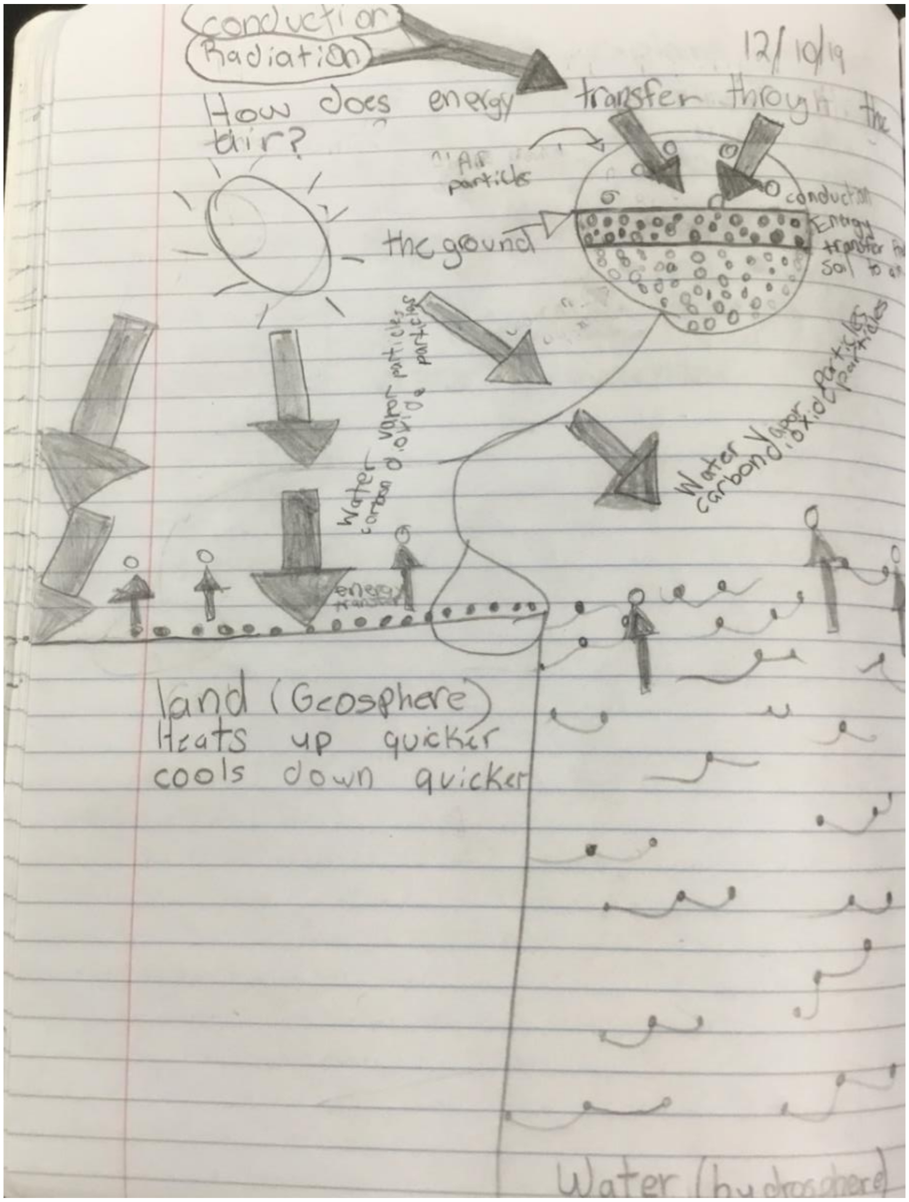
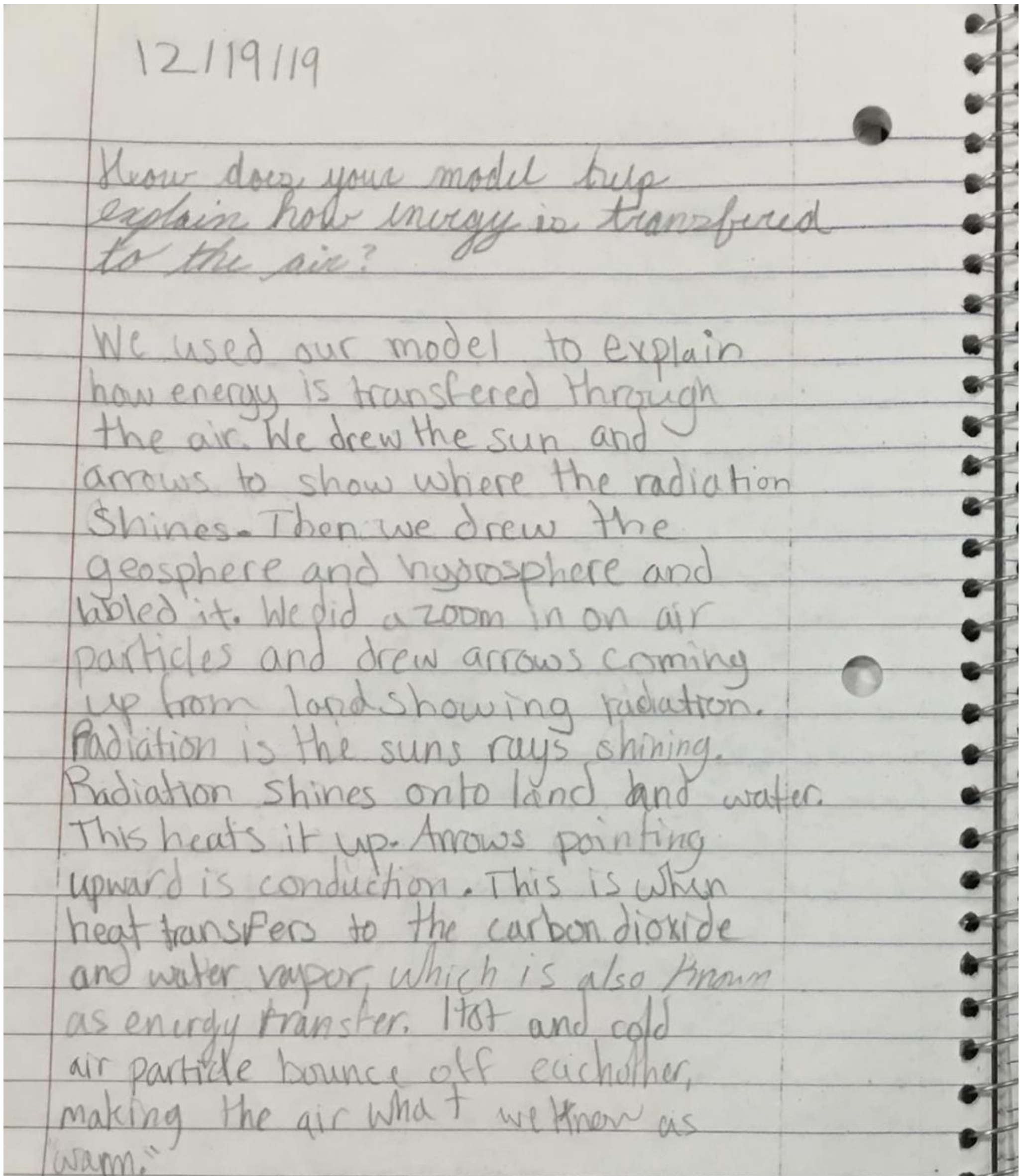


Figure 6

Example Three of a Student Learning Product



12/19/19

How does your model help explain how energy is transfered to the air?

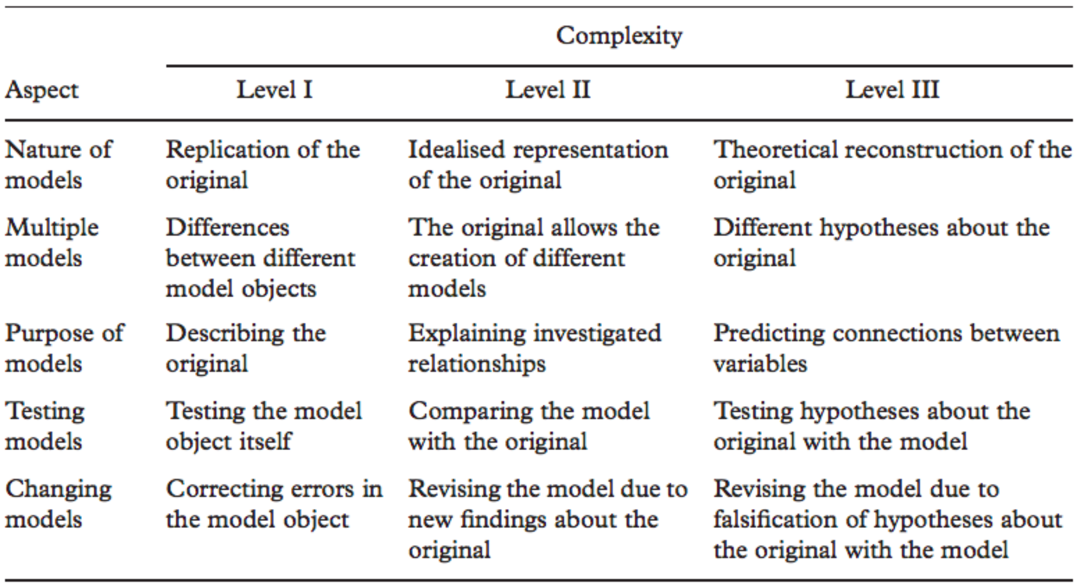
We used our model to explain how energy is transfered through the air. We drew the sun and arrows to show where the radiation Shines. Then we drew the geosphere and hydrosphere and labled it. We did a zoom in on air particles and drew arrows coming up from land showing radiation. Radiation is the suns rays shining. Radiation shines onto land and water. This heats it up. Arrows pointing upward is conduction. This is when heat transfers to the carbon dioxide and water vapor, which is also known as energy transfer. Hot and cold air particle bounce off eachother, making the air what we know as warm."

Data Analysis

This study examined how the NGSS practice of developing and using models was enacted in three fifth grade classrooms. To learn more about the teachers' conceptions of scientific models, I first analyzed data from the SUMS using descriptives to characterize the landscape of fifth grade teachers' understanding of modeling across RPP participants. I conducted this descriptive analysis with SurveyMonkey analytics. I also tabulated descriptives of the survey responses for the three case study participants in order to determine how their ideas about modeling were consistent with or diverged from the larger group of survey respondents. In addition, I coded the interview recordings of each case study participant according to the theoretical framework for understanding models depicted in Table 4 (Upmeier zu Belzen & Kruger, 2010). For each instance of any of the five aspects of modeling, I assigned a code of one, two or three based on the complexity levels described in Table 4.

Table 4

The Theoretical Framework for Understandings of Models (Upmeier zu Belzen & Kruger, 2010)

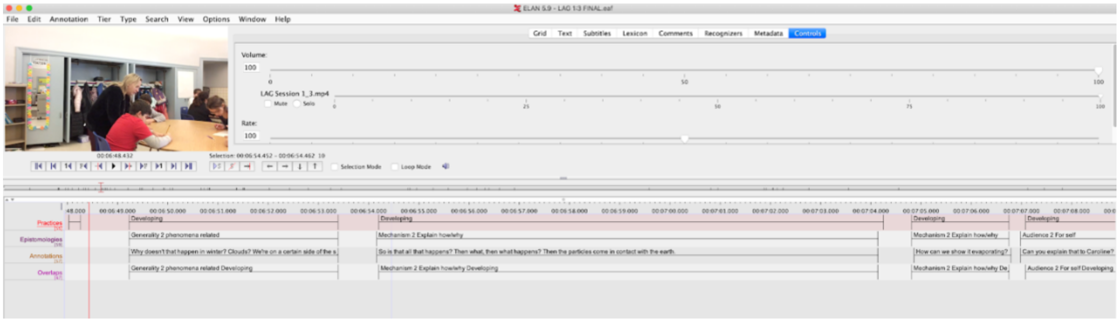


	Complexity		
Aspect	Level I	Level II	Level III
Nature of models	Replication of the original	Idealised representation of the original	Theoretical reconstruction of the original
Multiple models	Differences between different model objects	The original allows the creation of different models	Different hypotheses about the original
Purpose of models	Describing the original	Explaining investigated relationships	Predicting connections between variables
Testing models	Testing the model object itself	Comparing the model with the original	Testing hypotheses about the original with the model
Changing models	Correcting errors in the model object	Revising the model due to new findings about the original	Revising the model due to falsification of hypotheses about the original with the model

I used ELAN (2018) software to code data from teacher interviews and classroom observations. As depicted in Figure 7, ELAN allows you to manually type codes or annotations or to create preloaded codes using drop down menus. ELAN uses a tiered model that allows for multiple coding schemes or levels of annotation to be visible at the same time and correlated with the same media timestamp. The customizable drop-down menus, multiple level coding bars, and easy timestamp referencing were particularly useful for this study. With these features, I was able to create and then select from multiple coding guides and add transcriptions of each segment. I was also able to create queries of intersections of data at different levels. This helped me create a profile for each teacher's conceptions of modeling.

Figure 7

Screenshot of Coding in ELAN (ELAN, 2018)



Practices: Developing | Developing | Developing | Developing

Epistemologies: Generality 2 phenomena related | Mechanism 2 Explain how/why | Mechanism 2 Explain how/why | Audience 2 For self

Annotations: Why doesn't that happen in winter? Clouds? We're on a certain side of the s | So is that all that happens? Then what, then what happens? Then the particles come in contact with the earth. | How can we show it evaporating? | Can you explain that to Caroline?

Overlaps: Generality 2 phenomena related Developing | Mechanism 2 Explain how/why Developing | Mechanism 2 Explain how/why De | Audience 2 For self Developing

Data from the SUMS and the interviews were compiled into a descriptive profile of conceptions of modeling for each case study teacher and her classroom. To learn more about the epistemic framing of classroom interactions, I conducted two rounds of coding of the classroom video using ELAN (2018). First, I coded data from the audio/video recordings of classroom observations for occurrences of modeling practices - *developing*, *using*, *evaluating*, and *revising* according to the definitions outlined in Table 5 (Gilbert, 2004). Second, I identified occurrences, or instances where one of the epistemic considerations from the Epistemologies in Practice (EIP) framework was prominent (Berland et al., 2016). These EIP considerations included *mechanism*, *generality*, *evidence*, and *audience*. Based on the range within each consideration described in the EIP framework, I created two descriptors (see Table 6); one descriptor represented a more naive framing of the EIP consideration and the other descriptor represented a more sophisticated framing of the EIP consideration. For each EIP consideration in my coding guide, the more naive representation was coded as 1 and the more sophisticated representation was coded as 2 (see Table 6).

I created drop down menus in ELAN for each code to ensure that I would be able to search, sort, and cross reference all of the codes in both frameworks in order to look for patterns. A code was assigned for each instance, or occurrence, which was defined as a spoken, gestured or drawn interaction among students or between the teacher and students that represented one or more of the descriptions from the coding guide for modeling practices adapted from Gilbert (2004) or the coding guide for Epistemologies in Practice (EIP) adapted from Berland et al., (2016).

Table 5

Coding Guide for Modeling Practices (adapted from Gilbert, 2004)

Code	Description
Using	Students use a model developed by someone else (often a consensus model of the scientific community) such as a diagram in a text or computer model to help them learn about a concept or idea.
Developing	Students create their own models to explain how or why a phenomenon(a) occurs.
Evaluating	Students question or test a model for its ability to explain how or why a phenomenon or range of phenomena might work or predict outcomes.
Revising	Students change a model in some way to incorporate new evidence or understanding, or to make the model useful in explaining new outcomes or a broader range of phenomena.

Table 6

Coding Guide for Epistemologies in Practice (EIP) (adapted from Berland et al., 2016)

Code	Description
Mechanism 1	The knowledge product describes what happened.
Mechanism 2	The knowledge product explains how or why something happened, a step-by-step mechanism.
Generality 1	The knowledge product characterizes the specific nature of only the phenomenon at hand.
Generality 2	The knowledge product explains a range of related phenomena.
Evidence 1	The information to be included in the knowledge product was determined by someone other than the creator(s) of the product.
Evidence 2	The information to be included in the knowledge product was determined, and therefore justified by the creator(s) of the product.
Audience 1	The knowledge product is created for the teacher to evaluate student understanding.
Audience 2	The knowledge product is created for students, by students as part of a collaboration to construct understanding.

Before conducting my own coding, to ensure that I was interpreting and applying my coding guide to the classroom video data consistently, I chose a colleague to help test the reliability of my coding procedures according to both coding schemes. My colleague had previously taught grade 5 for three years and he had both participated in and facilitated professional learning sessions about teaching modeling.

I provided my colleague with three, 20-minute video clips, one from each participant, for a total of 60 minutes (or 10% of the total video data collected). One clip was from the beginning of a lesson, one from the middle and one from the end to capture the variety of modeling practices that may have been enacted during different parts of the lesson. I provided my colleague with the coding schemes based on the modeling practices and Epistemologies in Practice frameworks described respectively in Tables 5 and 6. We had an initial training discussion about the codes, and then we individually coded the three selected video clips according to both frameworks. Then, I put both of our coding records into a spreadsheet and coded each of our work in a different color. Sorting our records by the timestamp, I found there were four possible outcomes, described below, and assigned each a different color code, as shown in Figure 8.

1. We coded the same occurrence with the same code.
2. We coded the same occurrence but assigned different codes.
3. My colleague assigned a code where I did not.
4. I assigned a code where my colleague did not.

Figure 8

Screenshot of Cross Referencing Modeling Practices Between Raters

1:43	Developing	🟩				
1:47	Developing	🟩				
3:39	Developing	🟩				
3:44	Developing	🟩				
4:13	Developing	🟧	🟩	talk with teams		
4:22	Developing	🟩				
4:23	Developing	🟩				
4:54	Evaluating	🟪	🟩	Teacher Q		
5:06	Evaluating	🟩		Teacher Q		
5:06	Developing	🟩				
5:29	Developing	🟩		Teacher Q		
5:33	Evaluating	🟩				
5:38	Developing	🟩				
5:47	Developing	🟩				40
6:18	Developing	🟩		Teacher Q		
6:31	Evaluating	🟩			same	39
6:49	Developing	🟧	🟩	Winter 2nd marker		
					I code	0
6:54	Developing	🟩				
6:55	Developing	🟩			Z code	1
7:04	Developing	🟧	🟩	2nd marker		
					Different	0
7:19	Developing	🟥	🟩	teacher Q		
7:37	Evaluating	🟥	🟩			
8:08	Developing	🟥	🟩	Teacher Q		
8:15	Evaluating	🟥	🟩			
8:34	Developing	🟥	🟩	T Gesture		

After the initial round of coding, we agreed on the codes in 72% of the records. We then had a conversation about each instance of disagreement and worked to calibrate our interpretation of both coding schemes. The most frequent discrepancy was that when teachers asked a question of a group while students were developing their model, my colleague consistently coded it as *evaluating* because the teacher was prompting students to evaluate their own thinking as they worked. I coded those same instances as *developing* because students were still in the process of developing their models, and the teacher's question was a scaffold to help them articulate their current thinking clearly as opposed to evaluating the merits and limitations of the model based on new evidence. The practice of evaluating focuses on evaluating the components and interactions of someone else’s or an iteration of your own model (Gilbert, 2004).

We reached agreement that the coding guide intended to focus on the modeling practice students were engaged in even if the teacher was facilitating through questioning. After this discussion, we reached 97.5% consensus across the 60-minute sample of video.

After calibrating the coding protocols with my colleague, I coded the remaining 540 minutes of video footage from all three classrooms in three sets. I coded the first third of each teacher's lesson in the first set. Then I coded the second third of all three classrooms, and finally I coded the last third of all three classrooms' lessons. I did this to make sure my interpretation of the codes and viewing stamina was consistently distributed across the three classrooms rather than analyzing one teacher's classroom all at once in the beginning of my analysis and another teacher's all at the end of the process. After coding all of the classroom video, I performed a cross reference query in ELAN to identify the intersection of any modeling practices with EIP considerations to determine if there were any patterns in the epistemic framing of classroom interactions.

To learn more about the effectiveness of students' models, I analyzed student diagrams and written explanations using a rubric (see Table 7) adapted from a template that was developed to assess students' model-based explanations across four categories: *components*, *interactions*, *explanation*, and *revisions* (Penuel, 2018). These categories were grounded in the components of models described by Marquez, Izquierdo, and Espinet (2006). The four rubric categories included 1) components or parts (both visible and invisible) that need to be included in an effective model of a given phenomenon; 2) interactions or processes that need to be represented; 3) a written explanation of the causal mechanisms involved to effectively explain the phenomenon; and 4) a description of one or more revisions that were made to the model during development. I added the specific content into the rubric template that was relevant to the lesson being taught using the learning outcomes from the FOSS (2019) curricular resources of the case study teachers. The completed rubric was reviewed by a fifth grade teacher leader who was participating in a Teacher On Special Assignment (TOSA) program with the RPP and who had experience both teaching the curriculum and with modeling professional development but who was not participating in the study. The rubric was also reviewed by a second member of the RPP leadership team.

Table 7

Model Based Explanation Rubric (Penuel, 2018)

Category	Partially Effective (1)	Approaching Effective (2)	Effective (3)	Exemplary (4)
Required components	Includes minimum components: Sun, radiant energy, ground (does not include particle level)	Includes most but not all required components (see Met for complete list)	Includes all required components: Sun, radiant energy, ground particles, Air particles	Includes all required components and additional components: carbon dioxide particles, water vapor particles, nitrogen particles Or describes the multiple levels of organization of components.
Interactions	Draws or indicates insufficient interactions necessary to	Draws or indicates some interactions necessary to explain the phenomenon	Draws or indicates all interactions and labels interactions to explain phenomenon: radiation,	Draws or indicates all needed and additional interactions (re-radiation) and

	explain the phenomenon: radiation, conduction.	but some interactions represented are inaccurate (see met for complete list)	absorption, conduction, energy transfer.	labels interactions to explain phenomenon (see met), all interactions represented are accurate.
Includes correct causal mechanisms	Includes at least one mechanism in writing (see Met), but mechanism is insufficient to explain the cause-and-effect relationships	Includes and describes in writing how some but not all (see Met) of the mechanisms account for the cause-and-effect relationships	Includes and describes in writing how each mechanism works to explain each cause-and-effect relationship between components: radiation from the sun to the ground, energy transfer through absorption, energy transfer through conduction at the particle level.	Includes and describes in writing how each required mechanism explains the phenomenon and describes how mechanisms work together to explain the phenomenon. Or describes extra mechanisms: re-radiation from ground particles that are absorbed by CO2 and water vapor in the air, not at ground level. Further conduction among air particles.
Reflection for how model has been revised in light of new information or evidence gathered	Does not describe a revision made	Describes revision made, but if reason for revision is given, it does not pertain to new information or evidence gathered	Describes one revision and includes why it was revised in light of new information or evidence gathered.	Describes more than one revision and includes why each revision was done in light of new information and evidence gathered.

When analyzing the student artifacts, I excluded the *revisions* category because revising is a process that would have occurred during a longer time frame over the course of a unit as students developed more understanding. This was outside the timeframe of my study and therefore the data were not available for me to analyze.

As shown in Table 7, codes from 1-4 were assigned to the data (e.g., student diagrams and written explanations) according to four performance descriptions for each category that progressively characterized effective model-based explanations. For each category, a code of 3 represented effective modeling practice. Overall, across the three categories evaluated in this study, a total between 3-5 was considered a *partially effective* explanation, a total between 6-8 was considered *approaching effective*, a total between 9-11 was considered to be an *effective* explanation, and a total of 12 was considered to be an *exemplary* model-based explanation.

Cross-Case Analysis

To answer the second research question, I conducted a cross-case analysis. First, to address teacher conceptions I compared the responses to the SUMS survey (Treagust et al., 2002) from each of the three case study teachers and identified overlaps and divergences in their responses on each of the five factors included in the survey (see Table 2). I also used data from the interviews with each case teacher (see Table 3) to look for similarities and differences in the teachers' concerns and priorities. Then, to gain insight into the epistemic framing of classroom interactions I compared the percentage of occurrences of each of the four modeling practices across each classroom (see Table 5). I also compared the percentages of occurrences of the Epistemologies in Practice (EIP) considerations (see Table 6) across classrooms

(Berland et al., 2016). Finally, to understand the quality of student explanations, I compared the percentage of student work products that demonstrated varying levels of overall effectiveness according to the description in the section above and the rubric in Table 7 (Penuel, 2018). I also compared the percentages of student work products across classrooms that demonstrated effectiveness in each of the rubric categories (components, interactions, and mechanistic explanations) depicted in Table 7.

Trustworthiness

Throughout the study, I used several strategies to ensure the trustworthiness of findings. Trustworthiness in qualitative research is intended to ensure that a study's findings are worth considering and are accepted within the academic community (Lincoln & Guba, 1985). Lincoln & Guba describe four areas that ought to be considered to establish trustworthiness; credibility, transferability, dependability, and confirmability.

Credibility refers to ensuring confidence in the trueness of the findings (Lincoln & Guba, 1985). To attend to credibility in this study, I moved through multiple phases of methodological triangulation to inform my interpretation of the data (Stake, 1995). Data from surveys and interviews were compared and synthesized to inform my interpretations of the teachers' conceptions of scientific modeling. Further, I considered data from three sources (i.e., survey, interviews and classroom observations) to draw inferences about the epistemic framing of classroom interactions. In addition, as described earlier, I met with a second scorer to establish high inter-rater reliability for how the coding guides were applied to interpret classroom observations. A critical peer also assisted in creating and establishing reliability of the rubric used to evaluate student work. Finally, member checking was used with the case study teachers who were invited to provide clarity and feedback on pieces of writing in which their actions or words were represented.

One way to ensure transferability, or the possibility that study findings have applicability to other contexts, is to provide thick descriptions of study accounts and interpretations in sufficient detail. This allows readers and other researchers to identify relationships to their own contexts and conceptual interests (Lincoln & Guba, 1985). In this study, I provided considerable contextual details so that others would be able to identify appropriate contextual connections and limitations to their own situations. Taken together, the participant and context descriptions, as well as portraits of each case, cross-case comparisons, and relevant portions of the discussion provide rich descriptions of the complex and nuanced nature of interactions in each of the three classrooms in this study.

Dependability demonstrates that the findings are consistent and could be repeated (Lincoln & Guba, 1985). In this study, I took care to carefully describe my sampling procedures, coding schemes, and interview protocols, while also defining terms important for the valid and reliable interpretation of my findings. Part of this process included the inter-rater reliability work with my coding guides and rubrics. Member checking also helped to establish that my findings and interpretations were grounded in data and were in line with teacher perceptions of their experiences and practices, although, as recommended (Lincoln & Guba, 1985), the participants were not external to the study.

Confirmability is sought to establish that findings have been shaped by the participants and not by researcher bias (Lincoln & Guba, 1985). Member checking is considered the most critical tools to establishing confirmability and was an important part of this study. I also used reflective memos throughout the stages of data collection and analysis in order to maintain awareness of my biases and take steps to ensuring my interpretations were an honest reflection of the data.

Chapter Summary

To summarize, this chapter provided details of the multiple-case study design I used to examine how three fifth grade teachers enacted scientific modeling in their classrooms. To better understand the teachers' conceptions of scientific models, how the classroom interactions were framed epistemically, and students' explanatory models, I gathered data from multiple sources, including data from the SUMS survey (Treagust et al., 2002), interview data, video of classroom observations, and student notebook entries.

Several techniques were used to analyze the data. Survey data was analyzed according to the factor descriptions in Treagust et al., (2002). Interview data were analyzed according to a framework for aspects of modeling by Upmeier zu Belzen & Kruger, (2010).

I also conducted two rounds of coding of the classroom observation video using ELAN (2018). First, I coded for modeling practices described by Gilbert (2004) and then for considerations of the Epistemologies in Practice (EIP) (Berland et al., 2016). Queries were run in ELAN (2018) to identify occurrences in which the two frameworks co-occurred. Finally, student notebook samples were analyzed using a rubric adapted from a template that was developed to assess students' model-based explanations (Penuel, 2018).

For the cross-case analysis, I compared the responses to the SUMS survey and interview data across each of the three case study teachers and identified overlaps and divergences in their responses. Then, I looked across all three cases for similarities and divergences from the within-case patterns that I had observed in the classroom observation data. In addition, I compared the percentage of occurrences of each of the four modeling practices across each classroom and the percentages of occurrences of the Epistemologies in Practice (EIP) considerations (Berland et al., 2016) across classrooms to identify any patterns that emerged across cases. Finally, I compared the percentage of student work products that demonstrated varying levels of overall effectiveness using the model-based explanations rubric (Penuel, 2018). and examined student work across the cases for similarities and differences between the rubric sub scores.

Several steps were taken throughout this study to ensure trustworthiness. Methodological triangulation was used to ensure that my findings were informed by multiple sources (Stake, 1995). Inter-rater reliability was established for the coding guides used to analyze classroom observation video. Teachers were invited to offer critical observations, interpretations, and other feedback that provided clarity on their cases and pieces of writing where their actions or words were featured. I also kept researcher notes that helped me attend to reflexivity. I continually questioned my assumptions and took care to interpret the data honestly and within the bounds of the cases, the data sources and analysis methods (Lincoln & Guba, 1985; Yin, 2018). Findings from these analyses are presented in Chapter 4.

CHAPTER IV

Findings

This chapter shares the findings from each of the three classrooms in this study. Each classroom served as its own case and provided insight into each of the research questions:

Research Question 1: How was the NGSS practice of developing and using models enacted in three fifth grade classrooms?

1. How did three fifth grade teachers conceptualize scientific models?
2. How did epistemic framing guide classroom interactions involving scientific modeling in three fifth grade classrooms?
3. To what extent did fifth grade students develop effective explanatory models?

Research Question 2: How were the experiences involving scientific modeling similar and different across three fifth grade classrooms?

First, I will describe how the case study teachers' ideas about scientific modeling fit in with those of their fifth grade teaching peers and why these teachers were selected for this study. Then I will present a portrait of each of the three cases and share findings related to research question one within each case. Finally, I will share the findings of a cross-case analysis to answer research question two.

Cases in Context

The three case study teachers were selected from the larger group of 18 fifth grade teachers who all responded to the SUMS survey described in chapter three (see results in Appendix D). The case study teachers were purposively selected from the group of survey respondents because they also identified themselves as being at a high level of use of intentionally teaching scientific modeling according to the CBAM and stood to offer great insight into classroom practice involving scientific modeling (Hall et al., 2006).

Overall, all survey respondents had relatively sophisticated conceptions of scientific modeling across all five factors in the survey. Responses on a few items suggested that many teachers had a naive conception that there is a correct version of a model that ought to be represented and that a model should be a replica of a system and how it works. This was opposed to a more sophisticated understanding that different models can represent different ideas or hypotheses about how a system works and that a model is not necessarily a replica.

All fifth grade teachers in the RPP received comprehensive, curriculum-based professional learning that included 30 hours of professional learning during their first year with the curriculum, and 5 hours every other year thereafter. The three teachers selected for the case study also received that professional learning, and shared their peers' tendency toward sophisticated conceptions of scientific modeling. They were selected as case study teachers because their responses to the item I added on the survey about teachers' levels of use of modeling indicated they valued and made an intentional effort to include modeling in their science teaching practice (see all responses to the item in Appendix E). The case study teachers were among 11 others who responded this way (level 4 or 5), and among four teachers who identified themselves as interested in further participation in the case study. One of those four teachers was unable to complete the classroom observations due to scheduling conflicts. The remaining three teachers were the case study participants whose classroom experiences are shared below.

Natalie's Classroom

Natalie and her students were excited to participate in the study and welcomed me warmly into their classroom. As an experienced teacher, Natalie's confidence and ease with her students created a sense of calm in her classroom. I noticed a great deal of mutual respect and caring among Natalie and her students which created a positive learning environment.

Teacher Conceptions

A picture of Natalie's conceptions of scientific modeling was generated from her responses on the SUMS Survey (see Natalie's responses in Appendix F) and through a conversation during a thirty-minute interview.

Models as Multiple Representations

Natalie's survey responses for this factor indicated she has a fairly sophisticated understanding that a scientific phenomenon can be represented with different models. Natalie's responses suggested she understands that different perspectives, versions, or parts of a phenomenon or system may be explained using different representations. Natalie agreed or strongly agreed with six of eight survey items having to do with models as multiple representations, which indicated a more sophisticated than naive conception of models as multiple representations.

Similarly, in her interview, Natalie shared that she thought scientists can have more than one model of the same phenomenon because each model might represent different aspects of the system or idea. Natalie explained, "Students might develop a model to show something related to a weather event, for instance energy transfer. And maybe, as they learn more and want to show a new aspect, they can make a new model, like about the wind patterns." (personal communication, March 16, 2020, 11:19)

According to her survey responses, Natalie disagreed with the idea that *a model has what is needed to show or explain a scientific phenomenon*. At first, this disagreement appeared to stand in contrast to Natalie's other responses, but during her interview she shared her belief that the students' discussions of their models were an integral part of using modeling as a sensemaking strategy. She shared that if a student drew a model, the model was a tool to help explain their ideas but that the artifact itself did not stand alone without the explanation. She explained that working with students to develop models is important because, "They use their models to try to explain their thinking, and sometimes if they aren't able to, it also makes their misconceptions clear" (personal communication, March 16, 2020, 7:52). This helped to clarify that Natalie viewed the artifact as working in tandem with a student's verbal explanation.

Natalie also disagreed with the statement that a model depends on an individual's different ideas. Again, this first appeared to be in contrast to the idea she shared during our interview that models help students explain their thinking and that models can change as students learn more or work together to represent their ideas more clearly. Further in her interview, however, Natalie made three references to the idea that if a student's thinking was not clear on their model, it could be an indication that she as the teacher "may not have shown that very clearly", or "might not have done a good job explaining" (personal communication, March 16, 2020, 17:25). This suggests that Natalie feels responsible to guide students to what is ultimately a correct version of the model.

Models as Exact Replicas

Natalie's survey responses for this factor showed a sophisticated understanding that models are often not replicas of the system or phenomenon. She strongly disagreed or disagreed with all eight items on the factor and since items for models as exact replicas are reverse coded in the SUMS, disagreement showed Natalie's more sophisticated conception of the factor.

During her interview, Natalie specifically discussed the idea that when students are developing models to show what is happening in a system that is too small for them to see, or has components that are otherwise not visible, the models will likely not look like the real thing:

> Like scale, when they [students] are making models say of how the salt particles and water particles are arranged in solutions, what they draw does not actually look like salt and water particles. They are usually colored circles or dots. Or when they try to draw rays from the sun to show [energy] transfer, they can't really see rays, but they draw arrows or lines to represent them. (personal communication March 16, 2020, 11:18)

Models as Explanatory Tools

Natalie strongly agreed or agreed with all five items for the factor models as explanatory tools. Natalie's responses suggest she has a clear understanding that models serve as explanatory tools. This was also supported in her interview when

Natalie shared how her thinking has changed as she has learned more about modeling and teaching with modeling:

> I've always done lots with diagrams, but then I looked around at their layers of the atmosphere diagrams and all 72 were similar. They just looked different if you were a good colorer [sic]. So they were basically copying from the book or another diagram. But now I realize when we're modeling, it's not a drawing, it's not a coloring, it's a way to explain your thinking. (personal communication March 16, 2020, 7:19)

Uses of Scientific Models

Natalie agreed that models are used to show how things work and to make and test predictions which are more sophisticated conceptions for this factor. Yet, Natalie disagreed that models are used to help formulate ideas and theories about scientific events. This disagreement is consistent with Natalie’s idea that there is a correct version of models that have been determined by scientists and that students' purpose of developing models is to come to the correct version determined by the experts, rather than a version that represents their own original thinking, albeit similar to other scientists.

Changing Nature of Models

Natalie’s survey responses on this factor suggested she had a sophisticated understanding that models can change if new data, evidence or findings are applied. This is supported by Natalie’s interview in which she said, “If something new is learned or understood, that can be added to the model. It's definitely an evolving piece of work” (personal communication March 16, 2020, 15:56).

Classroom Interactions

I was invited to observe Natalie and her students over the course of four days (200 minutes) in December of 2019, as they worked through a lesson focused on developing a model of how air heats up. Natalie launched the lesson by sharing with students that she had noticed on her way to school that morning that it was 17 °F; by the time of the lesson, she sent a few students out to take the temperature and it was 32°F. Students were asked to use what they knew from prior investigations about energy transfer earlier in the unit and work with their group of three or four students to develop a model that would explain how this phenomenon happened.

The observations I made of the interactions among Natalie and her students provided insight into what modeling practices (Gilbert, 2004) students used as they developed explanatory models of how air heats up. These observations also shed light on how decisions were made about learning and knowledge in their classroom, or their epistemic framing (Redish, 2004). Epistemic frames or considerations offer insight into how Natalie and her students determined, “What's going on here (Goffman 1974)?” and “What counts as knowledge here (Redish, 2004)?” Through my observations, I was offered a glimpse into the “ways they tackle their work” (Berland et. al 2016).

Modeling Practices

While visiting Natalie’s classroom, I observed 34 occurrences, or instances, of students engaged in one of the four modeling practices, *using, developing, evaluating or revising.* Occurrences included spoken, gestured or drawn interactions among students or between the teacher and students and ranged from a few seconds to several minutes. During most of the occurrences (67%) students were involved in the practice of *developing* models. This is consistent with Natalie's objective for the lesson which was to have students create their own models to help them explain how and why the air heats up throughout the day. Students engaged in the other three modeling practices to a lesser degree; *using* (18%), *evaluating* (12%), and *revising* (3%) (for frequencies see Appendix G).

Students in Natalie’s class spent a considerable amount of time working with their peers to develop explanatory models of how air heats up. The time students spent using models created by others primarily focused on consulting text and images in the FOSS Earth and Sun Science Resource Book included in Natalie’s curricular materials to discuss the concept of re-radiation and how that concept may apply to their own explanations (FOSS, 2019). Students spent some time evaluating their own models and other students’ models of how air heats up. This time was spent mostly on providing feedback on a) how well organized and easy to read the models were and b) what might be changed to make their models more clear or effective. In this lesson, Natalie’s students spent very little time revising their models. While this could be a goal for subsequent lessons, it was not part of Natalie's plans for students to go back to their models and make significant changes in this lesson.

Epistemologies in Practice

During my visits to Natalie’s classroom, I observed 34 occurrences relevant to the considerations in the EIP framework (Berland et al., 2016). It is noteworthy that the modeling practices and EIP considerations always co-occurred. In fact, it is the modeling practices that make the epistemic framing visible.

While developing their models, Natalie and her students clearly prioritized the explanatory nature and mechanistic features of models. In fact, 35% (for frequencies see Appendix H) of observed occurrences were framed around explaining the mechanisms involved in heating the air. This suggests that Natalie and her students considered explaining how and why a system works the way it does was necessary and important knowledge to their community when developing scientific models. This is a more sophisticated epistemic framing of the nature of scientific models. For example, as students were working on their models, Natalie offered a suggestion of how students might include interactions among components that they might not be able to see; “if your model is showing what's happening with things you can't see with your eyes, maybe those are things you can also write about?" (classroom video, 01:38:02).

In another instance, Natalie noticed the water particles one group had included in their model and encouraged the students to discuss, “How do the water particles interact?” (classroom video, 02:18:02). With this question, Natalie encouraged the students to move beyond simply describing what components were included in the system and talk more about including elements in their model that would help explain the mechanistic role particle interactions have in heating the air.

While there were many instances of sophisticated epistemic framing during Natalie’s lesson, there were some areas where the epistemic framing was more naive. Some classroom interactions (26%) during the lesson were framed in a way that the teacher was determining what needed to be included in the students’ models rather than the students determining what *evidence* they needed to explain their own ideas. For instance, at one point Natalie makes a suggestion that; "carbon dioxide, maybe that's something you can add to your model, because that's going to matter" (classroom video, 00:33:03). During another instance, Natalie called the students' attention to the class model she had been recording on the board and suggested, “There's one other part that I think we should add about the kind of particles that are able to absorb the radiant energy that comes from the geosphere and hydrosphere” (classroom video, 01:20:52).

There were also a few instances (15%) during Natalie’s lesson where the students’ models were framed as products for the teacher. There was an understanding by both the teacher and the students that students should show what they knew and were aiming for the correct version of the model. This was a more naive framing of the EIP consideration of *Audience*. For example, Natalie discussed appropriate labeling with one group and said, “You’ll probably want to put [label] what kind of energy transfer that is” (classroom video, 01:59:18). While labeling is a productive element to include in a model, in this case Natalie indicated with an encouraging tone that the label would demonstrate correctness of the model.

A more sophisticated epistemic framing of *Audience* would position the students and their peers as the audience of their own knowledge products, or models. Although this more sophisticated framing of *Audience* was less frequent during Natalie’s lesson (9%), an illustration of it was demonstrated when students began discussing how the phenomenon of the air heating up might help them understand what happens to air temperature during the night versus the daytime, or in summer versus winter. During this discussion, students became noticeably animated and excited. They begin to stand, move their arms in larger motions, raise their voices excitedly and talk at the same time. One student commented; “say, in the winter when the sun's out, why is it colder sometimes than say in the summer when the sun's out?” (classroom video, 00:15:04). It was clear they wanted to talk through these ideas out of genuine interest and curiosity; they were their own audience.

The contrast I observed between some classroom interactions involving *Audience* being framed as naive and others being framed as sophisticated was also observed for classroom interactions involving the EIP consideration *Evidence.* As described earlier in this section, many of the interactions involving *Evidence* were framed in a more naive way, however there were some examples (12%) of more sophisticated epistemic framing for *Evidence* in Natalie’s classroom. At one point, Natalie encouraged students to consider which ideas of their own would be valuable to their group’s consensus model. “What part of your thinking from your own notebook will you make sure it is included in your group's model?” (classroom video, 01:49:05). In this instance Natalie supports students to determine for themselves what evidence is valuable and important to help them develop and share their ideas.

The contrast in framing occurrences among Natalie and her students from moment to moment within the same lesson revealed the complexity of classroom interactions and epistemic framing. Amidst this complexity it is noteworthy that overall, 59% of Natalie’s classroom interactions reflected more sophisticated epistemic framing, while 41% reflected more naive epistemic framing.

Co-Occurrences

I also examined the ways in which modeling practices and EIP considerations co-occurred, or interacted, to see if there were any meaningful patterns (for results see

Appendix I). I found, however, that since the majority of classroom interactions involved the practice of *Developing* models (as opposed to *Using, Evaluating,* or *Revising*) the EIP considerations were largely distributed among the instances of *Developing* and the co-occurrences did not reveal any insights that had not already been captured by examining the EIP considerations directly.

Student Explanations

To address the third part of the first research question and better understand the nature of the students' models in Natalie's classroom, I examined the student knowledge products that Natalie's students shared with me. Only ten students were present in the classroom at the time they were able to share because there was a school assembly going on. All ten chose to share their work as part of my analysis which represented work from 45% of students in the class.

Half of the models from Natalie's students represented *effective* models overall, and half of them represented *approaching effective* (see description in chapter 3). A summary of the rubric scores is included in Appendix J. These results suggest that while many of Natalie's students had developed effective explanatory models about how air heats up, many others were still working toward this goal.

An example of an *effective* model from Natalie's class is depicted in figures 9, 10 and 11 below. In Figure 9, the model shows key components (Sun, radiant energy, ground particles, air particles, carbon dioxide particles and water vapor particles) and the interactions among those components (radiation, absorption, conduction, and energy transfer) to effectively show that energy is transferred to the air primarily from interactions involving Earth materials on the ground. In Figure 10, the model shows the transfer of energy through conduction, or contact, between soil particles on the ground and the air particles just above the surface. In Figure 11, the student tried to show re-radiation (smaller arrow) coming from the ground and being absorbed by carbon dioxide and water particles in the air.

Figure 9

Notebook Sample 10 Representing an Effective Model from Natalie's Classroom

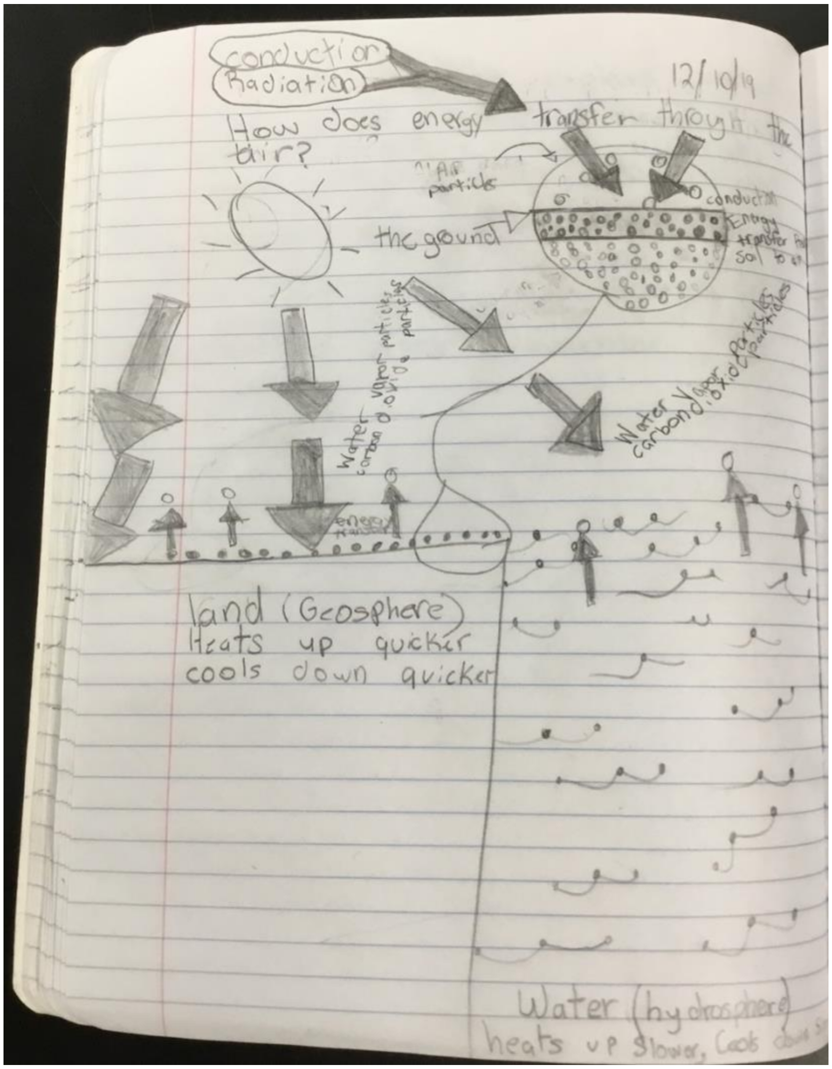


Figure 10

A Closeup of Notebook Sample 10 from Natalie's Classroom Showing Conduction

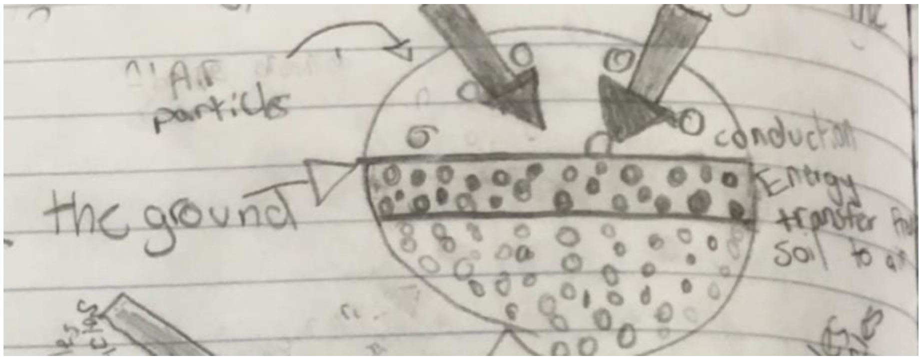


Figure 11

A Closeup of Notebook Sample 10 from Natalie's Classroom Showing Re-radiation

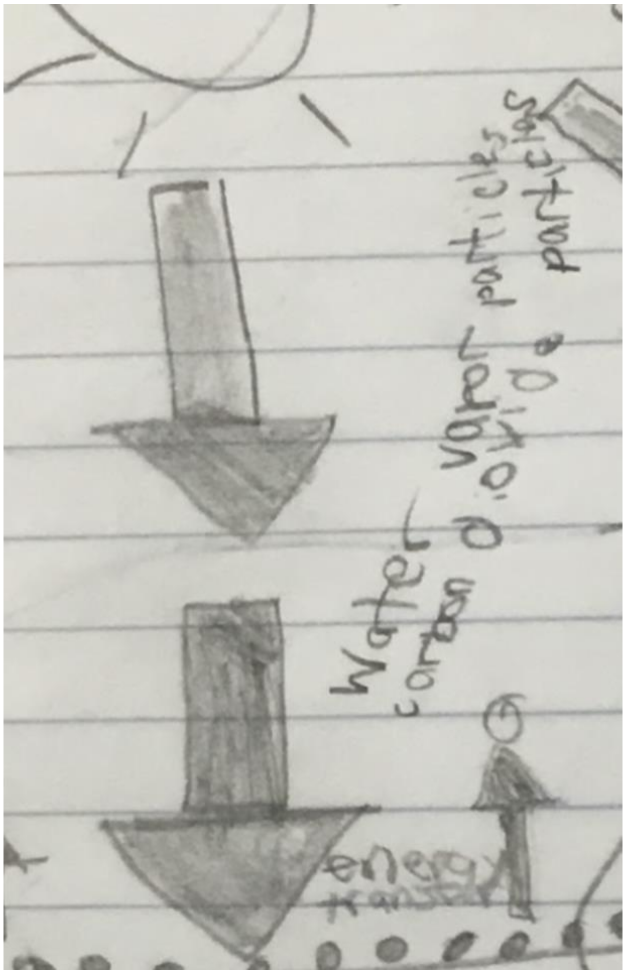
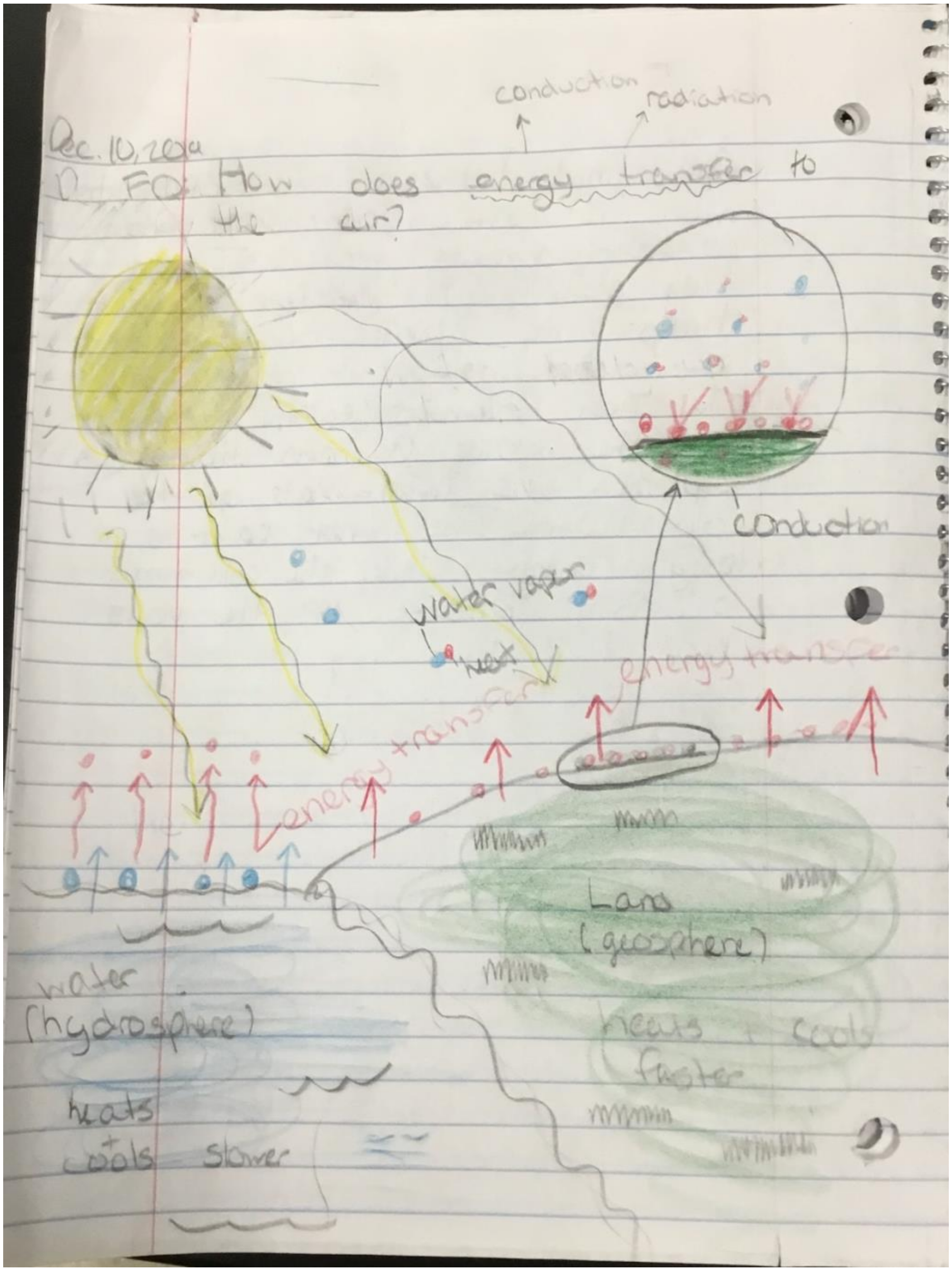


Figure 12 offers an example of a model that was scored as *approaching effective*. Here, the student’s model showed many components that contribute to an explanation of how air heats up, such as Sun, radiant energy, ground particles, and water vapor particles. However, there is less specificity about what some of the components represent, such as the unlabeled blue and red colored particles. Similarly, there were labels for some interactions such as conduction and energy transfer, although it is less clear what kind of process is taking place or how these interactions relate to the air warming up. It is challenging to discern if the student understood the processes or added the labels they thought they were supposed to include but were unsure of how the components interacted mechanistically. As with many models, a conversation with the student who created it might help clarify some of the ambiguity.

Figure 12

Notebook Sample 2 Representing a Model that is Approaching Effective From Natalie's Classroom

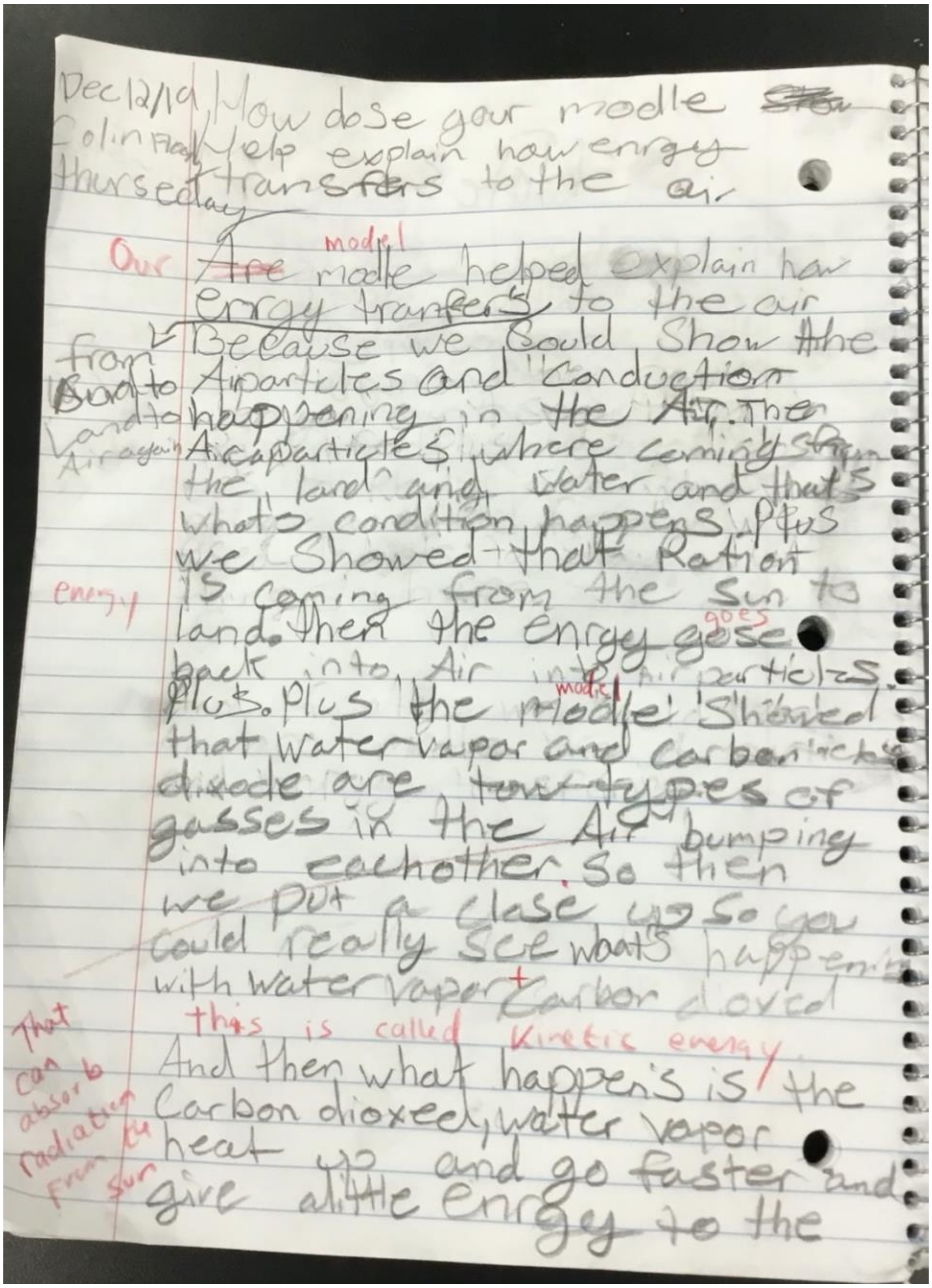


More students in Natalie’s class were able to include effective components in their models than were able to include effective interactions and mechanistic explanations. I observed that 90% of the samples demonstrated effective inclusion of the necessary components of the model which included Sun, radiant energy, ground particles, and air particles. On the other hand, 50% also demonstrated effective inclusion of the necessary interactions which were radiation, absorption, conduction, and energy transfer. Only 40% of the models included effective mechanistic explanations.

An example of an effective mechanistic explanation can be seen in the excerpt in Figure 13. The student explained that after the sun’s radiant energy is absorbed by the land some of it re-radiates into the air and it is only the carbon dioxide and water vapor particles that can absorb the re-radiated energy, and that the carbon dioxide and water vapor particles move faster and can transfer their energy to [other particles].

Figure 13

Excerpt From Notebook Sample 2, Explanation of a Model From Natalie's Classroom



Dec 12/19 How dose your modle ~~Show~~
Colin Fla
thursedday
Help explain how enrgy transfers to the air

Our ~~Are~~ model modle helped explain how
enrgy tranfers to the air
Because we could Show the
Airparticles and "Conduction
happening in the Air. The
Aircaparticles where coming from
the land and water and that's
what's condition happens. Plus
we Showed that Ration
is coming from the Sun to
land. then the enrgy goes gose
back into Air into air particles.
Plus. Plus the model modle Showed
that water vapor and carbon dioxide
diode are two types of
gasses in the Air bumping
into eachother. So then
we put a clase up so you
could really see what's happening
with water vapor + carbor dioxed
this is called Kinetic energy
And then what happen's is the
Carbon dioxeed, water vapor
heat up and go faster and
give alittle enrgy to the

from Sun to Air and to land to Air again

energy

That can absorb radiation from the sun

The finding that considerably more students in Natalie's class were able to include effective components than were able to include effective interactions and mechanistic explanations may relate to Natalie’s thinking (as expressed in her interview) that it was important for her to be sure that students ultimately arrived at the “correct” explanation of the phenomenon; therefore, she made explicit which components students ought to include. When working on the explanatory components of the model, despite their inclusion of the “correct” components, it was more challenging for students to articulate the interactions and mechanisms.

Case Summary

Overall, in the context of one 200-minute lesson over the course of four days, observed half-way through a unit on energy transfer and in one 30-minute follow-up interview, Natalie demonstrated a sophisticated understanding that scientific models are used to help explain how or why a phenomenon occurs and that models can represent many aspects of a phenomenon. Natalie understood that to help explain a person’s ideas, models may be abstract representations, and that models can be changed in light of new evidence to show new understanding of how a system works. Natalie used questioning to prompt students to move beyond describing changes to the air temperature and to try and explain the interactions among the mechanisms involved in warming the air. She encouraged students to show components of the Earth’s system that they could not see, such as air particles, to make their explanations clear and visible. These data suggest that Natalie had a relatively sophisticated understanding of scientific models and how she wanted to use them as a sensemaking tool in her classroom.

Natalie’s responses on the SUMS and in her interview also suggested that she held a more naive conception that models have a correct version that should be arrived at, as opposed to a more sophisticated conception that models represent a current and best explanation based on the evidence available thus far. While Natalie encouraged students to explain the processes involved in heating the air, she also consistently referenced the labels and components that students should include, or would need in their models, for them to be correct.

Prioritizing the correct version of a model is a common conception of teachers using modeling in their classrooms (Berland et al., 2016; Gilbert, 2004). Even though the scientific community has developed widely accepted models for certain phenomenon, when educators use a modeling-based teaching approach, there is still room for students to arrive at a similar understanding through their own modeling practice by collecting and determining what evidence best supports their understanding and what needs to be included in their model (Russ, 2014; Windschitl, Thompson, & Braaten, 2018).

Students in Natalie's classroom spent most of their time during this lesson engaged in the practice of developing models. That is, they talked about, drew, gestured and wrote about important components involved in explaining how air heats up. Students' work during class was also largely focused on the EIP consideration of mechanism or developing models that could explain how and why air heats up throughout the day by sharing ideas about how energy gets from the Sun to the Earth, how ground particles heat up, and how ground particles transfer energy to air particles through contact at the grounds surface. Natalie's more sophisticated epistemic framing during these interactions reflects her understanding of the purpose of models and her goals of engaging students in developing their own explanatory models.

During the course of Natalie’s lesson, there were also instances of a more teacher-directed approach to determining what evidence should be included in the students’ models. Natalie often drew students' attention to the class model she was creating on the board as an example of what students ought to include in their own models. The more naive epistemic framing is consistent with Natalie’s belief (as expressed in her interview), that it is important to guide students to what is ultimately the correct explanation of the phenomenon. There is a tension in Natalie’s instruction between using modeling as a tool to reach a correct understanding of already established concepts and using modeling as a sensemaking strategy in which the thinking processes are the goal for which students’ own thinking can help them arrive at an understanding of science concepts similar to the consensus of other scientists.

Student work collected from Natalie’s lesson showed that her fifth grade students were producing models that in some cases approached, and in other cases demonstrated effective explanations of how air heats up. Most of the students whose work I examined were able to include all of the relevant components needed to explain how air heats up (Sun, radiant energy, ground particles, air particles), and some of Natalie’s students were also able to show interactions that provided a comprehensive mechanistic explanation (energy transfer, absorption, conduction). When a model includes components that are not fully incorporated into the interactions and explanatory nature of the model, it may indicate that the teacher has helped the student identify what components are important before the student has developed a full understanding of how the components relate to one another. When the evidence to include is justified by the student, rather than the teacher, there is a stronger connection with its role in the mechanistic explanation of the process (Johnson-Laird, 1983; Nersessian, 2008).

Denise's Classroom

Denise's classroom was full of vibrant colors. There were thoughtful and inspiring messages painted as murals across most of the available wall space. Her classroom was incredibly well organized with a variety of manipulatives and supplies readily available for students to access independently. Denise's students came into the room excited and chatting, and with a clear sense that they were about to get right to work!

Teacher Conceptions

A portrait of Denise's conceptions of scientific models is shared below and was generated using information gathered from her responses to the SUMS Survey (see her responses in Appendix F) and from a conversation during her thirty-minute interview with me.

Models as Multiple Representations

Denise's responses to the SUMS survey suggested she had a sophisticated understanding that different aspects of a phenomenon could be represented with different models, and that the same phenomenon could be represented by different models. She agreed with all eight survey items for this factor.

Similarly, in her interview when asked whether a scientist could have multiple models for the same phenomenon Denise said, "yes, absolutely" and shared how she addressed this idea in her classroom; "We look at different models and talk about what information does this model give you, but this other model can't. We talk about the limitations of certain models" (personal communication, March 18 2020, 19:56).

Models as Exact Replicas

Denise's responses to the survey items in this factor suggested that she had an understanding that models are often not replicas of the system or phenomenon. Denise disagreed or strongly disagreed with six of the eight items, and since items for models as exact replicas were reverse coded in the SUMS, Denise's disagreement represented a tendency toward a more sophisticated conception of the factor. During her interview, Denise gave an example from her classroom of how a model may not be an exact replica of the system under study; "When we're in our physical science unit and we're modeling particles, it's not going to look like the real thing" (personal communication, March 18, 2020, 11:20).

On the survey, Denise agreed with the statement that the model shows what the real thing does and what it looks like. While Denise indicated in her interview that models may not look like the real thing, her response to the survey item suggested she did think a model needed to convey what the real system does, or how it works. This was consistent with her agreement to the statement that suggested a model needs to be close to the real thing. Again, it may not look like the real thing, but Denise's responses suggested she thought it should be close to the real thing in the sense that the model offers insight into some aspect of the system and how it works.

Models as Explanatory Tools

Denise strongly agreed or agreed with four of five items for this factor, suggesting she had an understanding that models provide insight into the mechanisms of how a particular system works or why it works the way it does. A comment from Denise’s interview revealed why she may have disagreed with the idea that a model can be a diagram, picture, map, graph or photo. She explained, “A model explains how something works or how the parts in a system work together. It's not just a diagram, it's not just a picture with labels. It's got to explain why or how things interact or something works” (personal communication, March 18, 2020, 05:55). Denise’s comments suggested she understood that a diagram or picture must be accompanied by annotations, visual elements, and a verbal or written explanation that shows the mechanistic features of the system.

Uses of Scientific Models

Denise agreed or strongly agreed with two of the three items on the factor called uses of scientific models. In her interview, Denise shared that she thought it was important for students to use models “to convey their scientific thinking in not just words but in some kinds of visual representation” (personal communication, March 18, 2020, 09:41). Denise skipped the item that asked if models could be used to make and test predictions.

Changing Nature of Models

Denise shared her understanding that models can change if new data, evidence or findings are applied. Denise strongly agreed with all three survey items included in the factor changing nature of models and she addressed this idea in her interview. “Their models may change because they've learned more. We'll talk about that. Now that we know this, how can we add that to what we already have?” (personal communication March 18, 2020, 14:04).

Denise went on in her interview to share some concern that students should ultimately arrive at an accurate or correct understanding of the concepts involved in the model.

> I want to give students the opportunity to try it, to be wrong, to mess up. But you have to balance it with wanting them to learn some content. Yes, you can take risks, but you need to be accurate too. At some point you need to see a more accurate representation. (personal communication, March 18, 2020, 23:18)

This suggested that while Denise understood that the purpose of scientific models was to explain ideas about how and why a phenomenon works the way it does, and that models can change as more understanding develops, she also had concern that students' ideas develop toward the correct, or already known, understanding of a particular concept.

Denise's concern for guiding students toward the correct version of a model seemed related to her concern about limited instructional time. During our interview, she shared her concerns about time at three different points.

> Also, as teachers we only have so much time. So, do you teach the content? But the modeling is so important. There's so much in the curriculum. I grapple with it every day. What is the most bang for my buck? I've got a limited amount of time. What do I spend my time on? (personal communication, March 18., 2020, 18:58)

Like Natalie, Denise described a tension between wanting to use modeling as a sensemaking practice, in which students construct conceptual understanding through the practice of modeling itself, and the pressure to “deliver” or “get through” the content so that students ultimately have a correct understanding.

Classroom Interactions

I was fortunate to have been invited into Denise’s classroom in December of 2019 over the course of four days (200 minutes) while her students worked to develop models of how the air outside warms up. Denise shared with her students that the thermometer in the dashboard of her car at 5:00 AM that morning had been 3°F. During their morning meeting she had also asked students to notice what the temperature was when they went out to recess. Later in science class, students eagerly reported that the temperature had risen to 26°F. They also reported that they didn't stay out for long!

Examining classroom interactions among Denise and her students gave me a window into how the NGSS practice of developing and using models was enacted in her fifth grade classroom. My findings are described in the following portrait of Denise’s classroom interactions.

Modeling Practices

Developing models was the most frequently used modeling practice during Denise’s lesson. In fact, 58% of the 60 observed occurrences of modeling practices were focused on *developing* models (for frequencies see Appendix G). This was consistent with Denise's goal for the lesson which was to have students create visual representations to help them explain how and why the air outside had heated up over the course of the school day. Students first worked as a group to share their ideas and consider evidence from previous investigations about energy transfer that might help them develop their models. Each group developed a model together and then, after observing one another's models and participating in a class discussion, each student created a model of their own.

I observed many fewer instances of the other modeling practices being used including *revising* (23%), *evaluating* (17%), and *using* (2%). I was not surprised by how many of the classroom interactions were focused on the practice of *developing* models over the other practices since using scientific modeling as a sensemaking strategy would warrant employing these practices over the course of a unit, more so than during the course of one lesson.

When students did engage in *revising*, it was primarily done after students worked as a group to develop a model. Denise led a class discussion in which she created a class version of a model with student input. Students then revised their original group models and finally created their individual model. While revising, students focused primarily on changing features of their models for clarity, such as adding labels, or a key. During the few occurrences of *evaluating* models, students mainly focused on providing feedback to one another about how to make their models clearer to a reader, as opposed to evaluating the strengths and limitations of the mechanisms or ideas shared in the model. When *using* models created by others, students were largely focused on consulting text and images in the FOSS (2019) Earth and Sun Science Resource Book to discuss the concept of re-radiation and how that concept may apply to their own explanations.

Epistemologies in Practice

Many interactions during Denise's lesson reflected sophisticated epistemic framing. In fact, of the classroom interactions related to *mechanistic* features or the explanatory nature of models (23%), all of them were framed in a more sophisticated way (for frequencies see Appendix H). Both Denise and her students emphasized that accounting for and explaining the interactions among the components in the system were critical to the model. From their point of view, this was shared knowledge that counted in their classroom. For instance, during one small group exchange, students discussed how to show energy being transferred through conduction among air particles.

> (Student 1) "We need to show the particles, like next to each other."
>
> (Student 2) "You have to put them [air particles] next to the hydrosphere and geosphere."
>
> (Student 3) "Yes, because, well, first the air particles have to get the energy to touch each other so they have to touch the geosphere and hydrosphere. They get their energy from there.
>
> (Student 1) "You need to show conduction when the particles touch.
>
> (Student 4) "We need to show some of the air particles touching each other.
>
> (Denise's classroom video, 01:16:16)

During another conversation one student shared:

> So what I'm trying to show here is that, so, from the sun, the sun is heating up the land and the water from the rays of radiation. The land and water particles start to move and heat up more. And then air particles up here [pointing to

> particles in her model], because they're moving around, they start to touch the land and water particles and get energy from contact, that's conduction. (Denise's classroom video, 02:31:28)

Additional instances of more sophisticated epistemic framing in Denise's classroom were observed in the classroom interactions (18%) in which students were determining for themselves what *evidence* to include in their models and justifying their decisions. For example, one student provided feedback to another group about what kind of evidence would be compelling to help explain the role of re-radiation in warming up the air. "I think [you] need to show water vapor-- for the re-radiation-- because you have to know what particles receive the re-radiation." (Denise's classroom video, 02:18:35)

Another example of students determining for themselves what counts as evidence was observed when one student discussed why she chose to include only CO_2 and water vapor particles in her model, but not oxygen and nitrogen.

> Well, those [CO_2 and water vapor] are the main radiation, conduction and re-radiation particles. Obviously, there are other particles, but they are not as important as these two [CO_2 and water vapor] for the radiation and re-radiation. Like conduction, you can use other particles, but they're not mostly used, I think these two [CO_2 and water vapor] are the main sources. (02:24:17)

This is an example of the student determining for herself what counted as evidence and what pieces were important to include or not include in her model. It does not mean that there may not be emerging conceptions, misconceptions or ideas that another student might challenge or add to during discussion.

There were also some instances in Denise's classroom of sophisticated epistemic framing for the EIP consideration *Audience* (15%). These instances were framed in a way that students were their own audience. Their own knowledge construction was the reason for producing the model and, therefore, they were the consumers of it. For example, one group of students discussed the large number of air particles they had included and discussed what purpose those particles served. "We have so many [air] particles that it is hard to understand which ones we are trying to show something with, and which ones are just there" (Denise's classroom video, 01:02:51). The students were determining for themselves what elements were meaningful for understanding their model.

While there were many occurrences of sophisticated epistemic framing observed throughout Denise's lesson, some interactions were also framed in a more naive way. Several classroom interactions (32%) between Denise and her students were framed in a way that positioned Denise as the audience for the students' models. For example, while students were working on their models, Denise reminded them;

> I am going to be looking at these. I am going to be looking for those things [gestured toward a list of components and interactions that had previously been listed on the board]. Can you look at your model and follow it? (Denise's classroom video, 01:26:42)

Denise wanted to be sure students included the correct information when she evaluated their models for understanding. This is a more naive epistemic frame for the EIP consideration *Audience.* When using modeling for sensemaking, a more sophisticated epistemic frame would position students as their own audience since the goal is for students to construct their own knowledge.

Another example of naive framing for *Audience* occurred when a student referred to the teacher-created class model and asked, “Is this arrow going up re-radiation?” Denise replied, “It’s whatever you make it” (Denise’s classroom video, 01:36:26). Denise wanted the student to make her own decisions about the model. The student, however, viewed the model the teacher drew not as a class consensus or as an example, but rather as the correct answer that she should mimic in her model.

The naive framing of *Audience* in Denise’s classroom related to the naive framing of another EIP consideration, *Evidence*. During these interactions (15%), Denise determined what evidence needed to be included in the students’ models, rather students making those decisions.

During a class discussion, for instance, as Denise drew a model on chart paper for the class she said;

> I'm going to do… [voice trailed off while drawing] Ok. So this is going to be my land [continued to draw]. What is the re-radiation heating? Not all the particles, only the CO_2 and water vapor. So maybe we have this one [drawing an arrow] heating a CO_2 and this one [drawing another arrow] heating a water vapor? (Denise’s classroom video, 01:15:13)

The occurrences of naive epistemic framing for both *Audience* and *Evidence* were similar because they both focused students' attention on the needs and input of an external influence which shifted the purpose of sensemaking away from the students. Taken together, these instances of more naive epistemic framing reflect the tension between the high value Denise placed on modeling as a sensemaking strategy (as shared in her interview) and her concern that students should ultimately arrive at the correct version of a model, as well as her concern for fitting all of her priorities into her instructional time.

A further illustration of the tension between Denise's goals for using modeling as a sensemaking strategy and her concerns for moving students to the correct version of the model can be seen in the fact that interactions framed as naive for *Evidence* and those framed as sophisticated for *Evidence* appeared in almost equal abundance in Denise's classroom. Overall, 51% of the interactions in Denise's classroom reflected sophisticated epistemic framing and 49% reflected naive epistemic framing.

Co-Occurrences

As I did with the interactions in Natalie's classroom, I examined the ways in which modeling practices and EIP considerations co-occurred in Denise's classroom to see if there were any meaningful patterns (See Appendix I for a numerical breakdown of these co-occurrences). I found, however, that since the majority of classroom interactions involved the practice of *Developing* models (as opposed to *Using, Evaluating,* or *Revising*) the EIP considerations were largely distributed among the instances of *Developing* and the co-occurrences did not reveal any insights that had not already been captured by examining the EIP considerations directly.

Student Explanations

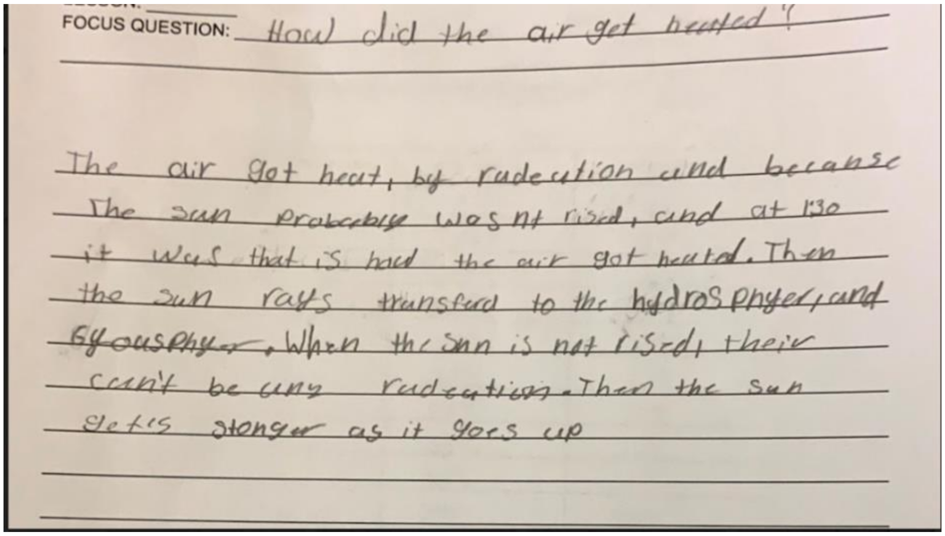
To address the third part of research question one, and understand more about students' model-based explanations, I examined student work from the modeling lesson in Denise's classroom. I was able to view 15 notebook samples which represented 63% percent of students in the class. Some students were not present to share their notebooks on the day they were collected and a few left them at home, but of the students who were available, they were all eager to share their hard work.

I used the rubric described in Table 7 to help me understand more about students' models and their thinking. While none of the notebook samples were categorized as exemplary, several were categorized as *effective* (33%), many were categorized as *approaching effective* (47%), and a few were categorized as *partially effective* (20%) (see Appendix K for a breakdown of the scores on sub-categories). Looking more closely, 60% of the notebook samples included the necessary components to explain the phenomenon, while 44% also included the necessary interactions, and 33% of the students' models provided an effective mechanistic explanation. Accordingly, it may have been that students were looking at the model Denise drew as a tool to determine what to include and struggled more with articulating how those components interacted if they had not yet developed a full understanding of the concepts. Denise did express concern that she needed to teach the content and that the students ultimately had an accurate model so she may have felt compelled to be sure they had access to a correct example.

A *partially effective* model is depicted Figure 14. The model does include the components- sun, sun rays, and ground materials -- and it names the interaction between the sun and the ground as radiation. The explanation also articulates that the sun is the source of energy in the system, and it cannot be adding energy to the system at night, or when it had “not rised”[sic]. However, this students' model did not include components at the particle level, such as ground particles or air particles. It also did not discuss the interactions between particles such as conduction between ground particles and air particles.

Figure 14

Notebook Sample 10 Representing a Partially Effective Model from Denise's Classroom



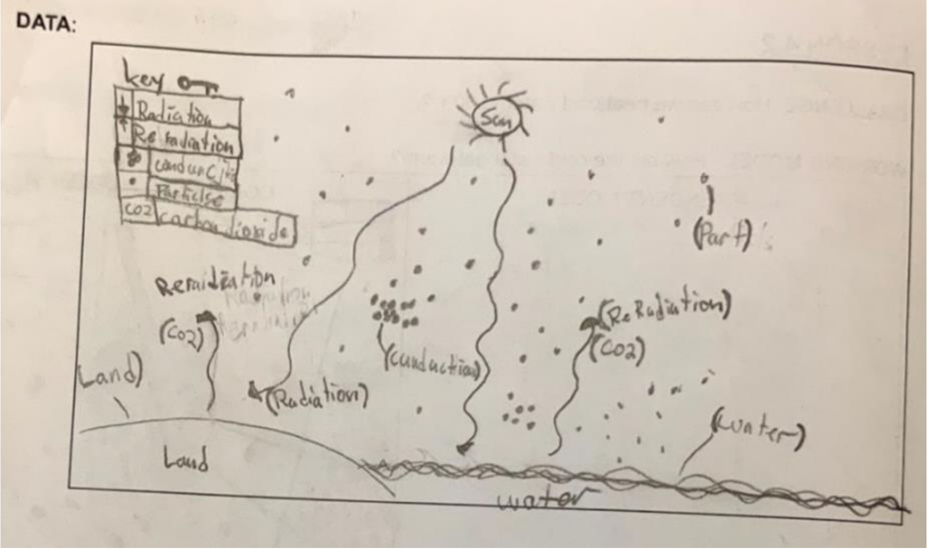
FOCUS QUESTION: How did the air get heated?

The air got heat, by radecution and because
The sun probabily wasnt rised, and at 1:30
it was that is had the air got heated. Then
the sun rays transferd to the hydrosphyer, and
Gyousphyer. When the sun is not rised, their
can't be any radecution. Then the sun
get's stonger as it goes up

Another notebook sample, depicted in Figure15, was rated *approaching effective.* It included many relevant components and interactions. For instance, it included the sun, radiant energy, particles in the air (specifically CO_2 particles in the air), ground materials, radiation, and re-radiation. However, the model did not include conduction between the ground and air particles which would have helped to explain an important mechanism involved in transferring energy to the air.

Figure 15

Notebook Sample 15 Representing a Model from Denise's Classroom that is Approaching Effective.



An example of an *effective* model from Denise's class can be seen in Figure 16. The model includes the components - sun, radiant energy, land particles, water particles, air particles, carbon dioxide particles and water vapor particles. It also includes interactions among those components including radiation to CO_2 and water vapor particles and to the ground, conduction at the Earth's surface, conduction in the air, and re-radiation. This effectively shows how energy is transferred to the air primarily from interactions involving air and earth materials on the ground. In addition to diagrammatic models, which are common in elementary school, models can also be written expressions of how or why a system works (Gilbert, 2004). Figure 17 shows another *effective* model which is a written explanation of the components and mechanisms involved in explaining how the air heats up.

Figure 16

Notebook Sample 2 Representing an Effective Model from Denise’s Classroom

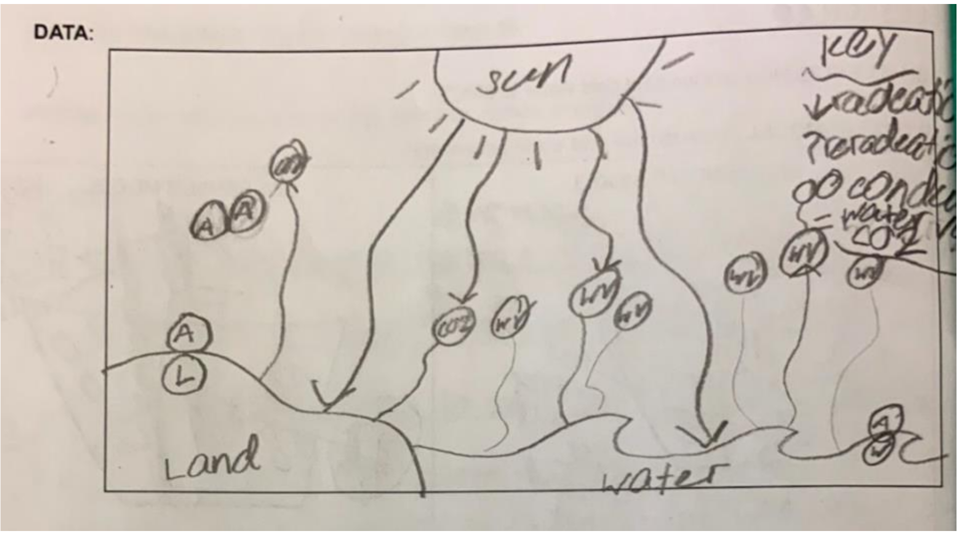
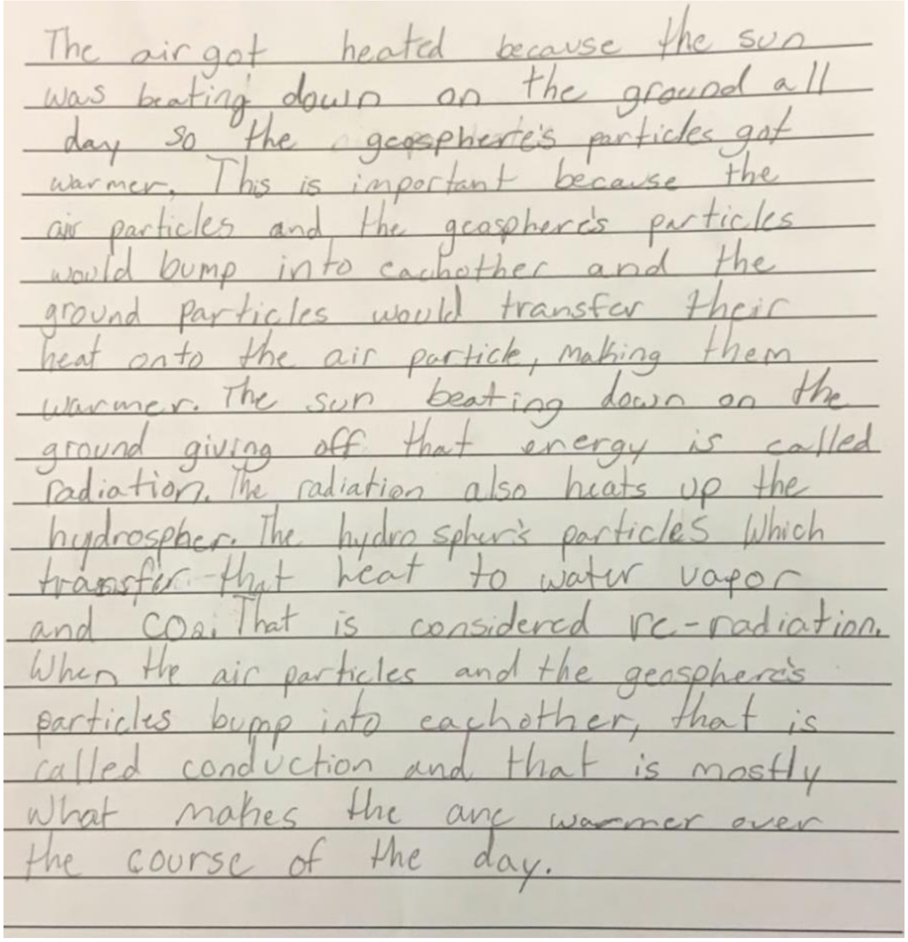


Figure 17

Notebook Sample 6 Representing an Effective Model from Denise's Classroom



The air got heated because the sun was beating down on the ground all day so the geospherte's particles got warmer. This is important because the air particles and the geosphere's particles would bump into eachother and the ground particles would transfer their heat onto the air particle, making them warmer. The sun beating down on the ground giving off that energy is called radiation. The radiation also heats up the hydrospher. The hydrosphr's particles which transfer that heat to water vapor and CO_2. That is considered re-radiation. When the air particles and the geosphere's particles bump into eachother, that is called conduction and that is mostly what makes the air warmer over the course of the day.

Case Summary

To summarize, in the context of one 200-minute lesson over the course of four days, observed half-way through a unit on energy transfer and one 30-minute follow-up interview, Denise demonstrated a sophisticated understanding that scientific models are used to help explain how or why a phenomenon occurs and that models can represent phenomenon in many ways. Denise understood that to help a person explain their ideas, they may use models that are abstract representations. Denise also clearly placed value on the helpful nature of visual elements in many models. Denise understood that models can, and should, be changed in light of new evidence. It was important to Denise that her students focused on the mechanistic nature of models and could visually show the components and processes involved in explaining how the air heated up from 3°F to 26°F over the course of a school day. Taken together, Denise's responses to the SUMS indicated a relatively sophisticated understanding of the purpose and nature of scientific models and she indicated in her interview that her intention was to use models as a sensemaking tool in her classroom.

Denise's responses on the SUMS and in her interview also suggested that she held a more naive conception that models have a correct version that can and should be arrived at, over a more sophisticated conception that models represent a current and best explanation based on the evidence available thus far. While Denise encouraged students to work together to explain the processes involved in heating the air, and to give each other feedback, she also spent considerable time making sure students had access to a class model and criteria list that represented what should be included in students' final models.

Students in Denise's classroom spent most of their time during this lesson engaged in the practice of developing models (talking, drawing, gesturing and writing) about the important components and interactions involved in explaining how the air heats up. Students' work during class was also largely focused on the EIP consideration of *Audience*, or a consideration of who the model is being created for. In this case, models were created with much of the attention paid to an outside viewer or audience that was often perceived as being the teacher who would evaluate the work. Considerable attention was also paid to the EIP consideration of *mechanism,* particularly *mechanism 2,* which showed Denise's priority on students understanding how and why the phenomenon occurred and not simply describing what happened.

The dual focus during Denise's lesson on the external audience (in this case the teacher), and also on emphasizing the sophisticated mechanistic nature of models revealed the tension in Denise's instruction between using modeling as a tool to reach a "correct" understanding of the concepts involved in the phenomenon, and wanting to use modeling as a sensemaking strategy in which the thinking processes are the goal and that students' own thinking can help them arrive at an accurate understanding of science concepts. Related to this tension is the equal division in Denise's lesson between the more naive *Evidence 1,* the teacher determines what is included in the model and the more sophisticated *Evidence 2*, the student determines what is included in the model.

Student work collected from Denise's lesson showed that her fifth grade students created models that showed a range of effectiveness in explaining how the air heats up. Most of the students whose work I examined were able to include all of the relevant components needed to explain how air heats up (Sun, radiant energy, ground particles, air particles), and some of the students were also able to show interactions that led to a comprehensive mechanistic explanation (energy transfer, absorption, conduction). When a model includes components that are not fully incorporated into the interactions and explanatory nature of the model, it may indicate that the teacher has helped the student identify what components are important before the student has developed a full understanding of how the components relate to one another. This may be expected if the teacher feels pressure to move the students to reach a correct answer within the timeframe of the lesson or unit.

Lydia’s Classroom

Lydia’s classroom was a bright space with a wall full of windows and it had the charm that comes with being one of the original classrooms in a school built in 1930. Students sat at large round tables in groups of four and there was a mutual sense of warmth and care among Lydia and her students.

Teacher Conceptions

A portrait of Lydia’s conceptions of scientific modeling shared below and was generated from her responses to the SUMS Survey (see Appendix F for her responses) and to some of the questions in a conversation during her eighteen-minute interview.

Models as Multiple Representations

Lydia understood that many models can represent different versions of a phenomenon and that models can show how different information is used. In her interview, when Lydia was asked if she thought there could be more than one model that shows the same idea, she replied, “Absolutely, students might have different ways to show their thinking of the same idea even if they are trying to show the same concept” (personal communication, March 23, 2020, 14:21). Lydia agreed with five of the eight items for this factor on the SUMS survey.

Models as Exact Replicas

Lydia had a sophisticated understanding that models may not be exact replicas of a system or phenomenon. She disagreed or strongly disagreed with all eight items on this factor and since items for models as exact replicas were reverse coded in the

SUMS, Lydia’s disagreement represented a more sophisticated conception of the factor.

Similarly, during her interview, when asked if models need to look similar to the system they represent, Lydia responded with confidence.

> No absolutely not, as long as the ideas are the same. Like if you're drawing a diagram of the layered liquids [salt solutions of different concentrations and colors, layered in a straw] you don't know exactly how many red dots [salt particles] are actually going to be in there. But you know if it's concentrated there will be a lot and if it's not there will only be a few. It’s about showing the concept, not that it looks the same. (personal communication, March 23, 2020, 13:28)

Models as Explanatory Tools

Lydia also demonstrated a sophisticated understanding that models provide insight into the mechanisms of how a particular system works. She understood that models help us develop explanations for why phenomena we observe happen the way they do. She strongly agreed or agreed with all five items for the factor.

Consistent with her survey responses Lydia shared in her interview:

> I tell the kids to think about, you know, the model we all know of the Earth. You cut it in half and see the layers represented. We don't actually know, we didn't go cut our planet in half. We need to write it out and draw it out based on our best knowledge of what's going on down there. That’s not information we have directly. So we *think* it looks like this, and then that model can help us explain why other things happen the way they do like volcanoes, or how the

> giant plates can actually move. (personal communication, March 23, 2020, 12:18)

Uses of Scientific Models

Lydia also understood that models are used to formulate ideas. In her interview, Lydia explained, “Modeling helps solidify kids' conceptual understanding” (personal communication, March 23, 2020, 26:49). Lydia strongly agreed with two of the three items on this factor and her responses suggested that she may see models more as an explanatory and conceptual tool rather than a predictive tool.

Changing Nature of Models

Lydia also had an understanding that models can change if new data, evidence or findings are applied. During her interview, when asked if it would ever be appropriate to change a model, Lydia replied, “Of course. Like molecular models. If we have better technology to learn more, then we can change the models. We can change things when we get new information, or something new might happen” (personal communication March 23, 2020, 20:04). Lydia also strongly agreed with all three items included in the factor changing nature of models.

Overall, Lydia has a sophisticated understanding of scientific models. She believes that modeling is an effective strategy for students to build understanding of scientific ideas, and that taking the time for students to engage in the process is very important. This is reflected in the excerpt from her interview below.

> I think modeling is important because we're trying to get them to think about why things are the way they are. Some students think they have to get things right the first time. They need to know they have that permission to change it.

> It can be hard for kids to change their first thought. It takes time. You know, sometimes students are given assignments- all about vocabulary. I could find the answers on Google. It's all about the end [for some teachers]. They don't understand there's got to be a process to get there. Sure you can make them memorize stuff for a test, but then it's gone and you've lost the opportunity to really work on and think about ideas. They've lost a big chunk of the rung on that foundational ladder. When they go on in high school, I don't know how much understanding some of the kids have sometimes. When they compute formulas and stuff, say in chemistry, sometimes I think kids are throwing numbers together, adding them up, calculating it out and can make the formula work and get an answer, but why is it like that? What's the concept? (personal communication, March 23, 2020, 25:03)

It is apparent that Lydia cares very much about the process of students engaging in the work of modeling and sensemaking for themselves and that she is aware of the time it can take for students to truly develop meaningful ideas.

Classroom Interactions

I was first invited into Lydia's classroom on pajama day. (Had I known I would have worn my slippers.) Lydia's interactions with her students, and interactions among her students, during their science classes gave me a glimpse into how the NGSS practice of developing and using models was enacted in her fifth grade classroom. On pajama day, and the day after, in December 2019, I videotaped a 160-minute science lesson that focused on engaging students in developing models to explain the phenomenon of how the air heats up throughout the day. I then examined teacher and student classroom interactions for their use of modeling practices (Gilbert, 2004) and how classroom interactions were framed using the EIP considerations (Berland et al., 2016).

I noticed that although Lydia's class time was 40 minutes shorter overall, she had about the same amount of actual instruction because she had longer blocks of time and considerably less transition time than Natalie and Denise who were teaching in shorter periods. For example, one of Natalie's classes was interrupted by lunch on either side of her instruction, causing even more transition time. Overall, despite the difference in minutes, the arrangement of the schedules gave all three teachers relatively equivalent instructional time.

Modeling Practices

Students in Lydia's class were engaged in the practice of *developing* models for 81% of the 64 occurrences of modeling practices (see a more detailed breakdown of practices in Appendix G). Instances of the other modeling practices were much less frequent and included *evaluating* (16%), *revising* (3%), and *using* (0%). The prominence of *developing* as a practice was consistent with Lydia's goal for the lesson which was to have the students create visual representations to help them explain how energy was transferred to the air to heat it up. Students first discussed their ideas with a partner and then a table group. After that, groups of 4-5 students worked together to create a group model. Upon receiving feedback from their peers, students created individual models in their notebooks to share their ideas about how the air heats up.

Most of the instances of *evaluating* occurred when students participated in a gallery walk to observe and provide feedback to one another on the group models. The few occurrences of *revising* were observed after the students had viewed the feedback from other groups and considered changes, they might make to their models based on the feedback. There were no occurrences of the practice of *using* models during Lydia’s lesson. During previous lessons, students used the FOSS (2019) Earth and Sun Science Resource Book included in Lydia’s curricular materials to support their discussion of energy transfer by radiation and conduction during previous lessons. These readings may have informed students’ thinking for their own models, but they were not part of the lesson observed for this case study.

Epistemologies in Practice

An overwhelming 81% of the 64 occurrences I observed during Lydia’s lesson reflected sophisticated epistemic framing of classroom interactions (see a more detailed breakdown in Appendix H). A large portion of these occurrences (30%) demonstrated that Lydia and her students considered the mechanistic features and explanatory nature of models to be of high value to their classroom community. The mechanistic features counted as important knowledge to be included in their models. For example, one student shared with her group, “The particles, we need to make them moving everywhere. That means we need to make arrows. They're moving fast because they're hot. They're getting warmed up" (Lydia’s classroom video, 06:18).

In another example a group discusses their model in progress;

> (Student 1): Ooh! Our [air] particles near the ground and up higher are spaced out the same, but hot particles are farther apart. Well, they should be. Ours look all the same.

> (Student 2): So we just need to add more particles on the cold part, then they'll be closer together and the hotter ones near the ground will look right. (Lydia's classroom video, 34:21)

Evidence is another area in which interactions in Lydia's classroom reflected sophisticated epistemic framing. The occurrences that were framed this way (25%) demonstrated that students were making the decisions about what counted as evidence in their models and how it was justified. For instance, when observing another group's model, two students debated whether including water was a necessary element to include. The first student commented, "They didn't draw the water, but you don't need to draw the water. Her group member responded, "Yes, you do, you need both water and the land (Lydia's classroom video, 53:43). These students were negotiating what elements were necessary or not in order to explain how the phenomenon works.

In another example, when Lydia stopped to talk with one group, a student explained why the group thought it was important to include air particles directly next to the surface of the land.

> We're drawing air particles next to the land so we can show the conduction. The rays go straight to the land, and to the water, and then they go back up. So we're making particles to show that heat is going to the land, but then it's the particles of the land that give the heat to the air particles. We think it's better like this. (Lydia's classroom video, 33:24)

I also observed sophisticated epistemic framing for the EIP consideration of *Audience.* In these occurrences (20%), students were centered as the audience for the models they were creating. As a class, they were trying to make sense of how the air heats up and even the models of other groups were considered tools for everyone to think about these ideas. For example, while observing another group's model, two students considered what ideas the authors were trying to convey. They saw themselves as the audience for the work of the class trying to figure out how the system worked. The first student asked, "I wonder why there are dots at the bottom. What is it trying to show?" The second student made another observation, "And I'm also wondering why there are the same amount of dots in every section?" (Lydia's classroom video, 52:51).

Another example occurred just as students were getting started with their group model. One student asked, "Ok, what do we need in this? What about the air?" A second group member responded, "How do you want to show that?" (Lydia's classroom video, 05:30). It was clear they believed the model was for them.

Finally, there were a few occurrences (6%) in which students in Lydia's class considered how the concepts involved in their models might apply to related phenomena. This is a sophisticated framing of the EIP consideration *Generality.* In one example, a student wondered how the system might work differently in the winter; "Why doesn't that happen in winter? Because of the clouds? We're on a certain side of the sun?" (Lydia's classroom video, 06:53).

In another example, two students considered what happens at night and how the system might work similarly or differently in the winter versus the summer.

> (Student 1): Oh yeah, and at night the sun goes down and it starts to get colder, except some of those air particles start to...like in winter it doesn't happen

> because there are really, really cold particles. Well it does happen sometimes if you're closer to the sun. The water gets warmer slower than the land.
>
> (Student 2): But that doesn't explain how the air gets warmer. (Lydia's classroom video, 01:36:08)

This interaction demonstrated that sophisticated framing does not mean students have necessarily developed ideas agreed upon by other scientists, only that they are involved in the process of how decisions get made about what knowledge counts, and how knowledge is constructed.

It was clear that Lydia worked hard to put students in control and at the center of the modeling work. There were instances, however, where the interactions were framed in a more naive way. The naive framing of *Audience*, in which the teacher, rather than students, is positioned as the audience for the models, represented 9% of occurrences. This was demonstrated when Lydia commented to one group; "You've got arrows going down. I need to see the transfer going back. You told me that with your words" (Lydia's classroom video, 11:30).

Another example of this is when one group of students was reading the feedback left for them by other students. One student in the group said, "They want labels on rays and atmosphere, that's it. One person wanted a key and I think that's a good idea" (Lydia's classroom video, 01:33:38). The student framed the feedback in terms of what someone else wanted from their model, as opposed to feedback that could help them further their thinking. Although, the student did seem to think some of the feedback was useful.

As students developed their models, a few occurrences (6%) demonstrated a naive framing of *Mechanism,* in which students provide a descriptive account of a phenomenon but have not yet developed, or articulated, a mechanistic or explanatory account. This was observed when a student described what he thought was happening but did not yet discuss how the parts interact to produce the observable phenomenon. “It starts when the sun's rays shine down. And then when the sun heats up the surface the surface heats up the air particles" (Lydia’s classroom video, 05:19).

Co-Occurrences

As with Natalie’s and Denise’s cases I examined the co-occurrences between modeling practices and the EIP considerations but gained no new insight since the majority of EIP considerations were distributed within the practice of *developing* models (see details in Appendix I).

Student Explanations

To address the third part of research question one and understand more about students’ model-based explanations I examined the models developed by all 22 students in Lydia's class using the rubric described in Table 7. Eight of the models (36%) were *partially effective, eight* models (36%) were *approaching effective,* six models (27%) were *effective*, and none (0%) were *exemplary* (see scores on subcategories in Appendix L). Thirty-six percent of the models included the necessary components to explain the phenomenon, while 32% of the models included the necessary interactions, and 27% of the models provided an effective mechanistic explanation.

A *partially effective* model from Lydia’s class is featured in Figures 18 (the diagrammatic portion) and 19 (the companion written portion). The model depicted in Figure 18 included several components involved in explaining how the air is heated, including the sun, radiant energy (rays), ground material (hot land/cool water), and air particles. The model also explained that the sun’s radiant energy is the driver of energy transfer in the system. The model was more limited in showing or explaining the interactions and mechanisms involved in the transfer of energy throughout the system that result in warming air. For example, sun rays are indicated in the diagram, however it is unclear how the energy from those rays transfers to another part of the system.

Figure 18

The Diagrammatic Portion of Notebook Sample 18 Representing a Partially Effective Model from Lydia's Classroom

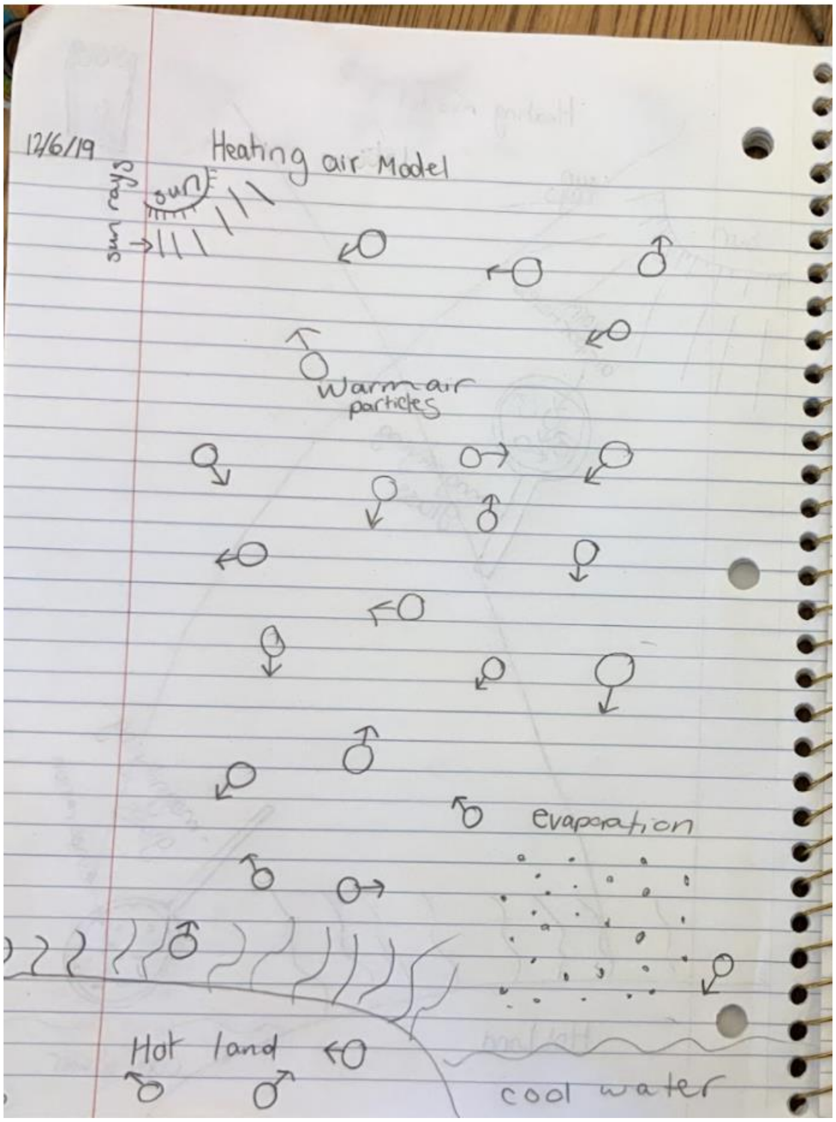
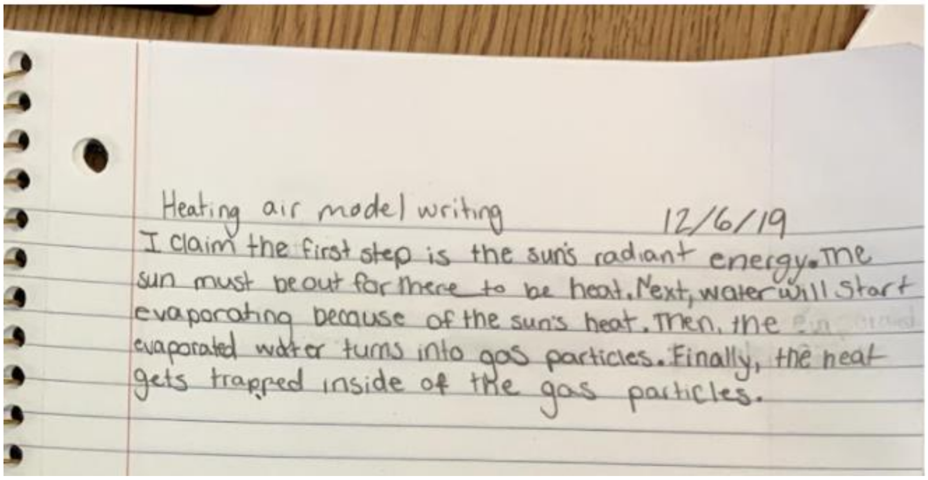


Figure 19

The Written Portion of Notebook Sample 18 Representing a Partially Effective Model from Lydia's Classroom



Heating air model writing 12/6/19

I claim the first step is the sun's radiant energy. The sun must be out for there to be heat. Next, water will start evaporating because of the sun's heat. Then, the evaporated water turns into gas particles. Finally, the heat gets trapped inside of the gas particles.

An *approaching effective* model from Lydia's class is featured in Figure 20 (the diagrammatic portion) and Figure 21 (the companion written portion) of one student's model. This model included the necessary components to show how energy is transferred to the air, including the sun, radiant energy (rays), earth particles, and air particles. It also indicated that the sun's radiant energy is transferred to the Earth's surface and that the energy is then transferred from the Earth to the air. While the model indicated that there are air and earth particles involved in the system, it is limited in explaining the interactions among these particles to show how the air is warmed.

Figure 20

The Diagrammatic Portion of Notebook Sample 9 Representing an Approaching Effective Model from Lydia's Classroom

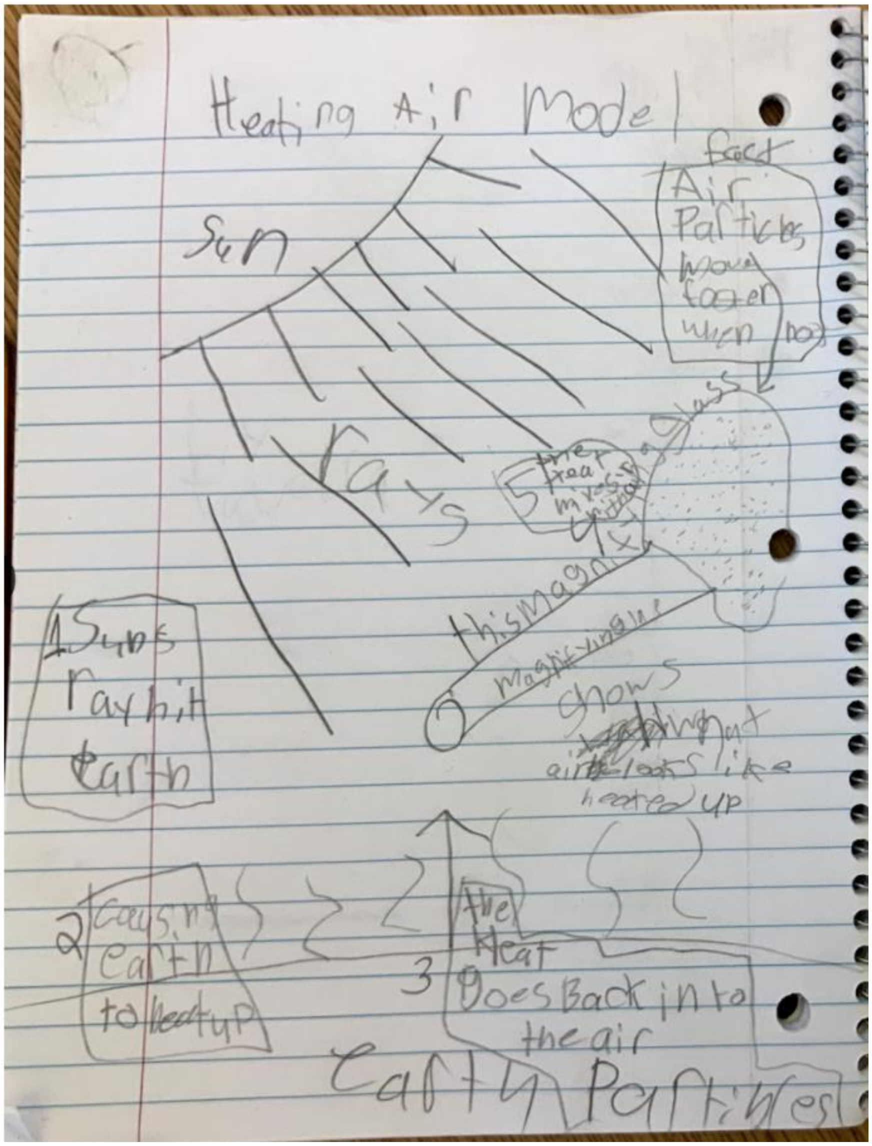
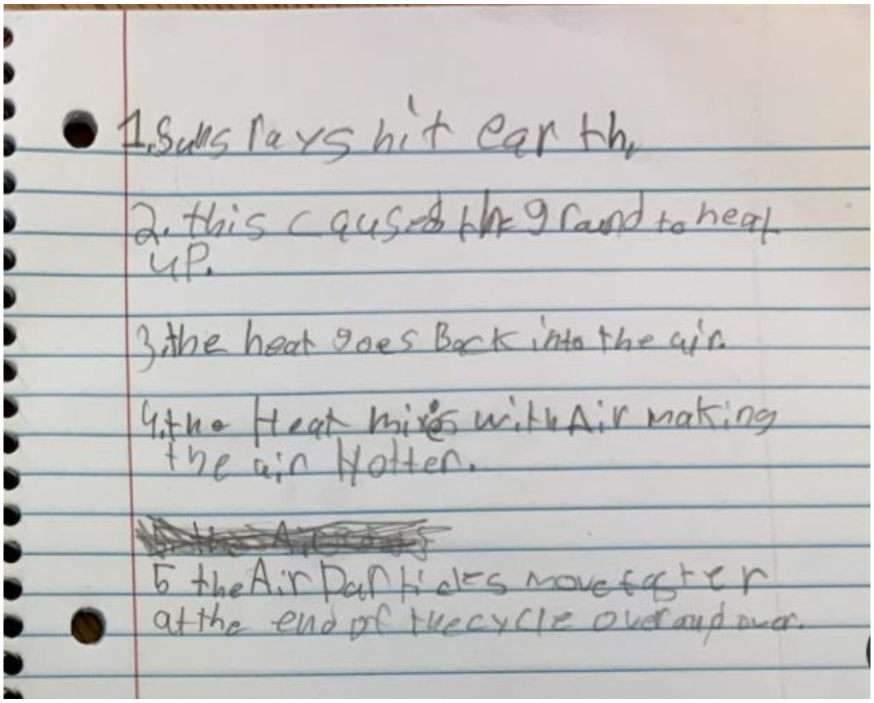


Figure 21

The Written Portion of Notebook Sample 9 Representing an Approaching Effective Model from Lydia's Classroom



1. Suns rays hit earth.

2. this caused the graund to heat up.

3. the heat goes Back into the air.

4. the Heat mixes with Air making the air Hotter.

5 the Air Particles move faster at the end of the cycle over and over.

An *effective* model from Lydia's class is featured in Figures 22 (the diagrammatic portion) and 23 (the companion written portion). This model included the necessary components to help explain how the air is heated. It included the sun, radiant energy (rays), earth particles, and air particles. This model also explained the mechanisms involved in energy transfer. For example, in the written entry the model explained that when air particles come in contact with the warmed surface of Earth, energy is transferred to the air particles by contact. The diagrammatic portion supported the idea that energy is transferred at the particle level with the inclusion of earth particles at the surface. There was also some indication that the student is working through the concept of reradiation through the sun's rays that are shown as being reflected to some of the air particles. However, this concept is not yet fully developed in this model.

Figure 22

Diagram From Notebook Sample 20 Representing an Effective Model From Lydia's Classroom

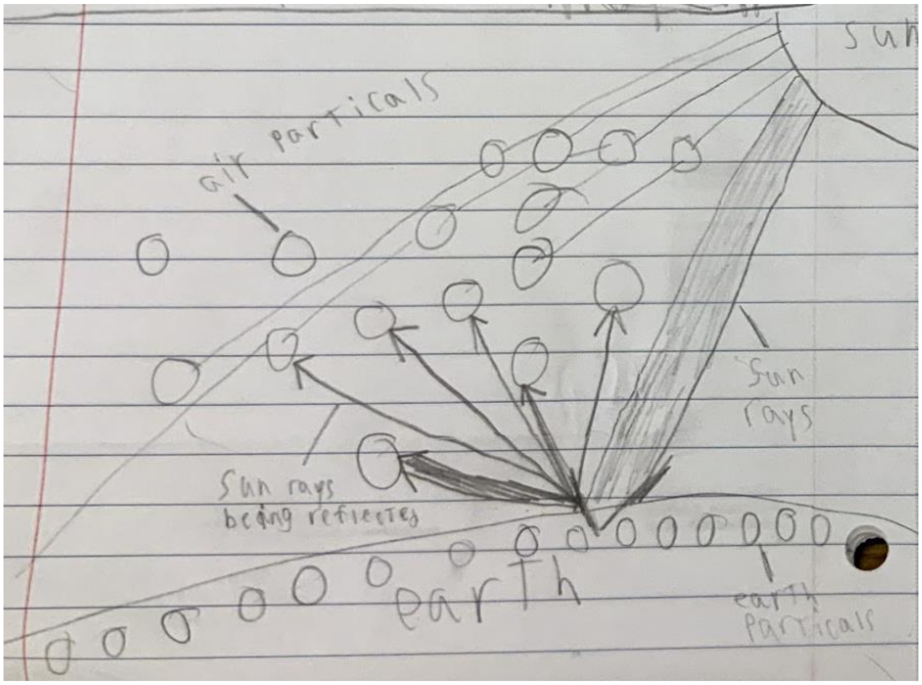
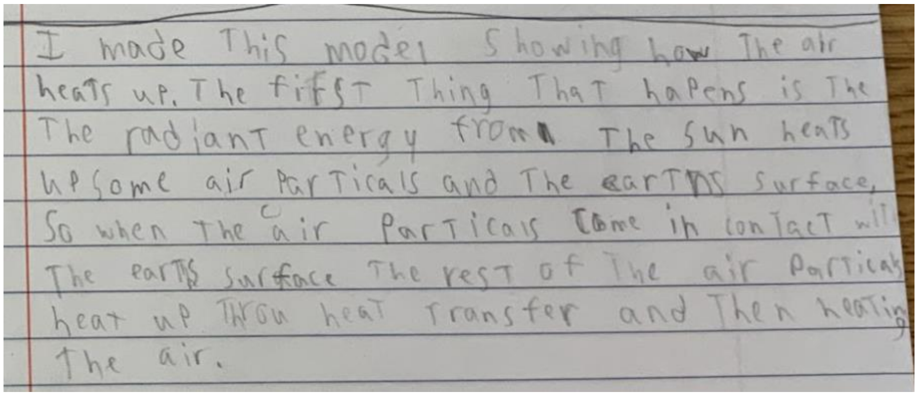


Figure 23

Written Explanation From Notebook Sample 20 Representing an Effective Model From Lydia's Classroom

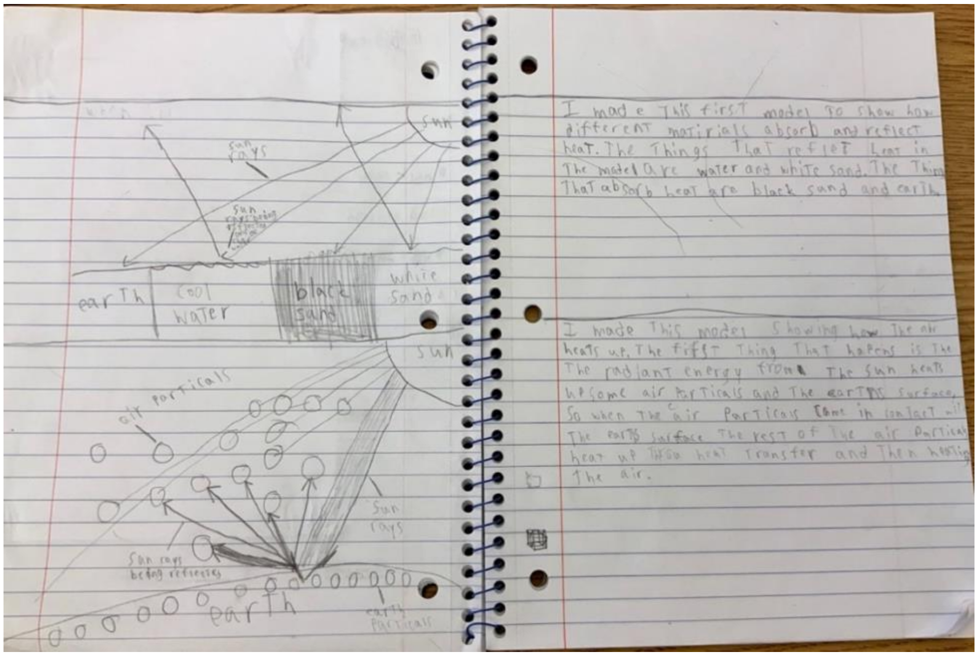


I made This model Showing how The air
heats up. The first Thing That hapens is The
The radiant energy from The sun heats
up some air ParTicals and The earThs surface,
So when The air ParTicals come in conTacT wi
The earThs surface The resT of The air ParTicals
heat up Throu heaT Transfer and Then heating
The air.

I observed that several of the models from Lydia's class attempted to incorporate concepts that the students considered to be related to the phenomenon of air heating up. This suggested that students were working on figuring out how multiple concepts and mechanisms might be related to their explanation of how air heats up. For example, the models shown in Figure 24 demonstrated how a student created two models as they worked to explore how multiple concepts fit together, ultimately creating an effective model of how the air heats up as also seen in the same notebook entry in Figures 22 and 23.

Figure 24

Multiple Models in Notebook Sample 20 From Lydia's Classroom



I made This first model To show how different matirials absorb and reflect heat. The Things That reflet heat in The model are water and white sand. The Things That absorb heat are black sand and earth.

I made This model Showing how The air heats up. The first Thing That hapens is The The radiant energy from The sun heats up some air particals and The earths surface. So when The air particals come in contact with The earths surface The rest of The air particals heat up throu heat transfer and Then heating The air.

Case Summary

Overall, Lydia demonstrated a sophisticated understanding that scientific models are used to help explain how or why a phenomenon occurs. Lydia understood that to help a person explain their ideas, they may use models that are abstract representations and that phenomena can be represented in different ways. Lydia also understood that models can be changed in light of new evidence. It was important to Lydia that her students focused on the mechanistic nature of models and that she took the time during her instruction to let students talk about and develop their ideas and their models for themselves. Taken together, Lydia's responses to the SUMS indicated a relatively sophisticated understanding of the purpose and nature of scientific models and she indicated in her interview that her intention was to use models as a sensemaking tool in her classroom. Lydia's interview responses suggest that she is aware of the time it takes to truly let students work through their ideas and develop deep conceptual understanding. Lydia seemed confident that taking this time was important and worthwhile.

Students in Lydia's classroom spent most of their time during this lesson engaged in the practice of *developing* models (talking, drawing, gesturing and writing) about the important components and interactions involved in explaining how the air heats up. It was clear from classroom interactions that there was a priority placed on understanding how and why the phenomenon occurred and not simply describing what happened. Students in Lydia's class also worked to integrate into their models multiple concepts that they had learned throughout the unit. There was also a demonstrated commitment to students taking responsibility for decision making during the modeling practice and that students viewed the work as important to themselves trying to make sense of the phenomenon.

Student work collected from Lydia's lesson demonstrated a range of effectiveness in explaining how air heats up. Students worked to include the components needed to explain how air heats up (Sun, radiant energy, ground particles, air particles), and the interactions that led to a comprehensive mechanistic explanation (energy transfer, absorption, conduction). While only a portion of students were able to meet this goal by the end of my observations, there was a willingness among the class to take the time to share ideas, and to try and put different conceptual pieces together.

Cross-Case Analysis

Looking across cases to see how the NGSS practice of developing and using models was enacted in 3 fifth grade classrooms provided me a window into how experiences in Natalie, Denise and Lydia's classrooms were similar and how they differed. Interpretations of these observed patterns were used to answer the second main research question.

Teacher Conceptions

Natalie, Denise and Lydia all had fairly sophisticated conceptions of scientific models according to their responses on the SUMS survey (Treagust et al., 2002). This level of sophistication was also apparent in their interviews, as all three teachers discussed the importance of the explanatory and mechanistic nature of models and the role they wanted modeling as a sensemaking practice to play in their classrooms. It was important to all of them that students have experience developing models to help them explain how or why a system works the way it does.

Natalie and Denise expressed the idea that it is also important for students to ultimately arrive at an accurate or correct version of a model. There was a clear tension between wanting students to make sense of the phenomenon for themselves the constraints of time, and the need to progress through the curriculum. Lydia also acknowledged the great deal of time it takes to attend to sensemaking through modeling in the classroom, although she was more at ease with taking the time during her instruction and less concerned about whether students would arrive at a correct version of the model by the end of the lesson.

Classroom Interactions

In all three case study classrooms, the prevalence of coded practices suggested students spent most of their time engaged in the practice of *developing* models. Specifically, students in Natalie, Denise and Lydia's classrooms spent 67%, 58% and 81% of their time, respectively, developing models. There was some time spent evaluating, revising and using models (for a breakdown of the data see Appendix G), but students spent most of their time actively constructing models to explain how the air heats up. This concentration of time on *developing* models across the classrooms makes sense because of where the lesson was situated in the curricular sequence. The purpose of this particular lesson was to develop an explanatory model to explain how the air heats up. Over time and after more investigation, it would be more appropriate for students to return to their models to evaluate their ideas and revise their models to reflect new insight and understanding.

While engaged in the practice of *developing* models, teachers and students in all three classrooms paid considerable attention to the mechanistic features and explanatory nature of their models. It was clear that the mechanistic interactions involved in the phenomenon of heating air were an important part of building knowledge and constructing meaning in these classroom communities. In fact, this sophisticated epistemic framing represented the most frequent occurrence in Natalie's (35%) and Lydia's (30%) classrooms and the second most frequent in Denise's classroom (23%) (see Appendix H for more details).

Although attending to the mechanistic and explanatory features of models was prioritized in all three classrooms, there were differences when looking at the epistemic framing of the EIP considerations of *Evidence* and *Audience*. These two considerations are related because they both address whether it is the students or the teacher who is making the decisions about what to include in the model and who the model is for. Naive epistemic framing of *Evidence* and *Audience* conveys an external influence, or decisions being made by the teacher, whereas sophisticated epistemic framing conveys the centrality of the students' role in making these decisions (Berland et al., 2016).

Natalie and Denise took on a more direct role in determining what evidence or components needed to be included in their students' models, whereas in Lydia's classroom, the students took on more of the ownership and decision making about what ought to be included in their models. For instance, in Lydia's classroom sophisticated epistemic framing for occurrences involving *Audience* and *Evidence* represented 45% of total occurrences, whereas sophisticated epistemic framing of these considerations represented only 21% and 28% of the occurrences in Natalie and Denise's classrooms respectively.

In contrast, naive epistemic framing of occurrences involving *Evidence* and *Audience* were more prominent in Natalie (41%) and Denise's (47%) classrooms than they were in Lydia's (12%). In Natalie and Denise's classrooms, there was an emphasis on the correctness of the models as a learning product and that it would be evaluated by the teacher. In Lydia's classroom, an emphasis was placed on the process of creating models as a tool to further students' understanding of the phenomenon of warming air.

Student Explanations

The models from Natalie and Denise's classrooms included more examples of effective explanatory models than did the models from Lydia's classroom (for a breakdown of the data see Appendix M). This pattern was consistent with the epistemic framing of interactions in Natalie and Denise's classroom that emphasized students working toward the correct version of the model, and the framing in Lydia's classroom that emphasized the time it takes students to work through their ideas and determine what knowledge is meaningful to consider in relation to their explanatory models.

There were some interesting patterns in the student models when looking between categories of the rubric (see Table 8). For instance, I observed that the difference between the categories *components* and *interactions* was larger for the models from Natalie and Denise's classrooms than it was for the models from Lydia's classroom. This suggested that students in Natalie and Denise's classroom were able to include more components but were not necessarily able to fully explain how those components interacted. This pattern is also consistent with Natalie and Denise's emphasis on making sure their students knew what evidence or components to include in their models, even if students were not yet fully able to articulate the interactions among them. The more consistency between categories in the models from Lydia's classroom suggested the inclusion of components in the models was more aligned with the degree to which students could articulate the interactions among them. It is important to note that the number of notebooks I was able to examine were different across the three classrooms. Given the opportunity to examine more of the notebooks I may have gained further insight into the similarities and differences across the classrooms.

Table 8

Percent of Student Work Samples that Attained an Effective Score on Categories Within the Modeling Rubric (Penuel, 2018)

	Student Work Samples That Scored Effective on Sub-categories (%)		
Rubric Categories	Natalie (n=10)	Denise (n=16)	Lydia (n=22)
Components	90	60	41
Interactions	50	44	32
Explanation	40	33	27

It was also noteworthy that there were many models from Lydia's classroom that attempted to integrate multiple concepts into their explanations. This reflected the sensemaking work students were doing, even though fewer students developed a full mechanistic understanding of how air heats up by the end of the lesson.

Chapter Summary

All three case study teachers, Natalie, Denise and Lydia, demonstrated a sophisticated understanding of scientific modeling and expressed the desire to prioritize modeling as a sensemaking strategy in their classrooms. Natalie and Denise expressed a tension between taking the time it takes for students to engage in the hard work of sensemaking through modeling and the need for students to arrive at a correct version of the explanatory model. Lydia also acknowledged how much time this work takes but felt less pressure for students to arrive at a correct version of the model.

The three teachers' conceptions and concerns were reflected in their classroom practice. All three classrooms focused time on students developing explanatory models and paid attention to the mechanistic features of their models. Natalie and Denise played a more direct role in determining the criteria of the students' models, and Lydia more often put students in this decision-making role.

Student work from each of the classrooms also reflected the epistemic priorities of their teachers. More of the models from Natalie and Denise’s classrooms were effective overall than were the models from Lydia's classroom. This reflected the prioritization of developing the correct version of the model as a product for teachers in Natalie and Denise’s classrooms. In Lydia’s classroom there were fewer effective models, although there were examples of students working toward integrating multiple concepts as they worked toward a mechanistic understanding of how air heats up.

CHAPTER 5

Discussion

This qualitative multiple-case study was designed to examine the ways in which the NGSS practice of developing and using models was enacted in three fifth grade classrooms. The purpose of this final chapter is to summarize key findings from chapter four and to discuss implications, limitations and recommendations for future research. By considering these implications we can support teachers to create learning environments in which students can develop the skills they need to make sense of complex scientific phenomena and be better prepared to develop solutions to the problems they will be called on to solve.

Summary of Cases

This study sought to explore and compare how the teachers and students in three fifth grade classrooms used the NGSS practice of developing and using models to make sense of the observed phenomenon of how the air heats up. The first research question guiding this study was: How was the NGSS practice of developing and using models enacted in three fifth grade classrooms? Three particular areas of interest included:

A. How did fifth grade teachers conceptualize scientific models?

B. How did epistemic framing guide classroom interactions involving scientific modeling in fifth grade classrooms?

C. To what extent did fifth grade students develop effective explanatory models?

The second research question asked how experiences of enacting modeling practices were similar and different across the three classrooms. Data were collected from several sources including the Students Understanding of Models in Science (SUMS) survey (Treagust et al., 2002) administered to teachers; interviews with teachers; classroom observations and video recordings; and student artifacts.

As students worked their way through developing explanatory models, classroom interactions were viewed through a lens of social constructivism (Dewey 1916,1938; Bruner, 1977; Vygotsky, 1978) and epistemic framing (Goffman, 1974; Redish, 2004). In addition, Berland et al.'s (2016) Epistemologies in Practice (EIP) framework was used to examine how epistemic considerations were framed during classroom interactions and related to student artifacts.

This study was conducted with the teachers and students in three fifth grade classrooms in different schools over the course of a multi-day lesson focused on developing explanatory models of a particular phenomenon, how the air heats up. All SUMS survey (Treagust et al., 2002) and interview data were analyzed to understand more about the teachers' conceptions of scientific modeling using Upmeier zu Belzen & Kruger's (2010) *Theoretical Aspect of Modeling* framework. Classroom observation videos were coded for modeling practices (Gilbert, 2004) and for EIP considerations (Berland et al., 2016) using ELAN (2018). Student developed models were coded using an explanatory model rubric (Penuel, 2018). After individual case analyses a cross-case analysis examined similarities and differences across the three classrooms.

Discussion of Findings

Taken together, the case and cross-case analyses revealed three important findings that are each discussed in turn in relation to the relevant literature.

Finding one: *Teachers demonstrated that they have knowledge of scientific models and an awareness of the role that scientific modeling can play in making sense of phenomena for their students.*

Overall, Natalie, Denise and Lydia demonstrated sophisticated knowledge of scientific models. All three of the case study teachers expressed understanding of the mechanistic features and explanatory nature of models. They knew that the purpose of scientific models was to explain how or why a system works the way it does. All three teachers also understood that multiple models can be used to show different aspects of a system and that models can and should change as more evidence is considered. These are sophisticated conceptions of the nature, purpose and features of scientific models (Gilbert & Justi, 2003, 2016; Nersessian, 2008; Upmeier zu Belzen & Kruger, 2010).

Natalie, Denise and Lydia also valued giving their students opportunities to engage in the work of modeling because it is important for sensemaking. This value is consistent with Russ' (2014) argument that students ought to engage in the work of science because it is productive for sensemaking, not because they are trying to mimic the work of experts. Russ' argument suggests that scientists develop and use models to make sense of the world, and since it is also the goal for students to make sense of the world they too ought to develop and use models. The role of modeling in the classroom is as a productive sensemaking strategy, not as mimicry of professional scientists (Jiménez-Aleixandre et al., 2000; Russ, 2014).

Modeling knowledge and a high value placed on modeling practices as demonstrated by the case study teachers is critical to engaging students in making sense of phenomenon (Berland et. al 2016). Teachers must understand the concepts and practices involved in how students construct knowledge if they are to support students in this work (Gilbert, 2004; Windschitl, 2002; Zangori et al., 2015).

Several scholars suggest that teachers, elementary teachers in particular, have not been given sufficient opportunities to develop the knowledge of scientific modeling they need to effectively support students in the work of developing and using models to make sense of complex phenomena (Akerson et al., 2009; Berland et. al, 2016; Justi & van Driel 2005a; Justi & Gilbert, 2003; Oh & Oh, 2011; Vo et al., 2015).

Natalie, Denise and Lydia's conceptions of scientific modeling are more sophisticated than is typical of elementary teachers (Oh & Oh, 2011; Van Driel & Verloop, 1999). In her interview Denise attributed this to her participation in the ongoing Research-Practice Partnership (RPP) focused on science education. When asked how she came to learn about modeling and make the decision to emphasize it in her practice, she replied, "I think it has come from [the RPP] workshops. The focus always included modeling, especially in the [advanced pedagogy] sessions" (personal communication, March 23, 2020, 04:43).

The RPP model includes trademarks of high-quality professional learning including sustained support for all teachers over years, coherence to the school's daily practice, and curriculum-based workshops for all teachers (Garet et al., 2001; Penuel, 2007; Short & Hirsch, 2020). Since 2013, Natalie, Denise and Lydia have been learning about the NGSS, its practices and how to provide students with meaningful opportunities to develop scientific understanding and practice that will meet the NGSS expectations. The case study teachers' participation in the RPP offers insight into why these teachers demonstrated more sophisticated conceptions of scientific modeling than is typically seen in the literature for elementary teachers.

There is also literature to suggest that when teachers are given professional learning opportunities to engage in and learn about the practice of scientific modeling, they are able to make effective connections between their knowledge of modeling and its application to their teaching practice (Berland et al., 2016; Justi & Gilbert 2003; Vo et al., 2015, 2019; Windschitl & Thompson 2006; Windschitl et al., 2008). Natalie, Denise, and Lydia had been afforded these professional learning opportunities and, thus, were well positioned to support their students in the work of using scientific modeling for sensemaking.

There was one area where two of the case study teachers expressed a more naive conception of scientific modeling. Natalie and Denise perceived that there was ultimately a correct version for a model of a particular phenomenon and felt it was important to guide their students toward this correct version. It is true that some scientific models share more widely agreed upon consensus within the science community than others. For example, it is widely agreed that the Earth revolves around the Sun, and less widely agreed if, how quickly, and why deep currents in the Atlantic Ocean are slowing down. All models, however, represent scientists' current understanding of how a system works based on evidence and is always subject to change in light of new information. Scientists characterize models as reflecting their current understanding or hypotheses, but not as having a fixed correctness (Gilbert, 2004; Nersessian, 2008).

For Natalie and Denise there was a tension between the fact that there is already wide consensus in the science community about the mechanisms involved in heating the air (and therefore constitutes known or correct knowledge), and the idea that students can engage in the work of constructing this same knowledge for themselves by engaging directly in the sensemaking work of science, in this case through modeling.

Lydia didn't express the same concern that her students arrive at a correct version of the model. She did expect and trust that her students would ultimately develop ideas consistent with scientific consensus about heating air, but spent less time sharing her concern for the anticipated end result and showed more concern for the discourse and thinking she knew students would need to do during their work with modeling.

There are certainly differences between the work of professional scientists, and the work of students in science classrooms; particularly in terms of background knowledge and experience. Important to modeling-based teaching, however, are the similarities between the two contexts. Scientists are typically working on figuring out puzzling phenomena for which there is not yet wide consensus in the scientific community. They engage in modeling because it is productive for sensemaking. Students of science, particularly in the elementary grades, are sometimes working on puzzling phenomena for which there is more widely agreed upon consensus in the scientific community. Since scientists, though, characterize their models in terms of their current understanding and not in terms of fixed correctness, students can still authentically participate in scientific modeling as a sensemaking strategy.

Regardless of how well established or contested the consensus, students and scientists bring their own models to bear on the work of other scientists. They may read the work of other scientists or test the ideas and models of their peers. In fact, it is the expectation of reasoning in science, whether student or scientist, that arguments will be evaluated and justified in terms of available evidence. Sensemaking through scientific modeling is a social and communal process. Sensemaking for scientists and students is inherently similar and it can be done meaningfully and authentically regardless of the scope of consensus for the phenomenon.

Previous research has found that teachers' ideas about scientific modeling influence their instructional practice (Arias et al., 2016; Oh & Oh, 2011; Schwarz et al., 2009; Vo et al., 2015). In this study, each teacher's conceptions of scientific models provided an important window into how modeling was enacted in these three fifth grade classrooms.

Finding two: *Teachers' knowledge of scientific models was related to their epistemic framing of classroom interactions.*

Consistent with the literature, I observed a connection between all three of the case study teachers' knowledge of scientific models and their classroom practice, specifically in their epistemic framing of classroom interactions (Berland & Hammer, 2012; Oh & Oh, 2011; Russ, 2018; Schwarz et al., 2009; Vo et al., 2015, 2019). Epistemic framing considers how a classroom community makes decisions about what counts as knowledge (Ryu & Sandoval, 2012; Kuhn et al., 207; Kawasaki & Sandoval 2019; Redish, 2004). For the EIP consideration of *Mechanism*, all three of the case study teachers demonstrated a constructivist epistemology and created environments in which students were involved in determining what was important and what counted as knowledge (Miller et al., 2018; Windschitl, 2002). This type of epistemic framing is authentic to science and productive for sensemaking (Berland et al., 2016; Jimenez-Aleixandre, 2000; Nersessian, 2008; Redish, 2004; Russ, 2014, 2018). Natalie, Denise and Lydia were all able to leverage their knowledge of scientific models in framing classroom interactions about the mechanistic features of models that supported students to engage in meaningful sensemaking to explain how the air heated up.

In each classroom, the inclusion of mechanistic interactions among system components in students' models was recognized as an important part of what counted as knowledge to students as well as to the teachers. Redish (2004) describes this shared recognition or frame as *knowledge as fabricated stuff*, meaning the students themselves made decisions about what counted as knowledge and how knowledge was constructed. In this context, students determined it was necessary to include the mechanisms involved in heating up the air in their models and not to simply describe or name what was happening. There was an expectation that for knowledge about explaining the phenomenon of air heating up to count in the eyes of the classroom community, it had to include a mechanistic explanation.

There were many instances in all three classrooms where the teachers' sophisticated knowledge of scientific models related to their similar epistemic framing of classroom interactions. There were other instances when differences in the teachers' modeling knowledge related to differences in their epistemic framing.

Natalie and Denise placed considerable emphasis on supporting their students to arrive at a correct version of a model that explained how the air heats up. This conception of a correct version of the model arose from their knowledge that many scientific models share wide consensus within the science community and are therefore considered largely “settled” or correct. It was important to Natalie and Denise that their students arrive at this same consensus understanding of how the air heats up. The conception of a correct version of a model, however, is a more naive conception of scientific models and stood in contrast to Natalie and Denise’s goal of giving students the opportunity to construct conceptual understanding for themselves by using modeling as a sensemaking strategy.

I found that Natalie and Denise’s conception of models as having a correct version related to their epistemic framing of classroom interactions for the EIP considerations of *Evidence and Audience*. During many instances, the teachers’ more naive conception of correct versions of models led both teachers to frame classroom interactions as *knowledge from authority* (Redish, 2004). This frame refers to the fact that teachers and students perceived that the knowledge that counted came from an outside authority. According to this frame, the outside authority could be the teacher, a textbook, or experts from outside the classroom such as professional scientists. This type of epistemic framing positions students to engage in figuring out what the right answer is according to the outside authority or the teacher, rather than constructing knowledge with their peers, and for themselves to explain a phenomenon. The instances when Natalie and Denise framed classroom interactions as *knowledge from authority* were focused on either telling students what counted as evidence and therefore needed to be included in their models, or by indicating that the audience for the knowledge product was the teacher who would be evaluating the students’ work.

Berland et al., (2016) characterize this framing as knowledge for performance rather than knowledge for sensemaking.

Framing classroom interactions as *knowledge from authority* worked in opposition to the idea of scientific modeling as a sensemaking strategy which both Natalie and Denise indicated was important to them. In these instances, Natalie and Denise unintentionally framed classroom interactions in a way that detracted from rather than promoted students engaging in authentic science for meaningful understanding (Hutchison & Hammer, 2010; Jimenez-Aleixandre, 2000; Miller et al., 2018; Russ, 2014, 2018).

Epistemic framing is a dynamic process in a classroom environment and can change quickly, across different situations, and from person to person (Berland & Hammer, 2012; Russ, 2018). For Natalie and Denise, there was a clear tension in the epistemic framing of classroom interactions throughout their lessons. At times classroom interactions were framed as *knowledge as fabricated stuff* and at others, *knowledge from authority* (Redish, 2004). The differences in framing shared a relationship with each teacher's conceptions of scientific models. In areas where their knowledge of scientific models was more sophisticated, Natalie and Denise tended to frame classroom interactions in ways that promoted students to use modeling practices as tools for sensemaking, to construct knowledge for themselves, which is consistent with how models are used in science (Gilbert, 2004; Nersessian, 2008; Russ, 2014). In areas where their knowledge of scientific models was more naive, Natalie and Denise tended to frame classroom interactions in ways that situated students as seeking knowledge from an outside authority. This positioned students, at times, as more as passive receivers of knowledge than as active constructors of their own understanding (Berland et al., 2016; Redish, 2004; Winschitl, 2002). Consequently, there were mixed messages sent to students about how decisions about knowledge and learning were made (Miller et al., 2018; Redish, 2004; Russ 2018).

Lydia’s epistemic framing of classroom interactions was more consistently characterized as *knowledge as fabricated stuff* (Redish, 2004). Similar to Natalie and Denise, there were many instances in Lydia’s classroom where the explanatory and mechanistic nature of models was framed as important knowledge within the classroom community by both teachers and students. However, classroom interactions that determined what evidence to include, or who was perceived as the audience for the models, were framed differently in Lydia's classroom than in the other two classrooms I observed. In Lydia’s classroom, these interactions were framed in a way that positioned students as the audience for their own work with the ability to determine what evidence to include and justify in their models. Students consistently showed they were engaged in the work of modeling because they were trying to make sense of the phenomenon, not to get the right answer or show the teacher what they knew (Berland et al., 2016; Jimenez-Aleixandre, 2000; Miller et al., 2018; Russ, 2004, 2018). This framing was consistent with a constructivist epistemology and was also consistent with Lydia’s sophisticated conceptions of modeling (Kuhn et al., 2017; Russ 2018; Windschitl, 2002). She did not express concern that her students might not arrive at the correct version of the model and did think it was important to take the time needed for students to think, talk and work on explaining the concepts together.

Across all three classrooms, even though there were differences in epistemic framing, the type of framing teachers displayed related to each of their conceptions of scientific models. This finding is supported by literature that shows a connection between elementary school teachers' knowledge of modeling and their classroom practice involving modeling (Oh & Oh, 2011; Ke & Schwarz, 2021; Schwarz et al., 2009; Vo et al., 2015, 2019). Understanding the existence and nature of connections between the teachers' knowledge of scientific models and how these conceptions related to epistemic framing of classroom interactions provided insight into how the NGSS practice of scientific modeling was enacted in these fifth grade classrooms.

Finding three: *Students' models related to the epistemic framing of classroom interactions.*

In each of Natalie and Denise's classrooms there was a higher proportion of student models that were effective overall than there was in Lydia's classroom. An interesting pattern within these results was that in Natalie and Denise's classrooms, compared to Lydia's classroom, there was a larger discrepancy between the number of students who included all of the necessary components and the number of students who could explain the interactions among these components.

In other words, students in Natalie and Denise's classrooms created models that included the components that would be involved in an effective mechanistic explanation of the phenomenon but struggled to fully explain the interactions involved in their own terms.

Lydia's students were not better able to explain the interactions, but their models more consistently reflected their efforts and struggles to make sense of the phenomenon. The models from Lydia’s classroom tended to be less complete. However, they also tended to include attempts and iterations of students trying to account for and incorporate multiple concepts that they thought might be important to explaining the phenomenon.

I found that the characteristics of the student models from each classroom related to the epistemic framing that was observed in that classroom. For example, there was evidence in many of the models from all three classrooms that the mechanistic nature of models was valued and important, which is consistent with how the EIP consideration of *Mechanism* was framed by all three case study teachers. Students and teachers in all three classrooms determined together that the mechanisms were important and counted as important knowledge to represent in their explanatory models.

There was also evidence in many of the student models and interactions from Natalie and Denise’s classrooms that students tried to incorporate what their teacher had indicated was required as evidence and produced the model for the teacher to evaluate but hadn’t necessarily fully constructed the mechanistic understanding for themselves. Many students in these two classrooms had a hard time articulating the mechanistic part of the explanation relative to all the components they were able to include. Natalie and Denise had largely framed classroom interactions involving *Evidence* and *Audience* more as *knowledge from authority* (Redish, 2004). I found there was a tension for students between deciding that the mechanistic features of the model were important and trying to make sense of those mechanisms for themselves and producing a model that would be evaluated as correct.

Lydia framed more of the interactions involving *Evidence* and *Audience* in her classroom as *knowledge as fabricated stuff*, meaning the students viewed themselves as responsible for determining what evidence needed to be included, and as consumers of their own knowledge products. The students were working for their own understanding. Students were also not as far along in producing explanatory models, but their models were more consistent with their own emerging ideas and students appeared less concerned about producing a correct model.

In this case study, I found that the teachers' conceptions of scientific models, their epistemic framing of classroom interactions, and the nature of students' models as knowledge products were all related. Natalie and Denise expressed sophisticated knowledge of scientific models in many areas such as models as explanatory tools, and more naive conceptions in others such as models having a correct version. In their classrooms there was a mix of epistemic framing of classroom interactions between *knowledge as fabricated stuff* and *knowledge from authority* and students' models tended to respond to an expectation of getting the correct version of the model. Students were receiving mixed messages as to whether knowledge was something to be constructed from their own experience or provided by an outside authority (Miller et al., 2018; Russ, 2018; Kawasaki & Sandoval, 2019; Redish, 2004). This response by students to try and deliver the right answer is well documented in the literature (Berland et al., 2016; Hutchison & Hammer, 2009; Jimenez-Aleixandre et al., 2000, Krist et al., 2019; Lemke, 1990; Miller et al., 2018; Oakes et al., 2000; Windschitl, 2002; Windschitl et al., 2008). Students often respond to the culture of school and what is set forth as the expectation of compliance with teacher expectations

(Hutchison & Hammer, 2009; Krist et al., 2019; Miller et al., 2018; Russ, 2014, 2018; Widschitl, 2002).

As was demonstrated in Lydia’s classroom, the concern for getting the right answer can be shifted in how we frame classroom interactions. Lydia more often framed classroom interactions in a way that positioned students to make the decisions about how to construct knowledge and what counted for knowledge. This is critical to using scientific modeling as a sensemaking strategy (Berland et al., 2016; Krist et al., 2019; Miller et al., 2018; Redish, 2004; Windschitl, 2002). The models that students developed were not yet as complete or well developed, but they reflected more of the students’ thinking and positing about relevant concepts. One of the pressures on teachers, of course, is that this kind of sensemaking and knowledge construction takes time (Chin et al., 2002; Krist, 2020; Krist et al., 2019; Winschitl et al., 2008). It can also be at odds with the structures and pressures of school and the school day, such as allocation of instructional minutes (Hutchison & Hammer, 2009; Miller et al., 2018; Oakes et al., 2000).

Findings from these three cases suggest that there is a relationship between the three teachers’ knowledge of scientific models, the ways in which they framed classroom interactions during a modeling lesson, and the characteristics of student developed models. If we want teachers to create learning environments in which students participate in authentic scientific modeling for sensemaking, we must consider the curricular and professional learning supports they need to engage in this difficult and complex work. We must also consider the larger context of schooling and education in which these teachers and students are situated.

Implications

Findings from this case study have several implications for teachers, school and district leaders, policy makers, and professional learning programs. These implications have the potential to impact opportunities for educators to improve teaching and learning for sensemaking in science.

Commit to High Quality Professional Learning

First, it is important for school and district leaders to make a commitment to providing elementary teachers with the high quality, sustained professional learning that they need and deserve. Findings from this case study suggested there was a relationship between all three teachers' knowledge of scientific models and how they framed and enacted modeling practices in their classrooms. Teachers themselves need meaningful learning opportunities to develop knowledge of scientific models, and the pedagogical content knowledge (PCK) (Shulman, 1987) necessary to engage students in the work of constructing scientific knowledge and skills (Garet et al., 2001; Short & Hirsh, 2020; Windschitl & Thompson, 2006).

Elementary teachers have not typically been prepared with the depth of science knowledge they need or experience with a constructivist approach to sensemaking in science (Oh & Oh, 2011; Windschitl & Thompson, 2006; Vo et al., 2015, 2019). In part, this is because scientific knowledge has historically and persistently been framed as belonging to an outside authority and as something that is transferred to students by a teacher or expert, rather than as knowledge students construct for themselves (Miller et al., 2018; Russ 2014, 2018; Schwarz et al., 2017; Windschitl, 2002; Windschitl et al., 2008, 2018). Supporting teachers to shift from what they experienced in school themselves to a more authentic modeling-based teaching approach is difficult and complex work. It is also worthwhile so that we can change the paradigm for the next generation of students (Miller et al., 2018; Seel, 2003; Windschitl et al., 2018).

Teachers deserve professional learning that is sustained and contextualized to their specific needs. Professional learning should support teachers over time as they learn more and their practice develops (Garet et al., 2001; Short & Hirsh, 2020). Natalie, Denise and Lydia all had the opportunity to work with a research-practice partnership (RPP) over many years. Their knowledge of scientific models and modeling practice was growing and developing. As it does with students, teacher learning takes practice and time to continually evolve. Expectations of elementary teacher expertise is high, in all subject areas, not only science. Educational leaders need to seek opportunities and professional learning partners with whom teachers can develop relationships and grow over time. Partners such as universities or other institutions that have the relevant expertise and infrastructure to be a sustained partner in the work offer promise for models such as research practice partnerships (Allen & Penuel, 2015; Coburn & Penuel, 2016; Coburn et al., 2013).

Professional learning opportunities also need to be contextualized to the classroom work of teachers. This means they should be curriculum-based and they should involve active learning (Garet et al., 2001; Penuel et al., 2007; Short & Hirsh, 2020). If we want teachers to understand what it means to construct a mechanistic understanding of phenomena and develop explanatory models, then they deserve to engage in these opportunities for themselves. There are no easy solutions, and a lot of competing priorities, but as educational leaders we ought to work hard and think creatively about how to practice what we preach. We ought to give teachers meaningful opportunities to develop knowledge and continually cultivate their practice.

Leverage Curriculum with Coherence for Students

A second implication from this study is that there is a need for high quality curriculum materials in order to support teachers and their implementation of a program that centers the authentic sensemaking work done in science. Teachers need opportunities to learn about scientific modeling and how it can be a powerful tool for sensemaking, and they also need curriculum resources that are designed to support that work.

The Next Generation Science Standards (NGSS) (NGSS Lead States, 2013) expect students to engage deeply with science concepts by figuring out how and why complex phenomena work the way that they do. To meet these expectations, it is important that science curricula not only create opportunities for students to use NGSS practices, such as developing and using models while developing their conceptual ideas, but also that the curriculum has coherence from the students' point of view. When asked what they are working on, students ought to be able to answer by sharing what they are trying to figure out. Students, not just teachers, should understand how one lesson builds from the previous or connects to next. When supported in this way, even early elementary school students can reason scientifically and make sense of complex phenomena (Penner et al., 1997; Louca & Zacharia, 2015; Manz, 2012; Ryu & Sandoval, 2012; Schwarz et al., 2017; Reiser et al., 2017). Students should have the opportunity to be presented with a complex phenomenon or problem, consider what questions they have about it, develop initial explanatory models to help them consider what they need to figure out, and make decisions about how they will go about that work. They should have opportunities to revisit, revise and find consensus in their class models often as they develop a mechanistic understanding of the phenomenon. These characteristics are at the core of modeling-based teaching (Reiser et al., 2017; Seel, 2003; Windschitl et al., 2018).

To date, many of the curriculum resources developed to support teachers and students in meeting the NGSS expectations have situated explaining phenomena and developing explanatory models at the end of lessons or courses to reinforce or apply ideas already taught, rather than situating phenomena and explanatory models in a way that drives learning from the student's point of view (Banilower, 2013; Reiser et at.; 2017; Windschitl et al., 2018). This was the case for the curriculum used in the case study classrooms, FOSS Next Generation (2019). FOSS has a long history of developing elementary science curriculum. FOSS materials contain many features that are educative for teachers in terms of understanding the NGSS expectations and provide students with meaningful and engaging sensemaking opportunities. The program has supported teachers and students across the US to develop active and sustainable elementary science programs that are highly supportive of teacher and student learning. However, in the edition used by the teachers in this study, modeling was positioned as an application of knowledge at the end of a sequence of lessons about energy transfer. Natalie, Denise and Lydia all worked to position modeling as a central part in the learning sequence. In the future, it will be easier for teachers to frame classroom interactions in productive ways if their curricular materials are designed with a modeling-based teaching approach that uses phenomena and the related pursuit of developing explanatory models in a way that has coherence for the students as well as the teachers throughout their courses.

Ensure Educational Policies and Expectations Complement One Another

A third important implication from this case study is that educational leaders and policy makers must take care that their policies and expectations function in ways that compliment rather than impede one another. Natalie, Denise and Lydia each expressed some level of concern or awareness of the fact that their students take a statewide science assessment in the spring of fifth grade. They recognized that stand-alone tasks, even ones that are well designed, still stand in contrast to the kind of modeling and sensemaking they were trying to prioritize in their practice. They were also aware that despite having supportive administrators, there was still implicit pressure for them to attend to making sure their students were prepared to perform well on the tests. Along with this implicit testing pressure was the teachers' concern for time. The case study teachers recognized that providing opportunities for students to do the work necessary to talk with one another, share ideas and construct knowledge together takes time. Denise, in particular, expressed concern for how to "fit it all in", a common concern for teachers, especially elementary school teachers who teach multiple subjects. When school and district leaders are creating or adopting policy, creating schedules, setting expectations, and conducting teacher and classroom evaluations, it is important that they consider the kind of meaningful teaching and learning that they want in their schools and that their policies and resource allocations support the most worthy of their goals.

Limitations

Findings from this study have several important implications for the education community. There are also limitations to interpreting the findings of this study that ought to be considered.

First, consistent with case study research methodology, this study sought to develop understanding of the particular contexts and complexities of each classroom or case. Case study research does not seek to make statistical generalizations, but rather to add insight to relevant theoretical understanding (Yin, 2018). Findings from this study should be considered in the context of relevant theoretical frames and not generalized to a larger population of classrooms or individuals.

Second, this case study examined classroom interactions in fifth grade classrooms in three suburban schools in the northeastern United States, with a majority of students identifying as white, and relatively low numbers of students qualified for subsidized lunch. It should be recognized that the ways in which classroom interactions among teachers and students play out will vary across grade levels, teaching contexts, and communities. While findings from this study were situated within the modeling-based teaching literature for elementary classrooms, the classrooms in this study only represent their own contexts. Future studies should be conducted across grade levels, contexts and communities to add to our collective understanding of modeling-based teaching in elementary schools more broadly.

Third, It should be noted that the comprehensive and ongoing nature of the support provided at all levels of the education system by this RPP was not typical for elementary school teachers across the country (Banilower, et al., 2007). The curriculum-based professional learning workshops were required of all teachers and supported through released-time by the district leadership. Thus, all teachers involved in the RPP, including the teachers in this case study, had an amount of support for their science teaching practice that is considerably more than is typical for teachers across the country (Banilower et al., 2007; Coburn & Penuel, 2016; Coburn et al., 2013). Further, all teachers in this RPP were supported with professional learning workshops and support for their science practice on an ongoing basis over years through regularly scheduled and required workshops, coaching, and regular access via email to science education experts at the university. The principals and central office administrators were also regularly supported through workshops and in school support for how to best support teachers in their continuing science practice.

Fourth, it is important to acknowledge that the SUMS survey data (Treagust et al., 2002) and interview data used in this study were self-reported. A strength of self-reported data is that it gives participants the opportunity to describe their own experiences. There is also the limitation, though, that respondents might respond in a way they think the researcher wants them to or will lead to them being perceived in a certain way (DeVellis, 2012). Importantly, survey data, interview data and classroom observations were used to triangulate findings and the teachers were given the opportunity to clarify their survey and interview responses through follow up conversations.

Fifth, it is important to note that the number of notebooks I was able to examine varied across the three classrooms. Given the opportunity to examine more of the notebooks I may have gained further insight into the similarities and differences across the classrooms.

Finally, it is important to consider the positionality of the researcher in this study. I am on the full-time leadership team of the RPP in which the teachers participate. In my role, I have facilitated professional learning sessions with the participating teachers and have had a professional relationship with them for several years. Throughout this study I maintained awareness of the potential influence of my role on participants; and thus, through my written solicitations and in conversations, I worked to be sure the teachers understood the goals of the research and that it was not in any way evaluative of them or their teaching practice. While I maintained awareness of my potential influence as the researcher, my role in the RPP also positioned me to have a trusting relationship with the teachers. Prior to this study, I had a collegial rapport with each of the teachers and have supported each of them in improving their practice previously. This may have contributed to their comfort participating in the study.

Future Research

Although there are many, I have selected two areas of further research that I think have the greatest potential to contribute new insights that are relevant to the findings in this case study. First, the EIP framework (Berland, et al., 2016) used in this study included four epistemic considerations to be examined during classroom interactions involving scientific modeling, *Nature* (or *Mechanism), Generality, Justification* (or *Evidence)* and *Audience*. When coding classroom video for the EIP considerations in this study, each occurrence was coded for the single EIP consideration that was most prominent for the given classroom interaction. This is consistent with how the EIP framework was used in other recent case studies (Vo. et al., 2015, 2019; Ke & Schwarz, 2021). Berland et al., (2016) discuss in the framework that the EIP considerations likely co-occur, since they involve complex classroom interactions among teachers and students. I also observed this possibility, but it was beyond the scope of data analysis in this study. Further research into the co-occurrences of the EIP considerations could offer insight into the complexity of epistemic framing during modeling-based instruction. In addition, use of the EIP framework across grade levels and in different contexts would also add to the body of literature seeking understanding of how teachers and students epistemically frame their classroom interactions during modeling.

A second area worthy of study related to findings from this study is that of epistemic justice (Miller et al., 2018). My case study examined teacher conceptions of scientific models and began to explore the relationship among those conceptions with epistemic framing of classroom interactions and students' explanatory models. In order to position students as the people who know and do science, we must be concerned with whether or not students see themselves as actively constructing knowledge that they determine to be scientifically meaningful (Miller et al., 2018). Findings from my case study and other research suggest that teachers, who hold a position of authority in classrooms, influence not only what students do in classrooms, but also how students perceive themselves as constructors of knowledge (or don't) (Manz, 2015; Stroupe, 2014; Russ, 2018). To date, much of the research on epistemic framing in classrooms has focused on what teachers are doing, saying and how they are responding to students. Considerably less research has found effective methodologies for examining the messages perceived by students as a result of teacher framing, or the ways in which students are framing classroom interactions (Russ, 2018).

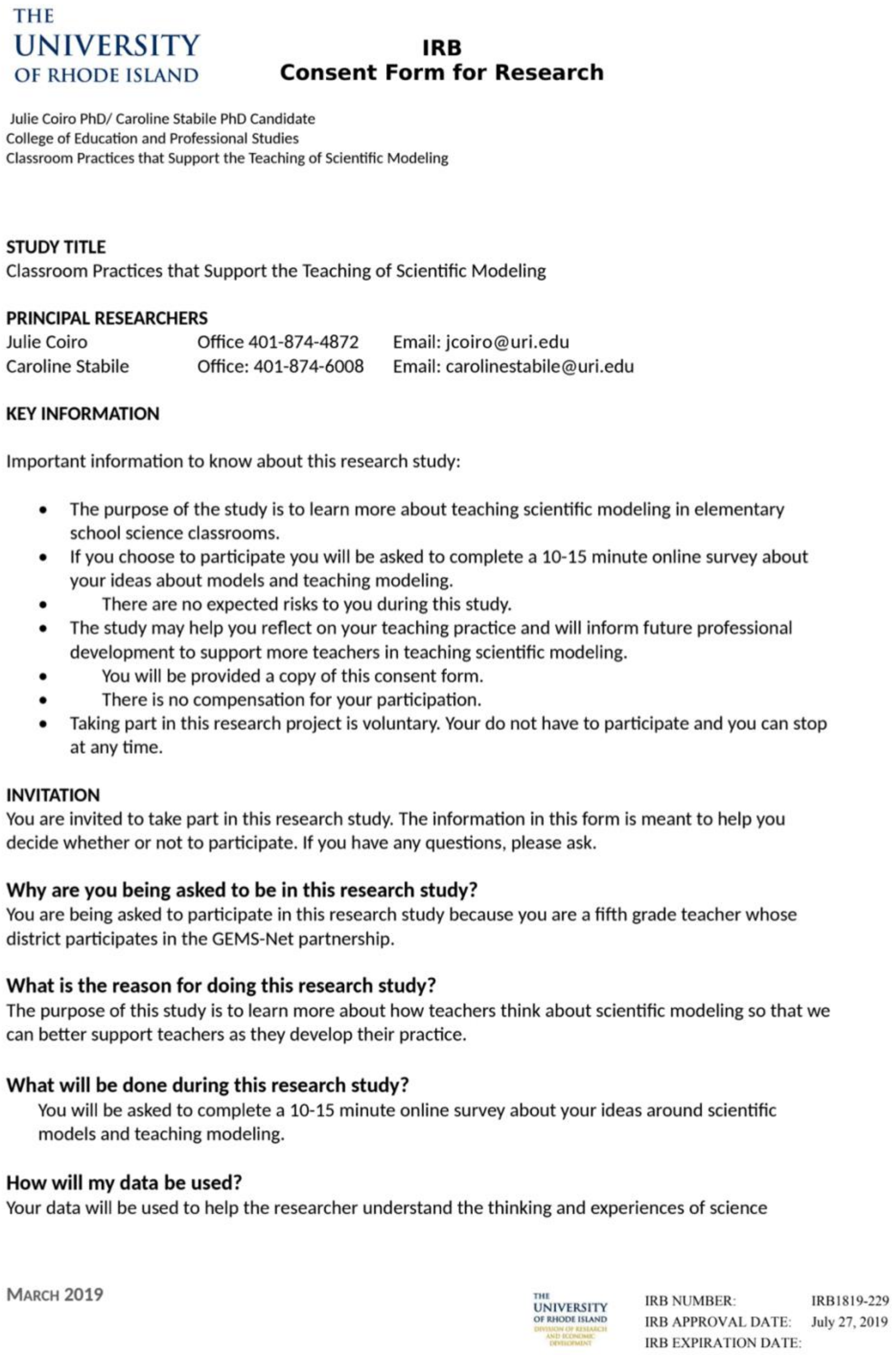
Russ (2018) argues that we need more research that examines the epistemic messages teachers send to students through the lens of how the messages are perceived by students. If teachers convey messages to students that how the students construct knowledge or determine what is valuable knowledge are unimportant or unvalued in classrooms, an epistemic injustice occurs (Miller et al., 2018). These individual injustices can and do accumulate and lead to epistemic oppression, or persistent epistemic exclusion (Dotson, 2018). This affects how whole communities' (in classrooms and in societies) ideas are valued and perceived by those within the community and by those in positions of power (Dotson, 2014; Ladson-Billings, 1995). To ensure we are working productively toward the goal of positioning students as the knowers and doers of science, including through modeling-based teaching, we need more research into the ways teachers' epistemic messages are being perceived by students.

The science education community continues to learn and grow from the dedicated students, teachers, school leaders and researchers trying to "figure it out". We've learned so much about the kind of teaching and learning that has the potential to prepare our children for an exciting, complex and challenging future. This is hard work and it is worthy work. Let us leave a legacy for our children of how we made sense of the world together and hand it to them better than we found it.

APPENDICES

Appendix A

Teacher Consent Form



THE
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IRB
Consent Form for Research

Julie Coiro PhD/ Caroline Stabile PhD Candidate
College of Education and Professional Studies
Classroom Practices that Support the Teaching of Scientific Modeling

STUDY TITLE
Classroom Practices that Support the Teaching of Scientific Modeling

PRINCIPAL RESEARCHERS

Julie Coiro	Office 401-874-4872	Email: jcoiro@uri.edu
Caroline Stabile	Office: 401-874-6008	Email: carolinestabile@uri.edu

KEY INFORMATION

Important information to know about this research study:

- The purpose of the study is to learn more about teaching scientific modeling in elementary school science classrooms.
- If you choose to participate you will be asked to complete a 10-15 minute online survey about your ideas about models and teaching modeling.
- There are no expected risks to you during this study.
- The study may help you reflect on your teaching practice and will inform future professional development to support more teachers in teaching scientific modeling.
- You will be provided a copy of this consent form.
- There is no compensation for your participation.
- Taking part in this research project is voluntary. Your do not have to participate and you can stop at any time.

INVITATION
You are invited to take part in this research study. The information in this form is meant to help you decide whether or not to participate. If you have any questions, please ask.

Why are you being asked to be in this research study?
You are being asked to participate in this research study because you are a fifth grade teacher whose district participates in the GEMS-Net partnership.

What is the reason for doing this research study?
The purpose of this study is to learn more about how teachers think about scientific modeling so that we can better support teachers as they develop their practice.

What will be done during this research study?
You will be asked to complete a 10-15 minute online survey about your ideas around scientific models and teaching modeling.

How will my data be used?
Your data will be used to help the researcher understand the thinking and experiences of science

MARCH 2019

THE UNIVERSITY OF RHODE ISLAND
IRB NUMBER: IRB1819-229
IRB APPROVAL DATE: July 27, 2019
IRB EXPIRATION DATE:

Cont. Appendix A

THE UNIVERSITY OF RHODE ISLAND

IRB
Consent Form for Research

Julie Coiro PhD/ Caroline Stabile PhD Candidate
College of Education and Professional Studies
Classroom Practices that Support the Teaching of Scientific Modeling

teachers.

What are the possible risks of being in this research study?
There are no expected risks to you as a result of participation in this study.

What are the possible benefits to you?
The benefits to you are that you may reflect on your teaching of scientific modeling.

What are the possible benefits to other people?
The benefits to to others are that this study will help the researcher better understand teachers' thinking about scientific modeling and how to provide more effective support for teachers in this area of teaching.

What will participation in this research study cost you?
There is no cost to you to be in this research study.

Will you be compensated for being in this research study?
There is no compensation for participating in this study.

What should you do if you have a problem during this research study?Your welfare is the major concern of every member of the research team. If you have a problem as a direct result of being in this study, you should immediately contact one of the people listed at the beginning of this consent form.

How will information about you be protected?
Reasonable steps will be taken to protect your privacy and the confidentiality of your study data.

The data will be stored electronically through a secure server and will only be seen by the research team during the study and for 5 years after the study is complete.

The only persons who will have access to your research records are the study personnel, the Institutional Review Board (IRB), and any other person, agency, or sponsor as required by law. The information from this study may be published in scientific journals or presented at scientific meetings but the data will be reported as group or summarized data and your identity will be kept strictly confidential.

What are your rights as a research subject?
You may ask any questions concerning this research and have those questions answered before agreeing to participate in or during the study.

For study related questions, please contact the investigator(s) listed at the beginning of this form.

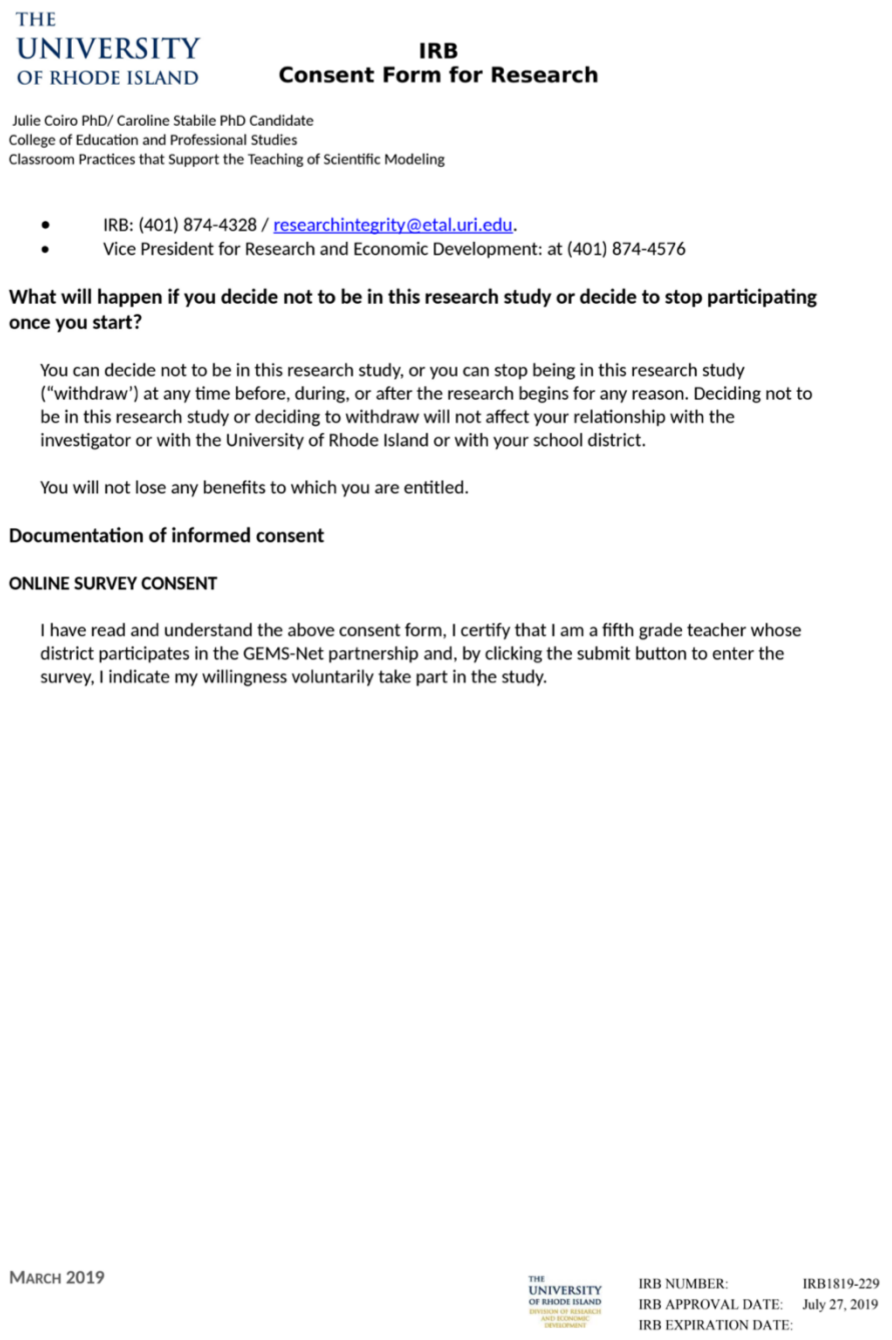
For questions concerning your rights or complaints about the research contact the Institutional Review Board (IRB) or Vice President for Research and Economic Development:

MARCH 2019

THE UNIVERSITY OF RHODE ISLAND DIVISION OF RESEARCH AND ECONOMIC DEVELOPMENT

IRB NUMBER: IRB1819-229
IRB APPROVAL DATE: July 27, 2019
IRB EXPIRATION DATE:

Cont. Appendix A



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IRB
Consent Form for Research

Julie Coiro PhD/ Caroline Stabile PhD Candidate
College of Education and Professional Studies
Classroom Practices that Support the Teaching of Scientific Modeling

- IRB: (401) 874-4328 / researchintegrity@etal.uri.edu.
- Vice President for Research and Economic Development: at (401) 874-4576

What will happen if you decide not to be in this research study or decide to stop participating once you start?

You can decide not to be in this research study, or you can stop being in this research study ("withdraw') at any time before, during, or after the research begins for any reason. Deciding not to be in this research study or deciding to withdraw will not affect your relationship with the investigator or with the University of Rhode Island or with your school district.

You will not lose any benefits to which you are entitled.

Documentation of informed consent

ONLINE SURVEY CONSENT

I have read and understand the above consent form, I certify that I am a fifth grade teacher whose district participates in the GEMS-Net partnership and, by clicking the submit button to enter the survey, I indicate my willingness voluntarily take part in the study.

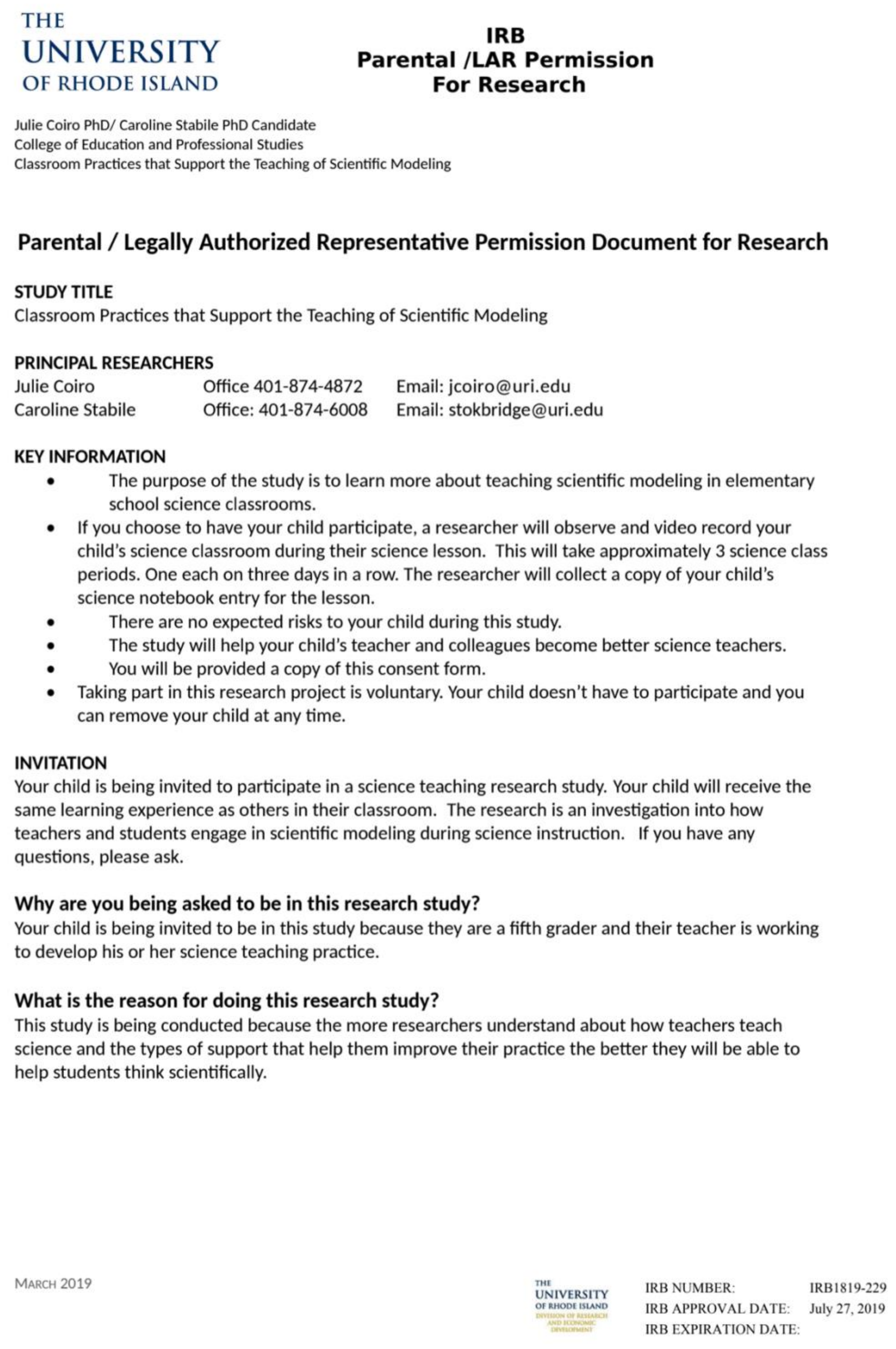
MARCH 2019

THE UNIVERSITY OF RHODE ISLAND
DIVISION OF RESEARCH AND ECONOMIC DEVELOPMENT

IRB NUMBER: IRB1819-229
IRB APPROVAL DATE: July 27, 2019
IRB EXPIRATION DATE:

Appendix B

Student Guardian Consent Form



THE
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OF RHODE ISLAND

IRB
Parental /LAR Permission
For Research

Julie Coiro PhD/ Caroline Stabile PhD Candidate
College of Education and Professional Studies
Classroom Practices that Support the Teaching of Scientific Modeling

Parental / Legally Authorized Representative Permission Document for Research

STUDY TITLE

Classroom Practices that Support the Teaching of Scientific Modeling

PRINCIPAL RESEARCHERS

Julie Coiro	Office 401-874-4872	Email: jcoiro@uri.edu
Caroline Stabile	Office: 401-874-6008	Email: stokbridge@uri.edu

KEY INFORMATION

- The purpose of the study is to learn more about teaching scientific modeling in elementary school science classrooms.
- If you choose to have your child participate, a researcher will observe and video record your child's science classroom during their science lesson. This will take approximately 3 science class periods. One each on three days in a row. The researcher will collect a copy of your child's science notebook entry for the lesson.
- There are no expected risks to your child during this study.
- The study will help your child's teacher and colleagues become better science teachers.
- You will be provided a copy of this consent form.
- Taking part in this research project is voluntary. Your child doesn't have to participate and you can remove your child at any time.

INVITATION

Your child is being invited to participate in a science teaching research study. Your child will receive the same learning experience as others in their classroom. The research is an investigation into how teachers and students engage in scientific modeling during science instruction. If you have any questions, please ask.

Why are you being asked to be in this research study?

Your child is being invited to be in this study because they are a fifth grader and their teacher is working to develop his or her science teaching practice.

What is the reason for doing this research study?

This study is being conducted because the more researchers understand about how teachers teach science and the types of support that help them improve their practice the better they will be able to help students think scientifically.

March 2019

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DIVISION OF RESEARCH AND ECONOMIC DEVELOPMENT

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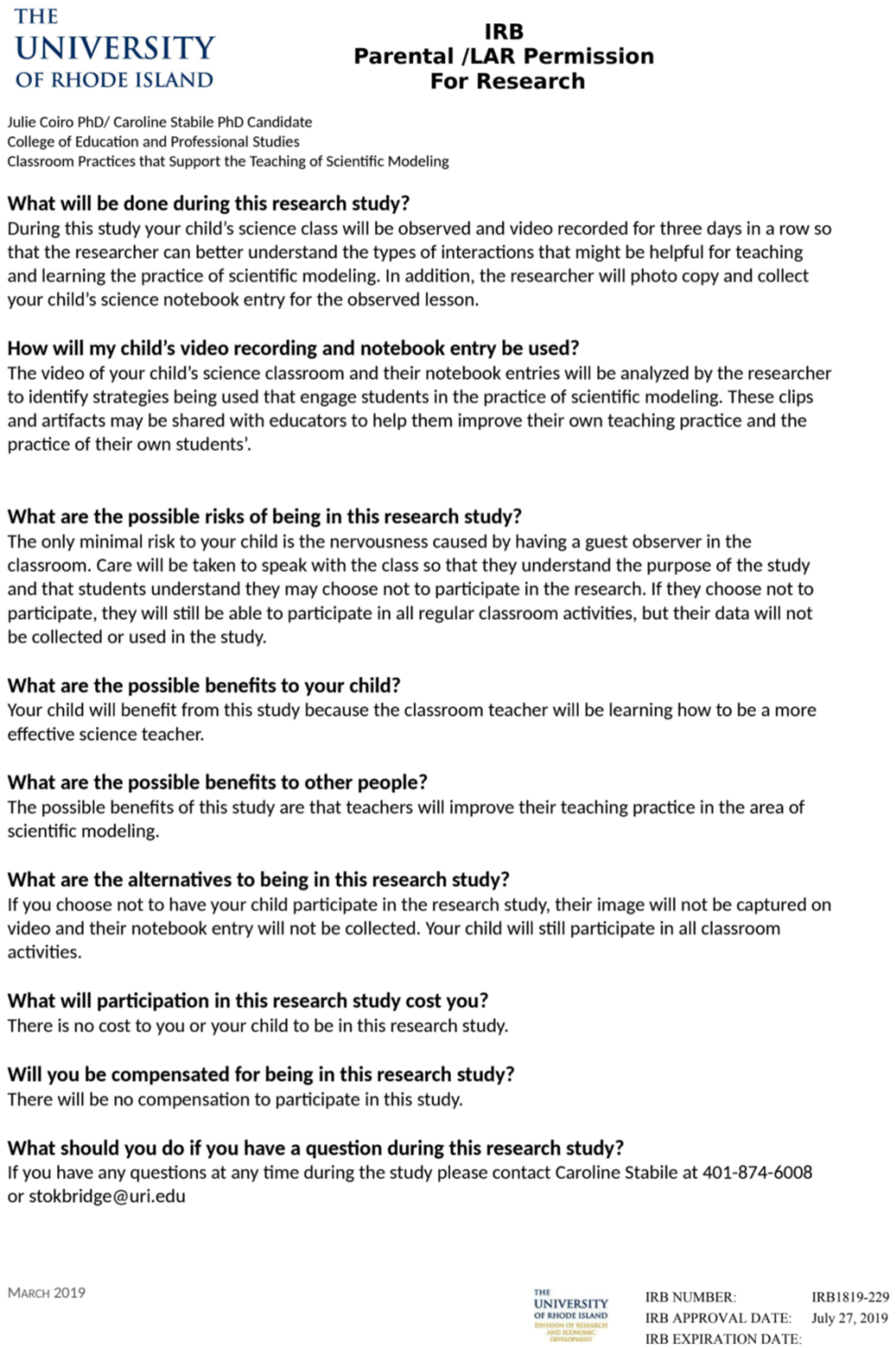

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IRB
Parental /LAR Permission For Research

Julie Coiro PhD/ Caroline Stabile PhD Candidate
College of Education and Professional Studies
Classroom Practices that Support the Teaching of Scientific Modeling

What will be done during this research study?
During this study your child's science class will be observed and video recorded for three days in a row so that the researcher can better understand the types of interactions that might be helpful for teaching and learning the practice of scientific modeling. In addition, the researcher will photo copy and collect your child's science notebook entry for the observed lesson.

How will my child's video recording and notebook entry be used?
The video of your child's science classroom and their notebook entries will be analyzed by the researcher to identify strategies being used that engage students in the practice of scientific modeling. These clips and artifacts may be shared with educators to help them improve their own teaching practice and the practice of their own students'.

What are the possible risks of being in this research study?
The only minimal risk to your child is the nervousness caused by having a guest observer in the classroom. Care will be taken to speak with the class so that they understand the purpose of the study and that students understand they may choose not to participate in the research. If they choose not to participate, they will still be able to participate in all regular classroom activities, but their data will not be collected or used in the study.

What are the possible benefits to your child?
Your child will benefit from this study because the classroom teacher will be learning how to be a more effective science teacher.

What are the possible benefits to other people?
The possible benefits of this study are that teachers will improve their teaching practice in the area of scientific modeling.

What are the alternatives to being in this research study?
If you choose not to have your child participate in the research study, their image will not be captured on video and their notebook entry will not be collected. Your child will still participate in all classroom activities.

What will participation in this research study cost you?
There is no cost to you or your child to be in this research study.

Will you be compensated for being in this research study?
There will be no compensation to participate in this study.

What should you do if you have a question during this research study?
If you have any questions at any time during the study please contact Caroline Stabile at 401-874-6008 or stokbridge@uri.edu

March 2019

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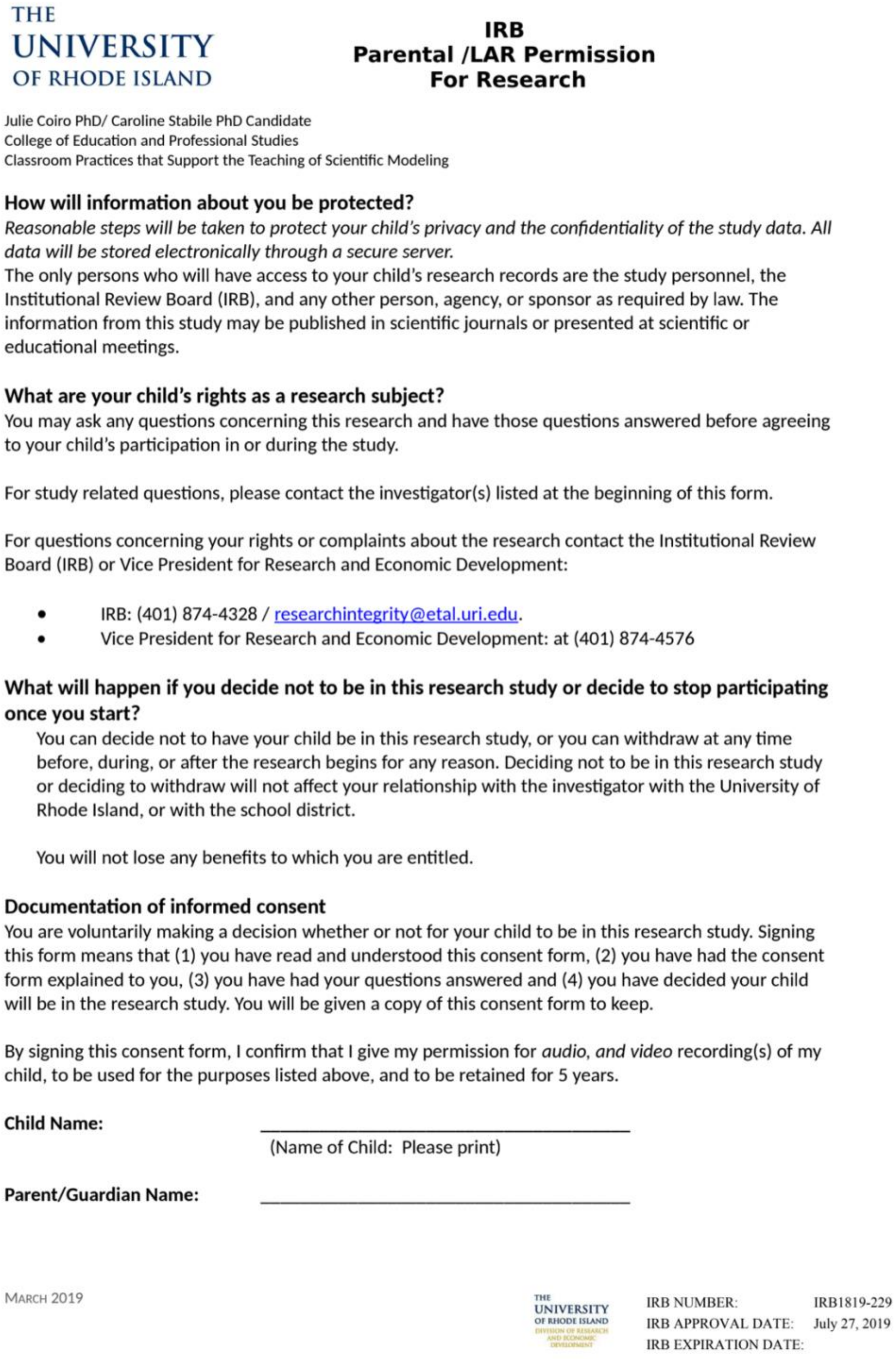

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IRB
Parental /LAR Permission
For Research

Julie Coiro PhD/ Caroline Stabile PhD Candidate
College of Education and Professional Studies
Classroom Practices that Support the Teaching of Scientific Modeling

How will information about you be protected?

Reasonable steps will be taken to protect your child's privacy and the confidentiality of the study data. All data will be stored electronically through a secure server.

The only persons who will have access to your child's research records are the study personnel, the Institutional Review Board (IRB), and any other person, agency, or sponsor as required by law. The information from this study may be published in scientific journals or presented at scientific or educational meetings.

What are your child's rights as a research subject?

You may ask any questions concerning this research and have those questions answered before agreeing to your child's participation in or during the study.

For study related questions, please contact the investigator(s) listed at the beginning of this form.

For questions concerning your rights or complaints about the research contact the Institutional Review Board (IRB) or Vice President for Research and Economic Development:

- IRB: (401) 874-4328 / researchintegrity@etal.uri.edu.
- Vice President for Research and Economic Development: at (401) 874-4576

What will happen if you decide not to be in this research study or decide to stop participating once you start?

You can decide not to have your child be in this research study, or you can withdraw at any time before, during, or after the research begins for any reason. Deciding not to be in this research study or deciding to withdraw will not affect your relationship with the investigator with the University of Rhode Island, or with the school district.

You will not lose any benefits to which you are entitled.

Documentation of informed consent

You are voluntarily making a decision whether or not for your child to be in this research study. Signing this form means that (1) you have read and understood this consent form, (2) you have had the consent form explained to you, (3) you have had your questions answered and (4) you have decided your child will be in the research study. You will be given a copy of this consent form to keep.

By signing this consent form, I confirm that I give my permission for *audio, and video* recording(s) of my child, to be used for the purposes listed above, and to be retained for 5 years.

Child Name: ____
(Name of Child: Please print)

Parent/Guardian Name: ____

MARCH 2019

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IRB
Parental /LAR Permission
For Research

Julie Coiro PhD/ Caroline Stabile PhD Candidate
College of Education and Professional Studies
Classroom Practices that Support the Teaching of Scientific Modeling

(Name of Parent/Guardian: Please print)

Parent/Guardian Signature: ____
(Signature of Parent/Guardian) Date: ________

Investigator certification:

My signature certifies that all elements of informed consent described on this consent form have been explained fully to the parent/guardian. In my judgment, the participant possesses the capacity to give informed consent to participate in this research and is voluntarily and knowingly giving informed consent to participate.

____ _______________
Signature of Person Obtaining Consent Date

March 2019

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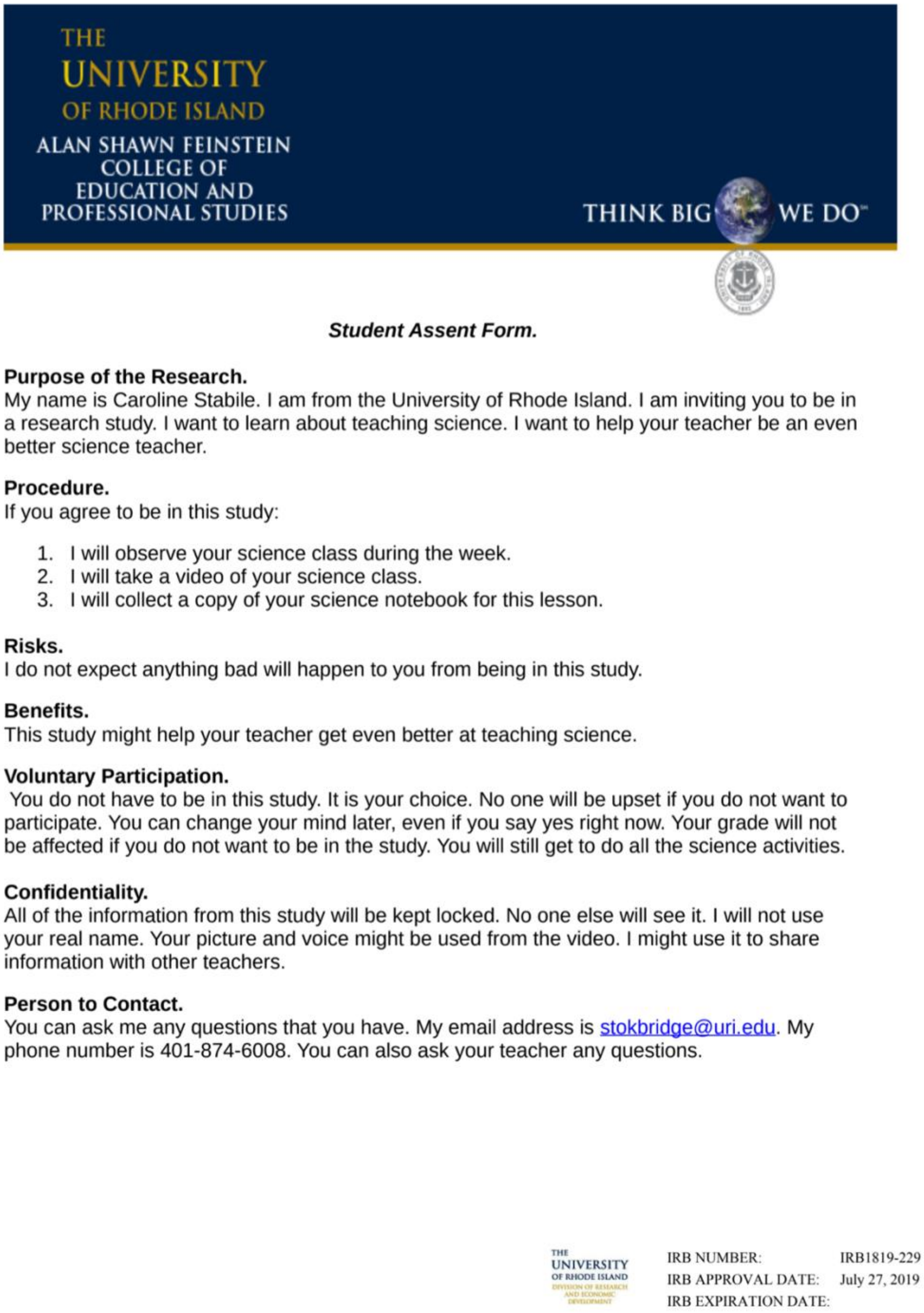
Appendix C

Student Assent Form



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ALAN SHAWN FEINSTEIN
COLLEGE OF
EDUCATION AND
PROFESSIONAL STUDIES

THINK BIG WE DO™

Student Assent Form.

Purpose of the Research.
My name is Caroline Stabile. I am from the University of Rhode Island. I am inviting you to be in a research study. I want to learn about teaching science. I want to help your teacher be an even better science teacher.

Procedure.
If you agree to be in this study:

1. I will observe your science class during the week.
2. I will take a video of your science class.
3. I will collect a copy of your science notebook for this lesson.

Risks.
I do not expect anything bad will happen to you from being in this study.

Benefits.
This study might help your teacher get even better at teaching science.

Voluntary Participation.
You do not have to be in this study. It is your choice. No one will be upset if you do not want to participate. You can change your mind later, even if you say yes right now. Your grade will not be affected if you do not want to be in the study. You will still get to do all the science activities.

Confidentiality.
All of the information from this study will be kept locked. No one else will see it. I will not use your real name. Your picture and voice might be used from the video. I might use it to share information with other teachers.

Person to Contact.
You can ask me any questions that you have. My email address is stokbridge@uri.edu. My phone number is 401-874-6008. You can also ask your teacher any questions.

THE UNIVERSITY OF RHODE ISLAND
DIVISION OF RESEARCH AND ECONOMIC DEVELOPMENT

IRB NUMBER: IRB1819-229
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Cont. Appendix C

Consent.

_____ I do want to be in this study.

_____ I do not want to be in this study.

____

Printed name of student

________________________________ ____________

Signature of student Date

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Appendix D

Survey Responses on the SUMS from 18 Fifth Grade Teachers (Treagust et al., 2002)

			Responses (%)			
Factor	Item	Statement	Strongly Agree	Agree	Disagree	Strongly Disagree
Models as Multiple Representations	1	Many models may be used to express features of science phenomena by showing different perspectives to view an object.	33.33	66.67	0.00	0.00
	2	Many models represent different versions of the phenomenon.	22.22	66.67	11.11	0.00
	3	Models can show the relationship of ideas clearly.	33.33	66.67	0.00	0.00
	4	Many models are used to show how it depends on an individual's different ideas as to what things look like or how they work.	11.76	64.71	23.53	0.00
	5	Many models may be used to show different sides or shapes of an object.	16.67	83.33	0.00	0.00
	6	Many models show different parts of an object or show objects differently.	16.67	77.78	5.56	0.00
	7	Many models show how different information is used.	5.56	88.89	5.56	0.00

	8	A model has what is needed to show or explain a scientific phenomenon.	22.22	72.22	5.56	0.00
Models as Exact Replicas	9	A model should be an exact replica.	0.00	0.00	77.78	22.22
	10	A model needs to be close to the real thing.	0.00	55.44	44.44	0.00
	11	A model needs to be close to the real thing by being very exact, so nobody can disprove it.	0.00	0.00	77.78	
	12	You should be able to tell what everything on a model represents.	5.56	16.67	77.78	0.00
	13	A model needs to be close to the real thing by being very exact in every way except for size.	0.00	16.67	77.78	0.00
	14	A model needs to be close to the real thing by giving the correct information and showing what the object/thing looks like.	17.65	41.18	29.41	11.76
	15	A model shows what the real thing does and what it looks like.	5.56	72.22	22.22	0.00
	16	Models must show a smaller scale size of something.	0.00	16.67	55.56	27.28
Models as Explanatory Tools	17	Models are used to physically or visually represent something.	55.56	44.44	0.00	0.00
	18	Models help create a picture in your mind of the scientific happening.	44.44	55.56	0.00	0.00
	19	Models are used to explain scientific phenomena.	27.78	72.22	0.00	0.00
	20	Models are used to show an idea.	22.22	72.22	5.56	0.00

	21	A model can be a diagram, picture, map, graph or photo.	38.89	44.44	16.67	0.00
Uses of Scientific Models	22	Models are used to help formulate ideas and theories about scientific events.	50.00	44.44	5.56	0.00
	23	Models are used to show how things work in scientific investigations.	33.33	66.67	0.00	0.00
	24	Models are used to make and test predictions about a scientific event.	35.29	58.82	5.88	0.00
Changing Nature of Models	25	A model can change if new theories or evidence prove otherwise.	55.56	44.44	0.00	0.00
	26	A model can change if there are new findings.	66.67	33.33	0.00	0.00
	27	A model can change if there are changes in data or belief.	50.00	50.00	0.00	0.00

Appendix E

Percent of Respondents on the Levels of Use Descriptions (Hall, Dirksen, & George, 2006)

Level	Description	%
1	I haven’t had the opportunity to learn much about the NGSS practice of developing and using models yet, but might be interested as I learn more.	0
2	I know developing and using models is a part of the NGSS, and I’m beginning to consider how it might fit into my teaching practice. I’m interested to learn more about it.	11.11
3	I know developing and using models is a part of the NGSS. I'm learning about it as I go and I engage students in this work the best I can where it is called for and described in our science curriculum.	27.78
4	I know developing and using models is a part of the NGSS. I think it is a valuable part and appreciate the opportunities to target this work when it comes up in our science curriculum.	22.22
5	I think developing and using models is an important NGSS practice and I work on it with my students whenever I see the opportunity.	38.89

Appendix F

Case Study Teachers' Responses to the SUMS Survey (Treagust et al., 2002)

Factor	Item	Statement	Natalie	Denise	Lydia
Models as Multiple Representations	1	Many models may be used to express features of science phenomena by showing different perspectives to view an object.	Strongly agree	Agree	Strongly agree
	2	Many models represent different versions of the phenomenon.	Strongly agree	Agree	Disagree
	3	Models can show the relationship of ideas clearly.	Strongly agree	Agree	Strongly agree
	4	Many models are used to show how it depends on an individual's different ideas as to what things look like or how they work.	Disagree	Agree	Agree
	5	Many models may be used to show different sides or shapes of an object.	Agree	Agree	Agree
	6	Many models show different parts of an object or show objects differently.	Strongly agree	Agree	Disagree
	7	Many models show how different information is used.	Agree	Agree	Disagree
	8	A model has what is needed to show or explain a scientific phenomenon.	Disagree	Agree	Strongly agree

Models as Exact Replicas	9	A model should be an exact replica.	Strongly disagree	Disagree	Strongly disagree
	10	A model needs to be close to the real thing.	Disagree	Agree	Disagree
	11	A model needs to be close to the real thing by being very exact, so nobody can disprove it.	Strongly disagree	Disagree	Strongly disagree
	12	You should be able to tell what everything on a model represents.	Disagree	Disagree	Disagree
	13	A model needs to be close to the real thing by being very exact in every way except for size.	Strongly disagree	Disagree	Disagree
	14	A model needs to be close to the real thing by giving the correct information and showing what the object/thing looks like.	Strongly disagree	Disagree	Disagree
	15	A model shows what the real thing does and what it looks like.	Strongly disagree	Agree	Disagree
	16	Models show a smaller scale size of something.	Disagree	Strongly Disagree	Strongly Disagree
Models as Explanatory Tools	17	Models are used to physically or visually represent something.	Agree	Strongly agree	Strongly agree
	18	Models help create a picture in your mind of the scientific happening.	Agree	Agree	Agree
	19	Models are used to explain scientific phenomena.	Strongly agree	Strongly agree	Agree
	20	Models are used to show an idea.	Agree	Strongly agree	Agree
	21	A model can be a diagram, picture, map, graph or photo.	Strongly agree	Disagree	Strongly agree

Uses of Scientific Models	22	Models are used to help formulate ideas and theories about scientific events.	Disagree	Strongly Agree	Strongly agree
	23	Models are used to show how things work in scientific investigations.	Agree	Agree	Strongly agree
	24	Models are used to make and test predictions about a scientific event.	Strongly agree	Skipped Item	Disagree
Changing Nature of Models	25	A model can change if new theories or evidence prove otherwise.	Strongly agree	Strongly agree	Strongly agree
	26	A model can change if there are new findings.	Strongly agree	Strongly agree	Strongly agree
	27	A model can change if there are changes in data or belief.	Strongly agree	Strongly agree	Strongly agree

Appendix G

Occurrences Of Modeling Practices For Case Study Teachers

	Occurrences (%)					
	Natalie (N=34)		Denise (N=60)		Lydia (N=64)	
Modeling Practices	freq.	%	freq.	%	freq.	%
Developing	23	67	35	58	52	81
Evaluating	6	12	10	17	10	16
Revising	4	3	14	23	2	3
Using	1	18	1	2	0	0

Appendix H

Occurrences of Epistemologies in Practice Considerations For Case Study Teachers

	Occurrences					
	Natalie (N=34)		Denise (n=60)		Lydia (N=64)	
Epistemologies in Practice (EIP)	freq.	%	freq.	%	freq.	%
Mechanism 2	12	35	14	23	19	30
Evidence 2	4	12	11	18	16	25
Audience 2	3	9	6	10	13	20
Audience 1	5	15	19	32	6	9
Generality 2	1	3	0	0	4	6
Mechanism 1	0	0	0	0	4	6
Evidence 1	9	26	9	15	2	3
Generality 1	0	0	1	2	0	0

Appendix I

Co-Occurrences of Modeling Practices And EIP Considerations for Case Study Teachers

	Modeling Practices/ EIP Co-Occurrences (%)		
Description	Natalie	Denise	Lydia
Developing/ Mechanism 2 Explain how/why	17.6	16.7	29.7
Developing/ Evidence 2 Self determined	8.9	11.7	17.2
Evaluating/ Audience 2 For self	0	5	14.1
Developing/ Audience 2 For self	5.9	1.7	10.9
Developing/ Audience 1 For teacher	8.9	15	7.8
Developing/Mechanism 1 Describe	0	0	6.3
Developing/Generality 2 Related Phenomena	0	0	6.3
Developing/ Evidence 1 Teacher determined	26.5	11.7	3.1
Revising/ Audience 1 For teacher	2.9	13.3	1.5
Evaluating/ Evidence 2 Self determined	2.9	5	1.5
Revising/ Evidence 1 Teacher determined	0	0	1.5
Using/ Mechanism 2 Explain how/why	14.7	1.7	0
Using/ Generality 2 phenomena related	2.9	0	0
Evaluating/ Mechanism 2 Explain how/why	2.9	0	0
Evaluating/ Audience 1 For teacher	2.9	3.3	0
Revising/ Mechanism 2 Explain how/why	0	5	0
Revising/ Audience 2 For self	0	3.3	0
Evaluating/ Evidence 1 Teacher determined	0	3.3	0
Revising/ Evidence 2 Self determined	0	1.7	0
Developing/ Generality 1 phenomena unrelated	0	1.7	0

Appendix J

Student Work Sample Rubric Scores and Totals From Natalie's Class

Notebook Sample	Components (4)	Interactions (4)	Mechanism (4)	Total (12)	Category Overall
1	3	2	2	7	Approaching Effective
2	2	2	2	6	Approaching Effective
3	3	3	3	9	Effective
4	4	3	3	10	Effective
5	3	3	3	9	Effective
6	3	2	2	7	Approaching Effective
7	4	3	2	9	Effective
8	3	2	2	7	Approaching Effective
9	3	2	2	7	Approaching Effective
10	3	3	3	9	Effective

Appendix K

Student Work Rubric Scores and Totals From Denise's Class

Notebook Sample	Components (4)	Interactions (4)	Mechanism (4)	Total (12)	Category Overall
1	2	2	1	5	Partially Effective
2	4	4	3	11	Effective
3	3	3	3	9	Effective
4	3	3	2	8	Approaching Effective
5	3	3	3	9	Effective
6	4	3	3	10	Effective
7	1	1	1	3	Partially Effective
8	3	2	2	7	Approaching Effective
9	2	2	2	6	Approaching Effective
10	1	1	1	3	Partially Effective
11	2	2	2	6	Approaching Effective
12	3	2	2	7	Approaching Effective
13	3	3	2	8	Approaching Effective
14	3	3	3	9	Effective
15	2	2	2	6	Approaching Effective

Appendix L

Student Work Sample Rubric Scores and Totals From Lydia's Class

Notebook Sample	Components (4)	Interactions (4)	Mechanism (4)	Total (12)	Category Overall
1	3	3	3	9	Effective
2	1	1	1	3	Partially Effective
3	2	2	2	6	Partially Effective
4	2	2	2	6	Partially Effective
5	3	3	2	8	Partially Effective
6	2	2	2	6	Approaching Effective
7	3	3	3	9	Effective
8	2	1	2	5	Partially Effective
9	3	2	2	7	Approaching Effective
10	2	2	2	6	Approaching Effective
11	2	2	2	6	Approaching Effective
12	2	2	1	5	Partially Effective
13	3	3	3	9	Effective
14	2	2	2	6	Approaching Effective
15	2	2	2	6	Approaching Effective
16	3	3	3	9	Effective
17	2	1	1	4	Partially Effective
18	1	1	1	3	Partially Effective
19	3	3	3	9	Effective
20	3	3	3	9	Effective

21	2	2	2	6	Approaching Effective
22	3	2	2	8	Approaching Effective

Appendix M

Percent of Student Work Samples at Each Level on the Modeling Rubric (Penuel, 2018)

	Student Work Samples Overall Effectiveness (%)		
Rubric Category	Natalie (n=10)	Denise (n=16)	Lydia (N=22)
Partially Effective	0	20	36
Approaching Effective	50	47	36
Effective	50	33	27
Exemplary	0	0	0

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