EXAMINING TEACHER SUPPORT FOR MEANINGFUL ENGAGEMENT IN SCIENTIFIC MODELING

By

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A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

Curriculum, Instruction, and Teacher Education–Doctor of Philosophy

2018

ABSTRACT

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Recent science reform efforts in science education have called for students appropriating authentic scientific practices that resemble the intellectual work of scientists. Among scientific practices, scientific modeling has been considered particularly important as a cornerstone of science as developing, testing, and revising models as embodiment of theory lies at the heart of scientific endeavor. Despite the increasing emphasis on scientific practices in general, and scientific modeling in specific in the field of science education, engaging classrooms in the practice can be especially challenging for teachers, even for those well-intended ones who are student-centered and inquiry-oriented in their pedagogy. While there is emerging research starting to focus on the interaction of teacher and students regarding the respective goals or expectations of certain scientific practices, there is little research about what aspects of teachers' instructional practices can support students' development in the practice of scientific modeling in a meaningful way.

In this dissertation study, I seek to address this research gap. I draw on situated cognition as my theoretical lens and use Epistemologies-in-Practices as my analytical framework to investigate how teachers might support students' meaningful engagement in modeling practices and what effects that support might have on students. In particular, I present a multi-case study of two upper-elementary teachers and one middle school teacher to examine what teaching practices teachers use to support modeling. I also investigate how that interaction might have impacted the nature of students' engagement in modeling.

As such, my overall research questions are:

1. How do teachers engage students in modeling practice in a meaningful way?
2. How do teachers' instructional practices seem to influence students' modeling practices?

In all three research studies, I found that teachers' instructional practices seemed to have influenced how students engaged in the practice of modeling accordingly. Further, it is the ways in which teachers emphasize the epistemic aspects of the practice that matter. The findings suggest that how teachers prioritize, unpack, contextualize, and scaffold the epistemic goals of modeling seem to contribute to students' meaningful engagement in the modeling practices. Also, the findings also indicate that it is important for teachers to connect the epistemic aspect of the practice with other dimensions for the purpose of meaningful engagement in the practice. I conclude the dissertation with implications for teacher professional learning and the direction for future research.

This dissertation is dedicated to mom, dad, and Keying.

ACKNOWLEDGEMENTS

First of all, I want to thank my co-chairs, Christina and Joe, for making this work possible. It has been a great honor to learn from both of you. Christina, thank you for always pushing my thinking since day one. I could not have asked for a better advisor. Joe, thank you for being a great mentor and showing me how to become a better scholar.

Next, I would like to thank my committee members, Gail and David. Thank you very much for your supportive feedback. It has been a wonderful journey to think with you and push the work forward.

Also, the dissertation would not be possible without my research team members on Building Models Project and Scientific Practices Project. Tom, Consuelo, Sebastian, Dan, Lynn, Cynthia, Steve, Li, Mete, May, Josh, Leema, Brian, Abe, Stina, Lisa, and Jeannette, thank you for inspiring my thinking. I am lucky to work with you on how to support students' modeling practices over the past six years.

In addition, I would like to thank my guidance committee, Andy, Alicia, and Amelia, who encouraged me to pursue this line of research. Thank you very much for your support and I learned a lot from working with each of you.

Finally, I want to thank my study partner, Wei Liao, for spending countless hours with me in the library study room. Without you, I would probably need another semester to get this work done.

Last but not least, I want to thank my family without whom I cannot make it. Mom and dad, thank you for everything. I am who I am because of you. Keying, thank you for your 100% support. You are the best partner I can ever imagine.

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Introduction

Within the past two decades, reform efforts in science education (Duschl, Schweingruber, & Shouse, 2007; National Research Council, 1996) have increasingly called for engaging students in authentic scientific practices such as scientific modeling, argumentation, and scientific explanation that resemble the intellectual work of scientists. This “practice turn” with respect to K-12 reform efforts (Ford & Forman, 2006) recognizes the importance of engaging students in communities of practices (Wenger, 1998) where they become active participants in generating knowledge and figuring out how the natural world work the way they do. In the Next Generation Science Standards (NGSS; NGSS Lead States, 2013), scientific modeling is highlighted as one of the eight core scientific practices in which students should engage in order to make sense of the world. Among scientific practices, scientific modeling has been considered particularly important as a cornerstone of science as developing, testing, and revising models as embodiment of theory lies at the heart of scientific endeavor (Lehrer & Schauble, 2006; Nersessian, 2008; Schwarz et al., 2009). Modeling is also pedagogical useful for science learners because “models serve the purpose of being a tool for thinking with, making predictions, and making sense of experience” and it can help them “establish, extend, and refine their knowledge” (National Research Council, 2012).

Despite the increasing emphasis on scientific practices in general, and scientific modeling in specific in the field of science education, engaging classrooms in the practice can be especially challenging for teachers, even for those well-intended ones who are student-centered and inquiry-oriented in their pedagogy. This is inherently so mainly because of the fundamental difference between the community of professional science and the community of school classroom, with respect to the interactions among members, the established norms and values of practices members engage in, and the contextual features and resources available to its members (Ford & Forman, 2006). Therefore, it is essential for students to engage in scientific practices in a meaningful way that aligns with both the discipline of science and the knowledge building classroom community (Berland et al., 2016).

While there is emerging research starting to focus on the interaction of teacher and student regarding the respective goals or expectations of certain scientific practices, there is little research about what aspects of teachers' instructional practices can support students' development in the practice of scientific modeling in a meaningful way. We know that teachers play a significant role in how practices are established and pursued in classroom communities. However, much prior research focuses on teachers' understanding about the practice of modeling (van Driel & Verloop, 1999; Henzi & van Driel 2011) rather than the role of teachers in guiding the epistemic aspects of classroom and how that might impact students' engagement (See Kelly et al. 2014; Lidar et al., 2006).

In order to address the research gap, in my dissertation work, I aim to advance the field's knowledge about 1) how students develop their modeling practices over time, and 2) how teachers can support students' development in modeling practices in a meaningful way. In this study, I draw on Epistemologies-in-Practices (Berland et al., 2016) as my analytical framework and seek to investigate how teachers might support students' engagement in modeling practices in a disciplinarily and knowledge-building way and what effects that support might have on students. In particular, I present a multi-case study of two upper-elementary teachers and one middle school teacher to examine what teaching practices teachers use to support modeling. I also investigate how that interaction might have impacted the nature of students' engagement in modeling.

As such, my overall research questions are:

3. How do teachers engage students in modeling practice in a meaningful way?
4. How do teachers' instructional practices seem to influence students' modeling practices?

One presupposition of this work is that science learning is situated; knowledge does not exist in the minds of individuals, neither does it transmit from person to person. Rather, the knowing and learning is fundamentally a social practice as learners participate within certain physical, cultural, and social contexts. In other words, learning cannot be thought of being abstracted from contexts, which affords or constrains what learners come to know. It is this situated view of learning that I base my work upon. In this dissertation work, I examine not only how individual students develop their modeling practices as they participate in modeling activities, but also how members of the science classroom community co-construct their knowledge and develop their collective modeling practices through constant negotiation of meaning over time.

Summary of Study Designs

In this dissertation, I present the three research studies in the format of three stand-alone papers that are thematically connected. The three research papers aim to offer a rich account about how teachers' instructional practices can influence students' modeling practices across different learning contexts.

First, all three research papers seek to address my overarching research question: how can teachers support students' meaningful engagement in modeling practices? In research paper 1, I examine how teachers' epistemological messages could influence students' modeling practices by comparing between two elementary teachers. In research paper 2, I focus on Mrs. M from research paper 1 who was productive in supporting students in certain epistemic considerations (e.g., Nature of Account and Generality) and explore how her instructional supports with respect to the two epistemic considerations affected students' uptake on those epistemic considerations. In research paper 3, I investigate how a middle school teacher uses scaffolding strategies to support her students in developing model-based explanations. While each research paper has a unique focus on certain aspects of instructional supports, I use the same theoretical framework (e.g., situated learning theory) to theorize how students' modeling practices develop and the interaction between teacher and students within the community of science classroom. I also use the same analytical framework (e.g., Epistemologies-in-Practices) to examine both teachers' instructional practices and the nature of students' modeling practices. Thus, all three research papers aim to examine how to meaningfully engage students in modeling practices by analyzing the meaning making processes of deciding what knowledge about modeling is valued within each classroom community.

Second, I use a variety of data sources as indicators of students' modeling practices and I triangulate them to provide a richer description of the nature of students' modeling practices. The data sources include 1) in-the-moment student practices (e.g., video-recordings of student working on consensus models) in research paper 1, 2) retrospective accounts of the engagement in the practice (e.g., semi-structured interviews) in research paper 2 and paper 3, and 3) the knowledge products (e.g., diagrammatic models and computer-based models) that students have developed over the course of the unit in all three papers. In terms of teacher practice, I use video-recordings of classroom teacher talk as my primary data source across the three research papers.

Third, the underlying design principles embedded in the curriculum materials are similar across the three research papers. In both curriculum materials (the evaporation/condensation unit for research study 1 and 2, and weather unit for research study 3), students are provided with multiple opportunities to create, revise, and evaluate their models of interest to answer the driving questions and explain the anchoring phenomena. Thus, a closer look at both contexts and a careful comparison between the kind of instructional supports teachers have provided may generate useful insights that apply to both elementary and middle school classrooms.

Synopsis

This dissertation consists of three research studies written as stand-alone articles. As such the reader of the dissertation may find areas where concepts are given shorter treatment in one section but more elaborated treatment in another section. There may also be some redundancy as ideas from one section are summarized in another section. The structure of the dissertation is as follows:

In research study 1, I seek to understand how teachers' instructional practices about modeling may influence students' uptake of the modeling practices by comparing and contrasting the practices of two upper elementary teachers (Mrs. M and Mr. H) engaged in a modeling-centered instructional unit in the same school. In particular, I examine teachers' messages about modeling over the course of the unit and focus group conversations in the consensus model activities as evidence to explore the relationship between teachers' messages and student practice. The findings suggest that each teacher is sharing complex messages about the importance of various aspects of the modeling practice – in a combination of ways. In Mrs. M's case, the focus group frequently attended to the epistemic aspects of modeling as they constructed their consensus models. I argue that Mrs. M's messages about modeling practices, "explain how and why" and "different phenomena", may have influenced the students' attentions to those epistemic considerations. In comparison, Mr. H sees models as a final product that students put information into and he prioritized "finish in time" as the primary goal of the modeling activities. I argue that these messages may have guided his focus students towards including what they learned over time into the model in a procedural manner without attending much to the epistemic aspects of modeling. I conclude the paper discussing in what ways and under what circumstances should teacher support the epistemic aspects of modeling practice as well as the direction for future research.

In research study 2, I argue that students' meaningful engagement in scientific modeling is guided by the epistemic considerations that characterize some of the norms and values of science. I illustrate meaningful engagement in scientific modeling through a case study of a 5th grade elementary science teacher who implemented a six-week modeling-based unit on evaporation and condensation. I analyze video-recordings of key modeling lessons throughout the unit and semi-structured pre- and post- interviews of eight focus students who reflected on their use of models with respect to the epistemic considerations to determine how the teacher and students engaged in the practice. Analyses of the data indicate that the teacher's consistency and scaffolding of epistemic considerations around the nature and generality of the model had a large impact on students' productive modeling engagement. At the end of the unit, students in this classroom were able to construct and revise their models with the goal of "explaining how and why" and use their models to explain unfamiliar phenomena involving evaporation and condensation.

Research paper 3 presents a case study of an experienced middle school teacher and examines her scaffolding strategies towards model-based explanation and its influence on student practice. The curricular context of the study is a modeling-based unit in which students have multiple opportunities to develop two types of models (diagrammatic and computer-based) to explain the driving question, "What causes a storm?" The findings indicate that, 1) the teacher used a combination of different questioning approaches (e.g., pumping, reflective toss, constructive challenge) to provide the appropriate scaffold to help students make sense of the target phenomenon, 2) the teacher provided mostly task-oriented teacher-centered guided instruction when scaffolding students' modeling work related to the web-based modeling tool, and 3) all five focus students made progress in identifying the key relationships and/or processes that cause the target phenomenon, which may be contributed to the teacher's scaffolding moves towards those areas. The analyses also suggest that the teacher's discrepancy in her scaffolding strategies (scaffolding for sense-making vs. scaffolding for task completion) may be due to her lack of understanding of the intent of the design of the modeling tool. Implications of this study are also discussed in terms of teachers' professional development in supporting students' modeling practices when using technology-based modeling tools.

The dissertation ends with a final chapter summarizing main findings and their implications for research.

Research Study 1: Supporting Students in Meaningful Engagement in Modeling through Epistemological Messages: A Case Study of Contrasting Teaching Approaches

Recent reform efforts in science education (Duschl, Schweingruber, & Shouse, 2007; National Research Council, 1996; National Research Council, 2012) have called for students' appropriation of authentic scientific practices that exemplify the work of scientists. While the move towards disciplinary learning has gained an increasing attention in those standards documents, little is known in the field of science education in terms of how to reach the goal. Therefore, the "practice turn" (Ford & Forman, 2006) poses significant challenges for teachers who are responsible to enact the new vision of science teaching and learning in the classroom community. As Ford and Forman (2006) point out, the intrinsic differences between the professional science community and the school science community cannot be ignored when thinking about how to implement those professional practices into the learning objectives for science learning in school settings. Similarly, Berland and her colleagues (2016) argue that, student engagement in the disciplinary science learning should be meaningful to both the discipline of science and to the knowledge building classroom community. In particular, "the classroom activities are organized around a goal that the students understand and recognize as the type of goal that their classroom community tends to work towards", which enables students to "experience the goals of science as sensible within their classroom communities" (p.1088). It is this view of meaningful engagement that I base this study on.

Scientific modeling, a key scientific practice in the domain of science, involves constructing, revising, testing models that are functioned to explain and predict phenomena (Schwarz, et al., 2009). Modeling is also identified as one of the eight scientific practices in the Next Generation Science Standards (NGSS; Lead States, 2013) that students need to engage in order to make sense of the natural world. For the past few decades, scholars in the field of science education have made advancement in terms of how a model-based instruction approach can support students' science learning at different grade level in the school system (Hmelo-Silver, Liu, Gray, & Jordan, 2015; Lehrer & Schauble, 2006; Louca, Zacharia, & Constantinou, 2011; Manz, 2012; Passmore, Gouvea, & Giere, 2014; Windschitl, Thompson, & Braaten, 2008). Methodologically, much research relied on instruments such as questionnaires or clinical interviews to elicit students' view about the nature of models (Grosslight, Unger, Jay, & Smith, 1991; Treagust, Chittleborough, & Mamiala, 2002). For example, Treaguest and colleagues (2002) developed an assessment instrument called Understanding of Models in Science consisting of 27 items of abstracted statements about models to measure secondary students' understanding of scientific modeling in Australia. The results indicated that students' ideas about nature of models were inconsistent with what scientists' view about modeling. Other research focused more on what students are "doing" with their models in the classroom contexts (Pluta, Chinn, & Duncan, 2011; Schwarz et al., 2009). For instance, Schwarz and her colleagues (2009) have developed a learning progression of scientific modeling based on empirical evidence from students who were engaged in curriculum materials that had features of modeling-based instruction. In particular, they found that students moved from illustrative models to explanatory models, developed more sophisticated views about the nature of modeling, and provided more nuanced reasoning about model revisions.

Despite the increasing emphasis on scientific modeling in the community of science education, engaging classrooms in the practice can be challenging for both teachers and students. The practice is typically unfamiliar and is sometimes seen as complex as it plays an important role in bridging patterns in data with theory development and revision. At the same time, teachers are critical to the enactment of practices in classroom. Yet, there is little research on how teachers' instructional practices can support students' meaningful engagement in scientific practices in general, or scientific modeling in particular. (McNeill, 2008; McNeil & Krajcik, 2008; Osborne, Erduran, & Simon, 2004; Tabak, 2004). Of the studies that do exist, teachers' explicitness in the definitions and goals of the scientific practices, has been identified as essential for students' performances in the related practices. For example, McNeil and Krajcik (2008) found that explicitly discussing the rationale behind scientific explanation resulted in greater student learning gains. While the findings highlighted the importance of the epistemological aspect of scientific practices, it remains unclear the ways in which teachers' discussion of the rationale behind scientific explanation helps students construct scientific explanation in a meaningful way. Within the practice of scientific modeling, for example, teachers might play an important role in scaffolding students to use scientific criteria for evaluating and revising models, which has been shown to play a critical role in how modeling unfolds over time (Cheng & Brown, 2015).

The focus on the epistemic aspects of the scientific practices, and modeling practices in particular, is essential for addressing the issue of how to engage students in scientific practices in a meaningful way. Specifically, with the advancement in the sociocultural perspective, a growing number of scholars have paid attention to the moment-by-moment interaction between teacher and students in order to interpret how the purposes and goals of the practice are construed and negotiated within a classroom community. For instance, research on framing (Berland & Hammer, 2012; Russ & Luna, 2013) indicates that the kind of knowledge and practices that are valued influences how teachers and students engage in the classroom activities. The findings revealed the tension existing between teacher and students and the importance of students' epistemological understandings about their learning contexts which may in turn shape their actions. In other words, what teachers intend to accomplish in an activity can be very different from what students think they are doing during the same activity. Also, another line of research studying "practical epistemology" (Wickman & Östman, 2001) analyzes teachers' epistemological moves and how that influence students' practical epistemology for science learning (Lidar, Lundqvist, & Östman, 2006; Lundqvist, Almqvist, & Östman, 2009; Wickman, 2004). While this type of work shed light on how students should be engaged in scientific practices (e.g., explanation, argumentation, interpreting data) as the actual practice unfolds in the classroom settings, little work has been done in the area of scientific modeling to unravel how teachers can support students' modeling practices in a meaningful way.

In order to address the research gap, this study explores how teachers who engage their students in modeling do so. In particular, by comparing and contrasting the practices of two highly qualified upper elementary teachers engaged in a modeling-centered instructional unit in the same school, I seek to understand their instructional practices in modeling and what impact that might have on students' practice. There are many aspects that could be studied about instructional practice. However, our prior work indicates that teachers' epistemological messages about modeling practices might play a powerful role. As such, in this study, I focus on teachers' emphasized messages about modeling and how that may influence student practice, and if so, in what ways. In particular, I am interested in examining how the meanings of modeling practices are created and enriched by teacher over time via his/her messages about modeling and how students may take up those messages and use them to guide their own modeling work. I hypothesize that those messages communicated to students could heavily influence the way students engaged in modeling because they have been reinforced by the teacher repeatedly over time under different contexts.

For this research, I ask the following questions,

1. What messages about modeling practices do the teachers emphasize over the course of a model-based unit?
2. How might teachers' emphasized messages about modeling influence students' engagement in scientific modeling?

Conceptual Framework

Epistemology as social practice. Traditionally, Epistemology is a branch of philosophy that investigates the nature of knowledge, about how we know what we know. The study of epistemology has informed educational research in many ways with regard to how people think about knowledge generation and justification and how that affects the process of learning. Depending on the learning theories drawn upon, epistemology has been conceptualized differently by researchers for different purposes. As Kelly and his colleagues (Kelly, McDonald, & Wickman, 2012) summarized in their review, three perspectives on epistemology have been particularly influential in the study of science learning; a disciplinary perspective that values knowledge structure in the discipline of science, a personal perspective that focuses on individual's way of knowing, and a social practices perspective that puts social interactions within a community at the center stage of what counts as knowledge. While each perspective views knowledge and knowledge generation in a unique way, they are not mutually exclusive.

In this study, I adopt a social practices perspective on epistemology to examine how teacher's messages about modeling conveys to students in terms of what idea and thinking is valued in the classroom community as well as how students may take up the ways of knowing in the context of a model-based unit. A social practices perspective on epistemology derives from sociocultural learning perspective, which views knowing and learning a fundamentally social practice as learners participate within certain physical, cultural, and social contexts. In other words, I view knowledge being accomplished through social interaction within particular learning contexts. I argue that a social practices perspective of epistemology is better positioned to answer my research questions with relation to students' meaningful engagement in scientific modeling, which should be aligned to both the professional science community and classroom science community. While a disciplinary view of epistemology lends itself to account for the knowledge generation process that resembles professional scientists' practice, it does not afford us the lens to vision how to achieve that goal within the classroom contexts. Also, the personal view of epistemology was limited in addressing the interactions between teacher and students, or among students themselves. According to Wickman (2004), "epistemologies are not entities of isolated individuals but of individuals participating in socially shared practices" (p. 327). It is perceived as an integrated part of a practice. Therefore, studying epistemology as a social practice is concerned with how people make meanings in action. In the next section, I describe in more details about the analytical framework that I use for this study to investigate the meaningful-making process within the classroom community related to modeling practices.

Epistemologies-in-Practices. In this study, I use Epistemologies-in-Practice framework (Berland et al., 2016) to examine students' engagement in modeling practice across the two settings. This framework has evolved from earlier work that focused explicitly on metamodeling knowledge (e.g., Schwarz & White, 2005) and the subsequent view that metamodeling knowledge is most meaningful in combination with engaging in elements of practices (e.g., Schwarz et al., 2009). By epistemic considerations, I refer to the purposes and goals of the work in which students are engaged. An important aspect of studying engagement in practices is to understand what epistemic considerations are guiding the work and in what ways those align with the norms and values of science.

For example, developing and revising models that address the mechanism of phenomena lies at the core of the scientific endeavor; therefore, considering the degree to which an explanation is mechanistic should guide learners who are engaged in modeling practice. These epistemic considerations that frame and guide practices are called "epistemologies in practice" (EIP). Table 1 is a summary of the four epistemic considerations and some of the ways that students might address each consideration.

Table 1. Epistemic considerations in students' Epistemologies in Practice

(Table from Berland et al., 2016)

Epistemic Consideration	Range of Students' Considerations
What kind of answer should our model provide? (Nature)	• Our model should *describe* what happened. • Our model should *explain how or why* something happened. In other words, it should articulate a step-by-step mechanism.
How do we justify our model? (Justification)	• We include the information in our models that others tell us to include (so it does not need to be justified). • We construct, evaluate, and justify our models using our interpretation of the available information (e.g., data, scientific theories, personal experiences, etc).
Who will use our model and how? (Audience)	• Our model is for the teacher to evaluate our understanding. • We collaboratively construct and use our model with our audience.
How does our model relate to other scientific phenomena and ideas? (Generality)	• Specific scientific phenomena do not relate to one another, so our model should characterize the specific nature of each individual phenomenon. • Generalized science ideas have little relationship to specific experiences or phenomena so our model should not connect across these ways of thinking. • Our models are created from and should explain a range of phenomena, so our model should show these connections.

Method

Research Design. I chose a case study design (Yin, 2009) to address our research questions. A case study design is appropriate for answering these questions because our research questions are descriptive and explanatory in nature and a case study design enables us to provide rich descriptions and insightful explanations of the influence of teachers in real classroom settings. Note that in this study I only examined a particular aspect of teachers' instructional practices, the messages about modeling practices teachers communicate to students, rather than characterizing all aspects of the teachers' instruction. Through this case study, I aim to explore how to support students' meaningful engagement in scientific modeling by offering a detailed picture of both teachers' messages about scientific modeling at over the course of a model-based unit and how they might in turn influence students' modeling practices.

Context and participants. To investigate the research questions, I analyzed 5th grade classrooms taught by two teachers (Mrs. M and Mr. H) in a Midwest suburban elementary school during the 2012-2013 academic year. Prior to this implementation, Mrs. M and Mr. H worked with our research group for seven years engaging upper elementary students in scientific modeling. Both teachers have master degrees in education and they have taught elementary school science in the same school for more than 10 years.

Both teachers taught a 6 to 8-week model-based unit (Baek, et. al, 2011; Kenyon, et. al, 2008) about evaporation and condensation at the beginning of the academic year – it was their 4th time teaching the unit. In the unit, students are asked to address a driving question whether or not they would drink the liquid from a solar still. To answer this driving question, students constructed an initial diagrammatic model to explain the phenomenon, and continuously evaluated and revised their models using evidence from their empirical investigations and scientific information. The evaluation and revision processes involve discussions within small groups and whole class. In each teacher's classroom, I focused on one group students (called "focus students") and video-recorded them in group time while they are evaluating each other's models of constructing consensus models. Each group consisted of four students selected by the teacher.

Over the seven years Mrs. M has worked with us, she becomes a firm believer in modeling-based instruction and sees how modeling practices could potentially change the traditional way students learn science. As a result, when we introduced the epistemic consideration framework to her, she immediately agreed with the goals of this work as it provided a framework to work towards with students (a way to evaluate whether the models were moving in a good direction). In the unit, she simplified the epistemic consideration framework into the acronym G.A.M.E. The letter G stood for generality, A for audience, M for mechanism (Nature), and E for evidence (Justification). After she introduced the epistemic considerations of modeling practices to students, she constantly referred back to the G.A.M.E framework. Therefore G.A.M.E became a common language among teacher and student. In addition, while Mrs. M spent a fair amount of class time lecturing (providing direct instruction), she was also very aware of students' ideas and tried to engage every student into the discussion. She also kept students on task with her energetic teaching style to help attract students' attention.

Mr. H has a strong background in science content. He is popular among students because of his humorous style of teaching and he constantly relates science to students' everyday life experience while teaching science. Similar to Mrs. M, Mr. H employs a teacher-centered pedagogical approach, but elicits and responds to students' idea frequently in his teaching, though more on a one-on-one basis. Compared to Mrs. M, Mr. H has less confidence in small group discussion and once told us in the interview that it was kind of a "mystery" to him, "sometimes it went very well, but not others". While Mr. H does not prioritize modeling as much as Mrs. M does in his teaching philosophy, he tries to implement the four epistemic considerations in his teaching and he communicated with Mrs. M every day about the curriculum and how everything went over the course of the evaporation/condensation unit. Therefore, I saw a great deal of consistency regarding the sequence of activities and the amount of time they assign for each activity between the two teachers.

Data Collection.

Video-recordings. The primary data for this analysis included video-recordings of key parallel modeling lessons in which students constructed, revised and evaluated their models of evaporation or condensation. Table 2 summarizes the whole class discussions and small group discussions that we video-recorded throughout the unit in both classrooms. As shown in Table 2, we video-recorded lessons in which students engaged in model development, evaluation and revisions rather than investigations such as those in lesson 3 and lesson 4. Each lesson took about two 45-minute class periods. Each 45-minute typically consisted of both whole class discussion led by the teacher and small group discussions among students. In total, we have recorded 14 class periods for Mrs. M and 12 for Mr. H.

For this study, I only analyzed the group discussions when students developed their consensus models, which took place in lesson 6 and lesson 11. The reason for analyzing students' discussions around constructing consensus models is that students were familiar with both the content and the practice, thus providing a good indicator of their overall engagement of modeling practices.

Table 2. A summary of video-recorded data

Lesson	Overview of the lessons	Video-recorded whole class discussions	Video-recorded Small group discussions
1	• Being introduced to an anchoring phenomenon (solar still) and driving questions	√	
2	• Being introduced to an anchoring phenomenon and driving questions of evaporation • Constructing initial models of evaporation	√	
3	• Conducting empirical investigations about evaporation		
4	• Being introduced to scientific ideas and simulation about evaporation		
5	• Evaluating/revising their initial models of evaporation • Evaluate others' second models of evaporation	√	
6	• Constructing a consensus model of evaporation • Using the consensus model for other phenomena about evaporation	√	√
7	• Being introduced to an anchoring phenomenon and driving questions of condensation • Constructing initial models of condensation	√	
8	• Conducting empirical investigations about condensation		
9	• Being introduced to scientific ideas and simulation about condensation		
10	• Evaluating/revising their initial models of condensation • Evaluate others' second models of condensation	√	
11	• Constructing a consensus model of condensation • Using the consensus model for other phenomena	√	√
12	• Using the models of evaporation and condensation to answer the driving questions about the solar still phenomenon	√	

Data Analysis.

Whole class discussion. Using written transcripts of all video recordings, I analyzed Mrs. M and Mr. H's talk in each lesson in the following steps. First, marked every sentence in which the teacher talked about models or modeling. I summarized the nature of the messages communicated to students regardless of whether it was explicit or implicit. For example, if the teacher stated, "we use models to explain how and why things happen", I coded this message as telling students that their models can be used to explain phenomena. For the teacher talk that was not explicitly about models or modeling, I considered whether it was communicated in a modeling context. For example, if the teacher said, "I really want you to think about the evidence piece" we coded this as a message about what evidence supported modeling because the teacher was talking about how to evaluate models. Note that the sentence could be in the form of either a statement or a question. In fact, both teachers asked a lot of questions about modeling, which still indicates values about the process of modeling. For example, if one of the teachers asked "How do you know the water molecules in your model go up into the sky?" she was probing the student to justify the ideas in his/her model and it sent a message about modeling that it was important to justify students' models. In addition, though the teachers' messages about modeling were often related to purposes/goals of modeling, their statements could also be non-epistemic in nature. For example, if the teacher said, "you really need to finish your model by the end of the hour", it sent a message about modeling that "while constructing models there's a time limit and you need to finish it in time."

After demarking each teacher's statement in their talk and summarizing the focus of the message, I used grounded analysis (Glaser & Strauss, 1967) to identify patterns across summaries of each teacher's messages about modeling in an iterative way for each teacher. By comparing and contrasting a number of summaries, I collapsed them into a more general theme with respect to messages of modeling that was evident across lessons. For each emerging theme, I count the number of sentences with regard to that particular theme in each lesson to track the consistency and relative frequency of that message about modeling over time. Table 3 illustrates how I code teachers' messages about modeling.

Table 3. An example of coding teachers' messages about modeling

Excerpts	Context	Messages about modeling	General theme	# of sentences
Mrs. M**: I love what Samantha said, "but why?"** Jane, **can your model explain why? Can your model explain that?** Can you come up and share your model, please? Tell us what we are seeing. Jane: Well, you are seeing a can and you're seeing the water droplets going to the can and they are forming on the can. Mrs. M: **Why are they going to the can?** Jane: Because it's cold. (class period 11, Mrs. M)	Mrs. M asked one student to present her initial model of condensation to class.	It is important for students' model to explain why. It is important to figure out the "why" part of the mechanism of a specific phenomenon.	Explain how and why	3
Mrs. M: **We are going to discuss why you use scientific models is important in understanding how and why phenomena work.** (class period 1, Mrs. M)	Mrs. M introduced the purpose of model to the class.	Scientific model is used to understand how and why phenomena work.		1

Small group discussion. In terms of analyzing small group discussions among focus students, I used the EIP framework as analytical framework to describe and characterize the nature of students' engagement in modeling practices. I also denote instances where the focus group is attending to the procedural/task-orientated aspects of the modeling practices. The goal is to reveal what practical epistemologies or epistemic ideas about models the focus group was attending to, and in what ways that may be influenced by teachers' messages about modeling. As such, I compared and contrasted the small group conversations with the whole class discussion data constantly to help analyze the influence of teachers' emphasized messages about modeling.

Findings

In this section, I organize my findings around the two research questions that I seek to answer. For each teacher, I first present an overview of his/her emphasized messages about modeling over the course of the unit and illustrate with classroom examples to show what each message entails. I next focus on the two lessons where students constructed their consensus models of evaporation and condensation to explore the relationship between teachers' messages about modeling and students' modeling practices. By comparing and contrasting each teacher's guidance on constructing a consensus model and focus students' dialogue where they constructed their consensus models with peers, I analyzed how the nature of students' modeling practices may have reflected each teacher's messages about modeling.

"Remember to explain how and why!"-Mrs. M's messages. In order to answer the first research question, in Figure 1, I list Mrs. M's five most frequently uttered messages about modeling that I identified as reflected in the number of sentences throughout the unit. They are "explain how and why", "explain multiple phenomena", "give each other feedback", "provide evidence", and "help audience understand", in the order of decreasing frequency throughout the unit. There were also other messages that Mrs. M have mentioned in the unit such as "revise models to make it better", but they were not as emphasized as those listed in Figure 1. Altogether I have video-recordings of 14 class periods (CP) from Mrs. M's class and the height of each colored bar reflects how many times a particular message about modeling has been uttered by Mrs. M in each class period. I used this representation because I want to show what messages Mrs. M emphasized in each class period and how frequently they are compared to each other. By doing that, I hope to have a better sense of the complex nature of the messages students received in that particular class period as well as the consistency of the messages across the unit.

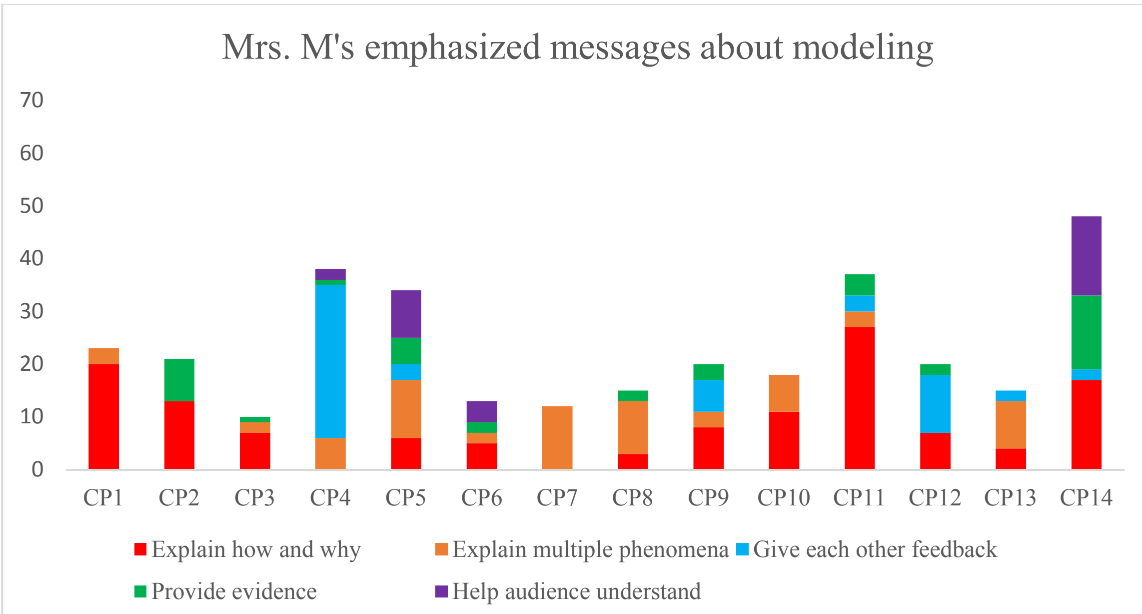

Figure 1. Mrs. M's emphasized messages about modeling practices throughout the unit

My analysis found that Mrs. M emphasized that models can "explain how and why" more than any other message she sent to her class, a total number of 128 sentences in her 14 class periods that we video-recorded. The message was also consistently emphasized across the unit, with only two class hours not mentioning it. This emphasis on the explanatory power of scientific models aligns with the Nature of Account epistemic consideration that we hope students to take up while engaged in modeling. The second most emphasized message Mrs. M communicated to students throughout the unit is "explain multiple phenomena." This message about modeling highlights the utility of models and aligns with the Generality epistemic consideration because it not only emphasizes using models to explain phenomena, but the same model should also be general enough to explain different phenomena.

Other than these two messages, Mrs. M also reiterated that “giving each other feedback” is an important part of modeling practice, and students need to not only give compliment to their peers what they like about their models, but also suggestions for improvement. In the unit, the class had an activity called “stars and wishes” where students evaluated each other’s models of evaporation. Since then, Mrs. M often used the word “stars” and “wishes” as reference to “give each other feedback” to engage students in the evaluating process of modeling practices. By asking questions related to stars and wishes about each other’s models, Mrs. M sent the message to students that giving each other feedback was an important part of modeling practices.

In addition to addressing the Nature of Account and Generality epistemic considerations, Mrs. M also emphasized the Justification and Audience epistemic considerations, though less frequently. In Figure 1, the bars of “provide evidence” and “help audience understand” represents Mrs. M’s emphasis on these two epistemic considerations. The message of “provide evidence” is often communicated to students by Mrs. M asking probing questions such as “what’s your evidence?” or “how do you know your model is correct? You need to show me evidence” when evaluating student models. In terms of the message about “help audience understand”, instead of asking questions, Mrs. M often phrased it as a reminder to students, “you need to consider your audience when revising your models” or “other people should be able to understand what’s going on when looking at your model.”

In the following section, I unpack the three most prominent messages about modeling emphasized by Mrs. M, “explain how and why”, “explain multiple phenomena”, and “give each other feedback” to show how those messages are communicated to students. In particular, I illustrate with classroom conversation excerpts to highlight how each message creates meanings in terms what types of knowledge and thinking are valued in the classroom community as well as how that message may shape students' practical epistemologies towards modeling practices.

"Explain how and why". Mrs. M emphasized "explain how and why" in various stages of modeling practices throughout the unit, and in different ways. For example, Mrs. M often emphasized that being able to "explain how and why" is one of the most important criteria evaluating a scientific model. Therefore, whenever students showed their models to the class or their group members, she often asked students to show how their models addressed "how and why". Also, Mrs. M sometimes asked specific questions related to the mechanism of evaporation or condensation to help students think about how their models can explain the phenomena. For example, for every phenomenon of evaporation or condensation that the class came up with, Mrs. M will always ask the similar "how and why" questions, "how and why does water appear on the cold can?", "How and why does dew form on the grass in the morning?" "How and why does your bathroom mirror fog up?" to reinforce this message that it was important for their models to attend to the mechanism of the phenomena. In other occasions, Mrs. M sent the message of "explain how and why" by commenting on students' work, "I went over group 3's model, and I see they were trying very hard to figure out how and why condensation happens."

Below is an excerpt that exemplifies the way in which Mrs. M sent the message to students that they need to "explain how and why." The conversation occurred in class period 11 when students have just constructed their initial model of condensation.

Mrs. M:	Let me ask, what do you think is happening? **How and why did that liquid get there?** Because some of you are saying it doesn't have to do with temperature. So **where did it come from?** What did it say in your model?
Sarah:	It got there because when the moisture in the air came in contact with the cold it does the opposite of evaporation
Mrs. M:	What do you think, guys? Now I would like a brave soul – Jack, would you please come up here and share your model with us? **I'm looking for the how**

> **and why pieces. I'm going to be asking you [the class] to help Jack tell us the how and why piece, the mechanism piece.**

At the beginning of the excerpt, Mrs. M asked the class about how and why condensation happened. Specifically, she asked students to think about "how and why" in terms of how the liquid get to the surface and where the liquid came from, with an explicit connection to student model (e.g., "what did it say in your model?). It is important to note that, by asking students do that, Mrs. M sent the message that tracing the matter in the phenomena is valued for the purpose of "explain how and why". This is essential because, in this way, the "explain how and why" message is not only related to the goal of modeling in general that students may not understand what that message has to do with their own work. Rather, it provides an accessible way for students to use the epistemic consideration to guide their own modeling work. In fact, throughout the unit, Mrs. M frequently asked students to trace matter ("where did the water come from?", "What did the water go?") and link those specific questions related to the mechanism of evaporation and condensation to epistemic consideration of Nature of Account.

Towards the end of the conversation, Mrs. M invited Jack to share his model with the class. Again, she emphasized that she was looking for the "how and why" piece and would like the class to help Jack figure out the mechanism piece. It is worth noting that, not only did Mrs. A bring up the message of "explain how and why" for the modeling sharing activity, more importantly, she prioritized "explain how and why" as the overarching goal of the activity in a way. I argue that it is how Mrs. A emphasized the message that could have significant impacts on how student view as what is valued in a particular modeling context (in this case, model sharing and evaluating activity).

"Explain multiple phenomena". Throughout the unit, Mrs. M constantly challenged her students to use their own models to explain other phenomena which were familiar to them, but not what they included in their model. In this way, students needed to think hard about what aspects of the mechanism should be included in the model so that their model can explain different phenomena.

Below is an excerpt of how Mrs. M asked students to use their own model to explain different phenomena of evaporation. The conversation happened in class period 9 when students were presenting their group consensus model of evaporation in front of the class.

Mrs. M:	Your group used open cup-closed up as your phenomenon of your model. Sue, **I'd like you to use this model to explain what happens to the dew on the ground in the morning and why it's not there when you get out.**
Sue:	So like the water would be the dew. The water molecules in contact with air molecules and they evaporated.
Mrs. M:	Can you show me where the water molecules are?
Sue:	The water molecules are here, and the air molecules are here. They are meeting the water molecules.
Mrs. M:	So I'm wondering what happens then. **What happens to those water molecules when they meet the air?**
Sue:	When they meet the air molecules, the air, if it's really hot, water will turn into water vapor really fast, but when the air molecules hit the molecules, it depends on the temperature at the time, it's gonna turn into water vapor and go out.

After the group had presented their consensus model, Mrs. M asked one group member, Sue to "use this model to explain what happens to the dew on the ground in the morning and why it's not there when you get out", which is a different phenomenon of condensation than the group used. This reflects Mrs. M's message about modeling, "use models to explain different phenomena". The student response also demonstrated that she understood what Mrs. A asked for. She first made an analogy between the two phenomena and then generalized the process of evaporation, water molecules in contact with air molecules, which is key to the epistemic consideration of Generality.

Mrs. M then followed up with two additional questions about how evaporation happens, "Can you show me where the water molecules are?" and "What happens to those water molecules when they meet the air?", which are related to the message about "explain how and why.” It is interesting that Mrs. M made connections between the two messages as they are closely related to each other. Based on our previous study (Schwarz et al., 2014), students found it necessary to figure out the mechanism first before they can use their models to explain other phenomena. By making connection between the two messages, Mrs. M created new meanings to both messages and provided students with accessible ways to think about and operationalize the message of “explain multiple phenomena”.

“Give each other feedback”. Mrs. M emphasized the importance of “give each other feedback” as a key part of model construction and how to do that early in the unit. Later in the unit, she reinforced the message by probing students to evaluate each other’s models during the presentation of consensus models. The message “give each other feedback” addressed a unique challenge that young learners often face when evaluating models; they do not know much about how to provide productive feedback to others, nor do they know much about how to handle their peers’ critiques, as they see them as different from those from teachers. For example, in class period 4, Mrs. M spent a fair amount of time setting up the norms of how to evaluate each other’s models with the activity “star and wishes”. The following excerpt happened at the beginning of that lesson when Mrs. M scaffolded the ways in which students should provide feedback to others with respect to their models and how to react to other people’s feedback.

Mrs. M:	We are going to evaluate each other’s model and we’re gonna be talking about criteria for evaluating a model. Remember I told you the story about Luka? This kid was just absolutely did not want anyone telling him what was wrong with his model. And then one day he realized, “Oh, wait a second. Tell me all the things that I did right and did wrong”. **Why would he want that?**
Jacob:	It helped him improve his model.
Mrs. M:	How do we improve our model?
Michelle:	To work on advice?
Mrs. M.	**But how do we give advice? What kind of advice?** Do you just walk to somebody’s model and say, “Go look my model. It’s better than yours”? What would you say, Sue?
Sue:	You can compliment them on one thing and give them ideas, advice, something.

Mrs. M: Correct. We call this thing "stars and wishes". **A star would be "I really like your use of molecules." A wish would be "I really wish you could distinguish between the water molecules and the air molecules". So that wish turns into something that they might do on their next model.**

In this excerpt, Mrs. M began by talking about the story of Luka to prompt students think about why it was useful to get feedback from other people. As the students got the idea that the purpose of getting feedback from others was to help improve the model, Mrs. M went on to scaffold specifically how to give advice in terms of "stars and wishes", which helped contextualized what "giving each other feedback" meant when evaluating models. In addition, Mrs. A also gave specific examples of what the stars and wishes" could look like. In particular, her examples focused on molecules, a key entity in the mechanism of evaporation and condensation. By using the example of molecules, Mrs. A also indicated that students could attend to the mechanistic aspect of the phenomena when evaluating each other's model, which is related to the "explain how and why" message. Similar to how she connected "explain multiple phenomena" with "explain how and why" in the previous example, in this case, Mrs. A combined the two messages of "give each other feedback" to "explain how and why" to emphasize that it is one valued way to give feedback to other people's models.

Influence of Mrs. M's messages about modeling. In this section, I present my analysis of the link between Mrs. M's messages about modeling and students' engagement in modeling practices in the context of the culminating modeling activity – consensus model building where a group of four students created a group model of evaporation and condensation. I first present a brief summary of the whole class discussions in which Mrs. M framed the goals of the activity in class period 7 and class period 13, where students constructed their consensus models of evaporation and condensation respectively. The purpose of presenting the synopsis of Mrs. M's instruction in those class periods is to provide readers with the context of the consensus model building activity. In the synopsis, I will highlight what messages Mrs. M foregrounded, which may shed insight on how they in turn influence the nature of student practice during the activity. Next, I present typical conversations among focus students when they are constructing consensus models to characterize the nature of student modeling practices and to identify how the teachers' messages might be taken up by students.

Constructing a consensus model of evaporation. In class period 6, Mrs. M gave students the task to construct a consensus model of evaporation in the small group of four. In the previous class periods, Mrs. M have discussed with students about the criteria of good models and how to evaluate each other's models. At the time of constructing consensus models of evaporation, students are familiar with the process of talking about the merits and limitation of other people's models by checking it with the criteria for good models, and each one of them has received feedback from their peers about their individual model of evaporation. Mrs. M began the hour by reviewing the criteria the class had agreed upon in the previous lesson and how these criteria were related to the epistemic considerations of modeling when evaluating models. After the review, Mrs. M continued to ask students to list examples of phenomena that their model can explain such as hair drying and nail polish drying. Mrs. M then emphasized that the main goal for students' consensus model is "not just be used for one of those things, but your model needs to be able to be used for all of those things". Later, Mrs. M reemphasized that the consensus model "can be used for all of the phenomena" and challenged students to use their consensus model to explain different phenomena such as "how you smell dirty feet", "how paint in Alicia's room dries", and "how your bathing suit dries" for the next day. It was evident that Mrs. M prioritized the message "explain multiple phenomena" as the primary goal of the activity, which is consistent with what we found Mrs. M did consistently over the course of the unit.

So how do Mrs. M's students take up her messages about modeling? What does Mrs. M's students' engagement in modeling look like? By analyzing Mrs. M's focus group conversations, I found that, while navigating through the process of drawing the consensus models, which is procedural and task-oriented, focus students in Mrs. M's class frequently have conversations that are epistemic in nature along the way. The four focus students were able to ask each other epistemic questions that Mrs. M emphasized and worked together on constructing a consensus model with the goal of explaining phenomena in different contexts. They also seemed to consider other classmates as the audience of their model and what they might think about the model.

At the beginning of the activity, the focus group first discussed what phenomenon they choose to focus on for their consensus model of evaporation. They agreed on only showing one open up, as opposed to a 2-cup experiment they did in the previous lesson. Then the group moved on to talk about how to show evaporation with an open cup, as shown in the excerpt below.

Sue:	What do you guys think the water level should be? At the top or the middle? [Task-oriented]
Emilia:	Are you going to show over time?
Jack:	Yes, let's write first week, and then second week.
Sue:	I also think it should not be water, but something with a smell. If it's a perfume evaporating, you can smell it because it's in the air. [Justification]
Ben:	I mean if we have water, it still explains it. [Generality]
Jack:	Just to make sure you put the molecules and stuff.
Ben:	So you think we should draw some water molecules at the bottom of the cup to show it evaporated into the air? [Nature]
Jack:	Well, we should at least have some water at the bottom of the cup.
Ben:	Should we have a week 3 and week 4? So they really get the idea. [Audience]
Sue:	But then you need more space for writing. [Task-oriented]
Emilia:	You can just draw a line so it doesn't take up all the room where you can write.
Sue:	Now do we want to add the molecules?
Ben:	Yes, I think so. So for somebody, they might think they were just going straight up, so make sure our molecules are going different directions. [Audience]
Emilia:	Yes, you should have a circle with an arrow. You don't have to make them that close together, remember one of the simulations, they spread out? [Justification]
Sue:	Yep.

This excerpt shows how Mrs. M's students worked on explaining how and why evaporation happened. At the beginning of the conversation, Sue asked the group where the water level should be so that their model can show change over time. Next Sue brought up a good point about showing "something with a smell" evaporation so that you have evidence that it goes into the air. However, this idea was not taken up by the group, though other group members gave their reasons. Ben said "using water still explains it", which indicates that his criteria of a good model is to explain phenomena and he sees both "something with a smell" and water would work. Jack added that, "just to make sure you put the molecules and stuff", indicating that he saw the key to explaining evaporation was to "put molecules and stuff", though he was not explicit about what he meant by "molecules and stuff." Maybe to clarify what Jack said, Ben asked if he meant "water molecules at the bottom evaporating into the air", which was related to the mechanism of evaporation. Then Ben suggested show two additional weeks so that "people really get the idea." At first, Sue was reluctant because she thought that meant less space for writing, which indicates that at that moment she was focusing more on the procedural aspects of the task. Towards the end of the conversation, when the group were adding molecules to their models, both Ben and Emilia referred to the simulation they saw in the previous lessons, molecules going different directions and spread out in the air. They used that as evidence to put into their model so that they could explain how evaporation happened. To sum up, even though the focus group were doing many procedural things with respect to the task of constructing a model of evaporation such as where to draw the line, how much space to leave out, what to label, etc, along the way the discussed the why they make the model in a certain way and those conversations are epistemic in nature and they serve the overall goal of explaining the phenomenon-water evaporates when left out in an open space.

After finishing the model, the focus group continued to talk about their model and they mainly focused on the epistemic aspects of modeling practices since they already had a final product done. The excerpt below characterizes the nature of the conversation the four focus students are engaged in.

Sue:	We have to explain it didn't seep through the cup, if someone asked that. [Justification] Our model cannot explain that. [Nature of Account]
Jack:	Well does this explain how paint dries? [Generality]
Sue:	Yes. The water molecules are leaving. This explains how nail polish dries. It also explains how you can smell stuff because molecules go away carrying scent.
Emilia:	How about label? Did you label it? Like an open cup. [Task-oriented]
Ben:	We know it's an open cup. If you shaded it in, it's obviously a closed cup. I bet if show it to somebody, they would know this is uncovered and this is covered [Audience]

Emilia: I'm just saying, it's good to label, just, just saying. [Task-oriented]

At the beginning of the conversation, Sue thought about an alternative idea about why water disappeared over time (water seeping through the cup instead of going to the air) and she proposed to justify in the consensus model why water molecules going to the air is correct, which relates to the justification epistemic consideration. Then Jack asked the question, "Well, does this explain how paint dries?" Jack's question was very important for answering our second research question because it reflected Mrs. M's messages about modeling, "using models to explain different phenomena". In the previous excerpt, Mrs. M asked one student to apply their model to explain why dew on the grass disappeared. Here, Jack was basically doing the same thing, asking his peer if their consensus model is general enough to explain other phenomena such as paint drying. We argue that it is highly likely that Mrs. M's message about modeling influence the kind of question Jack posed to the rest of the group.

Next Sue brought up two other phenomena, nail polish drying and smell traveling, and confirmed that their consensus model can explain all these phenomena because the mechanism is the same, "water molecules leaving" or "molecules going away". The recognition of the similarities among those phenomena and their consensus model could be used to explain all those phenomena strongly suggested the influence of Mrs. M's message about modeling, "explain multiple phenomena". As shown in this excerpt, this group of focus students asked each other epistemic questions while creating the consensus model and their conversation is epistemic in nature.

Constructing a consensus model of condensation. In class period 11, Mrs. M asked her students to construct a consensus model of condensation in small group and the way she framed the activity was not much different from that in class period 7 where students constructed their consensus model of evaporation. She again prioritized that models need to be general so that they can be used to explain different phenomena. The ensuing whole class conversation consisted of Mrs. M's asking students to list phenomena of condensation that students are familiar with in their everyday life and pushing them to think about how they can build a consensus model that can explain all the phenomena of condensation. She concluded the instruction with the comment that "remember, the phenomena that we list are going to be things that you have to explain with your model".

Similar to what I found in class period 7, the nature of the focus group's conversation when constructing the consensus model of condensation is epistemic in nature. The group seemed to be focused more on the "explain how and why" when they were constructing the consensus model of condensation. The following conversation happened during the middle of their discussion and showed how the group were trying to come up with an "explanation" for their model. Note here the word "explanation" does not necessarily mean a scientific explanation. An "explanation" of a model usually means the written text part of a diagrammatical model in the context of Mrs. M's class.

Ben: Guys, we can add little things later, but we need to put the explanation. [Task-oriented]

Sue: What are we putting into the explanation? Water molecules in the air are moving fast and freely? [Nature] Do any of you have any ideas?
Emilia: How did the fog or condensation get there? [Nature]
Sue: The water molecules that form water vapor are moving around when they come closer to a cold can they slow down and they clump together. [Nature]
Emilia: Yeah, they come together on the object. [Nature]
Sue: Yeah, and another comes, and another comes, and another comes…[Nature]
Emilia: Ben, write that down. [Task-oriented]
Ben: Done.
Sue: Did anyone have some other idea?
Jack: Then they formed water droplets. [Nature]
Sue: Yeah, they formed water droplets, which make the fog that we see. [Nature]

The excerpt started with Ben prompting his peers to do the "explanation" part of their consensus model, which is coded as a procedural/task-oriented move. Note how Emilia was trying to push the group to think beyond the "water molecules in the air moving fast and freely", which is itself a mechanistic piece of condensation. Her question "how did the fog or condensation get there" suggested the kind of answer she thought the consensus model should provide. This is essentially what we hope our students to consider when they were engaged in modeling practices. I argue that this may be influenced by Mrs. M's message about modeling, "explain how and why".

Towards the end of the conversation, when Sue asked if anyone had anything to add to the explanation, Ben added "they formed water droplets", which is another key piece of the mechanism because it linked the invisible molecular movement to something observable, the water droplet. Then Sue agreed and made it explicit that it was "what we see". In this excerpt, we see how the focus students engaged in the epistemic aspect of modeling practices, Nature of Account epistemic consideration in particular, even though the conversation started with a procedural move, trying to figure out what to put into the written text box next to their diagrammatical consensus model. It is also interesting to note that, this time the focus group did not attempt to address the message of "explain multiple phenomena" as they did in class period 7, which may be due to the time constraint. It is also likely that the focus group recognized that they needed to agree upon the “how and why” piece first before applying their models to explain different phenomena, which was how Mrs. M framed the goal of the activity.

“Everything you learned should be in your model somewhere!”-Mr. H’s messages. In Figure 2, I listed Mr. H’s top 5 messages about modeling practices identified over the course of the unit. They are “finish in time”, “explain how and why”, “explain multiple phenomena”, “work with others in harmony”, and “put information into the model”, in the order of decreasing frequency throughout the unit. Compared to Mrs. M, Mr. H emphasized two messages that are identical to Mrs. M, “explain how and why” and “explain multiple phenomena”, though in a less consistent and frequent manner. For example, in class period 1 and lesson 8 when Mr. H introduced the anchoring phenomena of evaporation and condensation, he asked many questions with respect to how and why things happened and highlighted the importance of figuring out the mechanism of evaporation and condensation when building models. In class period 6, 7 and 11 when students were constructing consensus models, Mr. H also pushed students to think how their models could be used to “explain multiple phenomena”. However, Mr. H did not prioritize it as the primary goal of constructing consensus models, but as one of the goals of consensus models (more on this in the next section). Apart from the two messages that shared with Mrs. M, Mr. H has three unique messages that she emphasized across the unit, “finish in time”, “work with others in harmony”, and “put information into the model”. In the following section, I illustrate each message with examples to show how Mr. H communicated those messages in his classroom as well as how that might have an influence on students’ practical epistemology towards modeling practices.

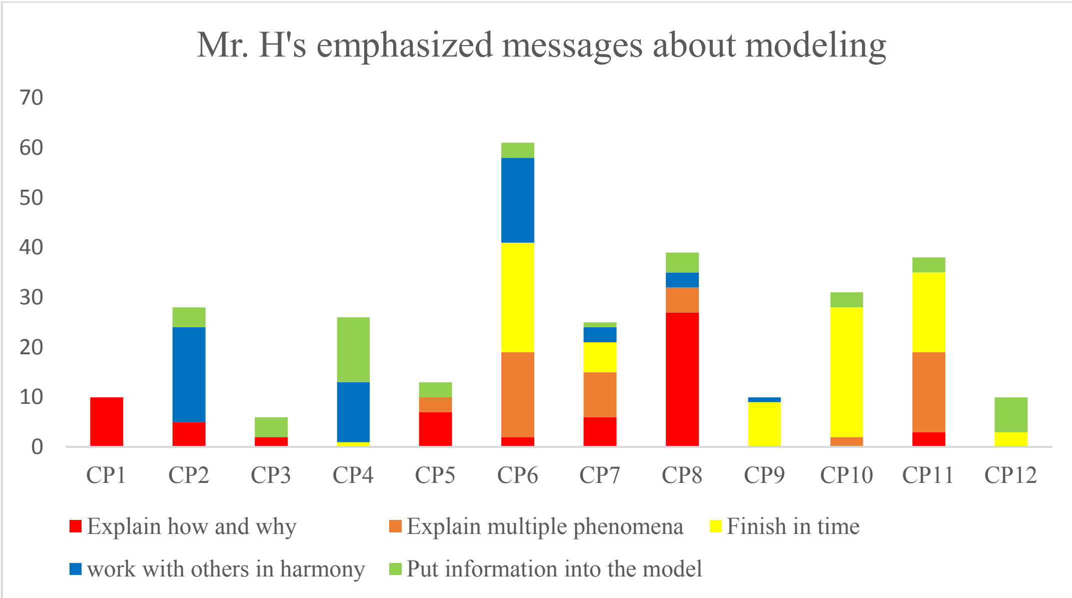

Figure 2. Mr. H's emphasized messages about modeling practices throughout the unit

"Finish in time". Of all the messages about modeling, "finish in time" was Mr. H's most predominant one that emerged since class period 7. The message is about finish constructing models in an expected time frame as required by the teacher. While it seems common that a teacher worries about finishing curriculum in a certain time frame towards the end of the unit, the way Mr. H sent the message of "finish in time" was unique and might have profound impacts on students' modeling practices. Not only did Mr. H being explicit about finishing in time as one primary goal of modeling activities, he also made particular instructions for students with respect to what they should do in the modeling activities given the time limit. In lesson 5, Mr. H started to worry about the amount of time his students spent on revising, evaluating, and constructing consensus models. Therefore, one message about modeling Mr. H communicated to the class, together with other messages, was to "finish in time". Sometimes, he was very explicit about that was his goal, as he told the class in class period 11, "My goal for this short hour is, you pretty much finish this up". Furthermore, Mr. H's message about "finish in time" is often in conflict of other epistemic messages about modeling that takes time for students to attend to in a productive way. This is exemplified by the following excerpt,

> "We have 6 minutes left for the rest of this hour. It sounds to me like you guys have a lot more work to do, unfortunately. All you are going to need to do is this. I need you, it is the last 6 minutes, you gotta kind of move forward. You need to take whatever ideas you got, and you make the best consensus model you can make out of the that so far. We got to get these models drawn up so you guys have a final copy in your packet tomorrow morning. I'm gonna give you the first 10 minutes to do that. So finish up please".

In the quote, Mr. H asked students to "take whatever ideas you got" and "get these models drawn up". It communicated to the students that finishing the model in time was more valued in Mr. H's classroom than any other goals at that particular moment. While it is understandable that teachers concerned with the time constraints to cover the materials, I argue that it was the degree to which Mr. H emphasized the message that may in turn influence students' practices.

"Work with others in harmony". As students were evaluating each other's models in lesson 5 and constructing consensus models within small group in lesson 6, Mr. H started to emphasize that "work with others in harmony" is the primary goal for those modeling activities involving working with peers. Unlike Mrs. M who supported students with strategies of how to provide and deal with critique and disagreement from peers, Mr. H tried to avoid potential conflicts among students. Mr. H was explicit about rules in terms of student interactions among peers (e.g. not hurting other people's feeling). He sent the message to students that caring about other people's feelings and "making comments positive" are the primary goals of evaluating each other's models because some of the students are "freaking out". In addition, he often mentioned "compromise" as an inevitable step students needed to take when working with peers and discouraged students from disagreeing with each other. For example, when asking students to construct consensus model, he mentioned that "we're going to have to compromise. Jack is going to have to give up a little bit. I'm going to have to give up a little bit and we're going to have to meet halfway and agree that what we combine together is going to be a good thing. You guys are going to do that in your groups as well". As such, Mr. H prioritized students being respectful to each other in order to create a safe environment to critically evaluating other students' model and persuading others with evidence, which are the norms and practices in the discipline of science.

"Put information into the model". This message reflects Mr. H's view about models being an end product that shows what students have learned. To Mr. H, model is something that he can use to check student understanding of the topic. In other words, while Mrs. M value students' use of model to explain phenomena, Mr. H cares about what is in students' model. The following excerpt illustrates how "put information into the model" was communicated to Mr. H's students. After students have conducted experiments and explored different computer simulations about particle movement, Mr. H asked his students to revise their initial model of evaporation in light of the new evidence they collected.

Mr. H:	The past 4 days, **we've been going through and looking at lots of information concerning models.** We've done experiments that have to do with evaporation. We've looked at scientific ideas that have to do with evaporation. We've looked at a ton of computer simulations that have to do with evaporation. There's a lot of information there, and we've said that it was all important. **We have to have it where?** [Put information into the model]
John:	In our model?
Mr. H:	**We have to have it in our model.** Our initial models, we made them with our own ideas. Now we've learned something, we have to really consider, "hey, is it enough?" If not, what are we going to change it to make it better? **We said that all this information we've been gathering, should be in our models somewhere. So you are going to be tuning in what types of things to be put into your model.** [Put information into the model]

In this excerpt, Mr. H indicated that students should include important things such as scientific ideas and computer simulations into their model when revising it. According to Mr. H, the purpose of modeling is to show understanding of the new knowledge students gained in relation to the topic (evaporation), which is different from Mrs. M's goal, explaining phenomena. This excerpt shows that Mr. H views models as a final product filled with students' newly obtained knowledge and to some extent models become a form of assessment upon which students could show their learning.

Influence of Mr. H's messages about modeling. In this section, I present my analysis of the link between Mr. H's messages about modeling and students' engagement in modeling practices, similar to the way I presented with the case of Mrs. M.

Constructing a consensus model of evaporation. In class period 6, Mr. H asked his students to construct a consensus models in small group. Below is the excerpt at the beginning of the class period demonstrating how Mr. H framed the activity. In particular, excerpt where Mr. H talked about using the majority rule as the criteria to resolve disagreement among group members for the sake of time.

> "Unfortunately, we don't have a lot of time so we really are going to have to work on majority rules. Even though you may disagree with something and you would want to be brilliant enough to work through that and find a good compromise, sometimes we might just have to say, 'Hey, two out of three, the majority wins. We're going to have to move on and use this idea'. Okay? We can't sit here and work through every little issue. So if the group feels strong enough that, 'You know what? We really do feel like this is the way we want to head'. Then that person has to be willing to understand that it's the majority rules and you have to move on. Okay? No hard feelings, though."

Mr. H said upfront "unfortunately we don't have a lot of time" and decided to use majority rule as the criteria to resolve disagreement among group members for the sake of time. In other words, he prioritized finishing in time to students' scientific discussion, which sent a strong message to students that time is very important in doing modeling activities. In addition, towards the end of the quote, Mr. H's highlighted the message about "work with others in harmony", that students have to make compromise and give up their ideas because of the "majority rules" and to move on with the group. The message of "work with others in harmony" also implicitly indicates that arguing with peers, no matter with good reasons or not, is not valued in Mr. H's classroom.

So how do Mr. H's students engage in the modeling practices as they create their consensus models? Compared to students in Mrs. M's class, students in Mr. H's class tend to be mainly focused on the task of drawing a model itself while engaging in modeling practices. The nature of the focus group conversation is task-oriented most of the time. Occasionally some group members attended to "how and why" as they were trying to figure out the mechanism of evaporation or condensation in both activities, but often times those conversations are not taken up by the group in a sustainable way.

The following excerpt happened at the beginning of the group conversation when Mr. H checked on the focus group how started to make a consensus model of evaporation.

Mr. H: Who's the artist?
Mary: I am.
Mr. H: Okay, as you guys are talking about the things you think you need for your model, **Mary, you need to be copying down-** [Task-oriented]
Sam: Wait, can we vote for ourselves?
Mr. H: Vote for what?
Sam: We're trying to figure out whose model to do.
Mr. H: I'm not talking to take your revised model. I'm talking now that you guys have done your revised model, what do you want to bring together for the consensus model? **So what things do you think you need in this consensus model?** [Put information into the model]
Mary: A thermometer.
Mr. H: So this is how it's going to work. **You bring out ideas and you've got to agree on it. Is a thermometer something you guys agree on?** [Work with others in harmony]
Ted: Yeah.
Mr. H: Okay, so who's the GAMEr? So does that fit with GAME? It does? Okay, what's another idea?
Mary: Well, I think we should have a timeline.
Mr. H: A timeline? Listen guys, she's the one throwing out all the ideas right now. She just said there needs to be a timeline. What do you guys think?
Group: Yeah.
Mr. H: Are you going to say yes to everything?
Group: No.
Mr. H: OK, see how you're doing it? **Make a list and you're going to work on showing that model.**

At the beginning of the conversation, Mr. H asked who the artist was, and made Mary was the one who needed to copy down the consensus model. Then Sam asked whether he could vote for himself. Mr. H was confused and then realized that the group wanted to pick one group member's model as the consensus model and they would probably use the "majority rule" to determine whose model they were going to use. Sam's question about voting illustrated how the "majority rule" were taken up by the students. After explaining to the group that they were not going to pick one model, but bring together all people's idea, Mr. H demonstrated to the group how "it's going to work", "bring out ideas" and "agree on them". While Mr. H asked the group whether Mary's proposal fits with the epistemic criteria of models, he did not spend time further ask about how it fit the criteria. Instead, he moved on to ask the group to think about another idea and make a list of what they want to include in the consensus model. As shown in the short conversation, Mr. H basically showed the group how he expected them to do while making a consensus model. Pick some components, agree on them among group and then put it into the model in a timely manner. By not probing further how the model fits with G.A.M.E criteria, he sent a message to the students that even though he mentioned it was important to check if the model meets the criteria, what the teacher really looked for was the procedure he just demonstrated.

The following excerpt occurred when Mr. H left the group and it was evident how big an influence Mr. H's messages about modeling on the nature of students' conversation around consensus model construction. It highlights how the group tried to figure out what to put into their consensus model of evaporation.

Jane: Okay, Sam, you pick something. [Task-oriented]
Sam: Humidity Rising.
Ted: Oh, we could put a heater in there. [Task-oriented]
Mary: Yeah, a heather. Wait, there's a heat lamp in Jane's model. We could use the heat lamp. [Task-oriented]

Ted: Well, we can do one bottle without a heater and one with a heater and see it…[Task-oriented]
Jane: No, you can't just talk, you're talking too much. Sam barely talks.
Sam: I just talked. I said we need to start drawing. [Task-oriented]
Jane: No! Sam, say something about the model.
Mary: Guys, we're not going to finish it today, just so you know. [Task-oriented]

At the beginning of this conversation, Jane asked Sam to "pick something" to include in the consensus model. After Sam picked "humidity rising" as one component of their consensus model, another student suggested a heater. What they were trying to do here is that each group member came up with something to put into the consensus model, which was exactly how Mr. H demonstrated in the previous excerpt. We would argue that this approach to modeling to some extent reflects Mr. H's message about modeling, putting information into the model and seeing it as an end product.

Towards the end of the conversation, while Jane wanted Sam to "say something about the model", Sam was eager to "start drawing", and Mary commented, "we are not going to finish it today". As is evident from the last three lines, Both Sam and Mary were worried about finishing it in time. They were no longer interested in negotiating what should be put into their consensus model and proposed to draw whatever they got thus far. I argue that this recognition of time might be influenced by Mr. H's goal of the activity, "finish in time".

Constructing a consensus model of condensation. Similarly, in class period 11, where students are supposed to construct their consensus model of condensation, Mr. H reemphasized the majority rule in order to save time. He again emphasized the time pressure and it was important to get the model done by the end of class period.

In terms of student practice, similar to lesson 6, Mr. H's focus students focused more on the procedural aspect of the task of constructing consensus models of condensation. The following excerpt exemplifies the kind of discussion this group of focus students had when constructing their consensus model.

Sam:	Mary, what are we supposed to write about?
Mary:	We are writing what you want in the consensus model. Write down your ideas, what you think should be in the consensus model.
	…
Ted:	OK, let's stop and share ideas.
Jane:	I have four things written down.
Mary:	I have one, two, three, four, five.
Ted:	It needs to show molecules, and then it needs to show temperature. [Task-oriented]
Mary:	Wait, why does it have to show temperature?
Ted:	It needs to show how condensation works. [Nature]
Jane:	Mine says it needs to have water droplets and timeline, and a thermometer. [Task-oriented]
Sam:	Mine says it should have condensation, and it should have labels. It needs to show water vapors, and it needs to show heat energy. [Task-oriented]

At the beginning of the excerpt, Mary told Sam and the group what they were supposed to do, writing down what they think should be in the consensus model. It was interesting to see when the group started to share their ideas, they focused on how many pieces each group member had come up with and what are those pieces. We argue that this may have much to do with Mr. H's messages of modeling, "put information into the model". With the goal of modeling being putting information students have gathered or experienced in class, it was no surprise to see the focus students spent most of their time showing the pieces of information without making connections among those pieces in service for other purposes such as explaining phenomena.

However, there was one instance in the middle of the conversation when Ted indicated that putting temperature in their consensus model could "show how condensation works". Unfortunately, Ted's idea of "show how condensation works" was a different goal that was not emphasized enough in Mr. H's class, thus had not been taken up by his peers. Instead, Jane was eager to move on to share with the group what she came up with. The ensuing conversation mostly revolves around what each focus student thought should be put into the model without much reasoning. Again, I argue that the Mr. H's message about modeling predetermined the structure of the activities of constructing consensus models and in turn directed students away from other purposes such as trying to figure out the mechanism of the phenomena.

Discussion

Overall, the findings suggest that each teacher is sharing complex messages about the importance of various aspects of the modeling practice – in a combination of ways. This emphasis ranges from procedural to epistemic and those messages are then reflected in students work. In Mrs. M's case, I found that the focus group frequently attended to the epistemic aspects of modeling as they constructed their consensus models. I argue that Mrs. M's messages about modeling practices, "explain how and why" and "different phenomena", may have impacted her students focus on the epistemic nature of modeling. Her emphasis on "give each other feedback" and the scaffoldings she provided in terms of how to evaluate each others' models also seemed to be crucial for her students to comfortably ask questions and give suggestions to their peers in a productive way. In comparison, while Mr. H also emphasized "explain how and why" and "explain multiple phenomena", he did it in a less consistent and frequent way. In addition, Mr. H sees models as a final product that students put information into and he prioritized "finish in time" as the primary goal of the modeling activities since class period 6. In terms of students evaluating each other's model, Mr. H's message about "work with others in harmony" potentially discourages students from giving critical feedback and in some way encourages students to compromise so that other don't "feel bad". These three messages may have guided his focus students towards including what they learned over time into the model in a procedural manner without attending much to the epistemic aspects of modeling that we value. In this section, I analyze and unpack possible mechanism that may account for the differences in students' modeling practices we see between Mrs. M and Mr. H's classes.

Foregrounding epistemic considerations. While previous studies (Christodoulou & Osborne, 2014; McNeil & Krajcik, 2008; Osborne, Erduran, & Simon, 2004) suggest that it is important for teachers to explicitly talk about the goals or definition of the scientific practices that students are engaged in, our findings further indicate that explicitness simply may not be enough. The way teachers talk about the goals of the practices under what circumstances also matters. In other words, saying "models are supposed to explain and predict phenomena" sporadically during the instruction may not result in epistemic nature of students' modeling practices, as illustrated by Mr. H's case. Our findings suggest that in order for students to engage in modeling practices in a meaningful way, teachers should foreground certain epistemic considerations as the primary goals of modeling activities and emphasize those epistemic considerations consistently in various modeling activities.

While our statistical analysis did not differentiate whether the teachers foregrounded or backgrounded certain messages, from the excerpts it was clear that Mrs. M strongly advocated "explain how and why" and "explain multiple phenomena" as the primary goals of all the modeling activities that students are engaged in. In contrast, though Mr. H also mentioned "explain how and why" and "explain multiple phenomena", those messages were not emphasized as much as Mrs. M's. I believe the extent to which teachers emphasize the epistemic goals of modeling may influence how much students take up those epistemic considerations in their own practices.

Another difference we see in how both teachers talked about "explain how and why" and "explain multiple phenomena" is the context under which they emphasized. For Mrs. M, she talked about "explain how and why" and/or "explain multiple" in all the 14 class periods we have video-recorded and most of them account for at least 1/3 of the total messages. In other words, whenever students were constructing, revising, evaluating, or presenting their models, Mrs. M always emphasized the importance of "explain how and why" and/or "explain multiple phenomena". On the contrary, Mr. H talked about "explain how and why" extensively in class period 1 and 8 when he introduced the anchoring phenomena of evaporation and condensation and emphasized "explain multiple phenomena" in class period 6 and 7 when students were constructing consensus models of evaporation, but not so much beyond that. In class period 5 where students were evaluating each other's model of evaporation and in class period 10 and 11 where students were constructing their consensus model of condensation, Mr. H almost did not mention "explain how and why" and "explain multiple phenomena" at all. I argue that because different modeling activities call for different skills and discourse patterns from students, students may see them as distinct activities that are not related to each other. Therefore, it is not uncommon for students to focus on the messages that teachers emphasized in the particular activity, as opposed to carry those epistemic goals of modeling from one activity to another. By emphasizing the epistemic considerations of modeling practices across different activities (constructing, revising, evaluating, presenting models), teachers help students to see the coherence between activities as well as the underlying goals that could help them engage in those activities in a meaningful way.

Epistemological messages vs. non-epistemological messages. Further, the findings also indicate that not only does it help should teachers foreground the epistemic goals of modeling practices consistently, they also need to balance those goals with other non-epistemological goals they have in the context of school settings. Here the term "epistemological" or "epistemic" refers to the ways of knowing that is aligned with how knowledge is constructed in the discipline of science. The findings suggest that, even though Mr. H emphasized scientific models being able to “explain how and why” when he asked students to construct a consensus model of evaporation, this message was counteracted by other messages he sent to students such as “finish in time” or “put information into the model.” It is understandable that when receiving mixed messages, students take up those messages that are easy to operationalize because “trying to figure out how and why” things happen in different phenomena is much harder than putting what they already know into the model. Other times, students may simply be distracted by those mixed messages and pick up the ones that they remember.

In addition, sometimes the non-epistemological messages constrained by school settings could be potentially contradictory to the epistemology of modeling practices. For instance, Mrs. H’s message about “work with other in harmony”, which encourages students to agree or compromise with each other, hinders students’ opportunities to test, negotiate their ideas with their peers in a critical way using evidence and ideas about what best forms of models might be. Therefore, balancing those different goals is crucial for supporting students in meaningful engagement in modeling practices.

Teachers’ views about modeling and science learning. While we acknowledge that teachers have many constraints such as finishing curriculum materials in a certain time framework, we need to ask further why Mrs. M has this concern, while Mrs. M doesn’t, even though they are in the same school. From the analysis above, we have some indication of some different views of what are “models” and what are “modeling” all about. While Mr. H might view models as an end product that students should fill with scientifically correct information, Mrs. M seems to emphasize the use of models instead. This finding is consistent with the differentiation Passmore (2013) made in her work, “model of” vs. “model for”. According to Passmore, “model of” defines model primarily by their ability to represent what we know about the world while “model for” defines models by their use as reasoning tools.

In addition, Mr. H’s seems to exhibit a view of modeling that aligns with a more traditional view of science learning in general, that student learn science individually for the purpose of acquiring correct scientific knowledge. This is consistent with previous studies in the field of science education investigating how teachers’ epistemological beliefs about science are related to student learning (Tsai, 2007; Yerrick, Pederson, & Arnasson, 1998). Mr. H’s traditional view of science learning may determine what he values as student learning. For example, because Mr. H was looking for the correct scientific ideas in students’ consensus models, his instruction would direct his students to make a list of what should be included in the consensus model so that he can assess them later. This view of science learning may also account for other non-epistemological messages he emphasized such as “finish in time”. It is possible that because Mr. H does not see the value in arguing with peers to figure out collectively how to construct a group model, he does not want to waste valuable class time on it.

Direction for future research

This study contributes to the field by providing empirical evidence in terms of how emphasizing the epistemic aspects of modeling practices can help students’ engagement in a meaningful way. In particular, I argue that it is the ways in which and under what circumstances teacher emphasizes those epistemic ideas about modeling that may have a profound influence on student practice. In terms of direction for future research, I present three areas that need to be further explored based on the findings of this study.

1) The findings suggest that Mrs. M's messages about "explain how and why" and "explain were productive because she prioritized those messages as the primary goals for modeling and unpacked what it means for each message in different modeling contexts in a way that is accessible to students. However, as this study is not mainly focusing on the scaffolding process of how Mrs. M did so, more work needs to be done to further investigate the mechanism of the interaction between teacher and students that help explain how students advance their thinking and practice in with respect to using those epistemic considerations to guide their modeling work.
2) While this study focuses on the epistemic aspect of modeling practices, the analysis also indicates that how teacher set up the norms of the practice (e.g., how to critique each other's model) is equally important. In fact, the social and epistemic dimensions (Duschl, 2008; Stroupe, 2015) of the practice are intertwined and in service to each other. Therefore, it is critical to examine how teacher help students develop those various aspects of modeling practice over time. A closer investigation into how these dimensions (e.g., conceptual, epistemic, social, and material) interact with each other as students participate in the practices can shed light on our understandings towards student learning in science-as-practice within classroom settings.
3) Methodologically, one of the strengths of this study is that it examines both teacher practice and student practice in action rather than relying solely on instruments such as survey and clinical interviews to do so retrospectively. This inquiry mode aligns well with my theoretical lens that learning takes place through the processes of knowledge building and meaning making from all participants (e.g., teacher and students) within a social historical context (e.g., classroom community). However, this line of research can

also benefit from looking at of teacher and students' interpretation of their own actions to triangulate and further unpack how they negotiate and reach a consensus on what knowledge about modeling is valued in the classroom community.

Research Study 2: "Explain How and Why!": Teaching with Epistemic Considerations to Foster Students' Meaningful Engagement in Scientific Modeling

Within the past two decades, reform efforts in science education (Duschl, Schweingruber, & Shouse, 2007; National Research Council, 1996) have increasingly called for engaging students in authentic scientific practices such as scientific modeling, argumentation, and scientific explanation that resemble the intellectual work of scientists. This "practice turn" with respect to K-12 reform efforts (Ford & Forman, 2006) recognizes the importance of engaging students in communities of practices (Wenger, 1998) where they become active participants in generating knowledge and figuring out how the natural world work the way they do. In the recent release of Next Generation Science Standards (NGSS; NGSS Lead States, 2013), scientific modeling is highlighted as one of the eight core scientific practices in which students should engage in order to make sense of the world. Among scientific practices, scientific modeling has been considered particularly important as a cornerstone of science as developing, testing, and revising models as embodiment of theory lies at the heart of scientific endeavor (Lehrer & Schauble, 2006; Nersessian, 2008; Schwarz et al., 2009). Modeling is also pedagogical useful for science learners because "models serve the purpose of being a tool for thinking with, making predictions, and making sense of experience" and it can help them "establish, extend, and refine their knowledge" (National Research Council, 2012).

Despite the increasing emphasis on scientific modeling in science education, some research indicates that modeling and other reform-based practices, can become proceduralized (Baek et al., 2011; Cohen & Ball, 2001). For example, students might create a model of a cell made out of different shapes of pasta, but never use that model to explain or predict cell function. Proceduralizing or essentializing any practice into components without considering their purpose in a classroom learning community engaged in knowledge production and revision renders that practice meaningless. By meaningful, I refer to students' productive disciplinary engagement (Engle & Conant, 2002) that is meaningful to the discipline of science and to the classroom community's knowledge building goals. In particular, teachers should "hold students accountable to others and to shared disciplinary norms" (Engle & Conant, 2002) and create a learning environment where students are active epistemic agents (Stroupe, 2014) to construct and evaluate knowledge collectively. With respect to "shared disciplinary norms," some of our prior work (e.g., Berland et al., 2016) identified several epistemic considerations relevant to the classroom community and the discipline of science that can be used for knowledge building in classrooms. I posit that using epistemic considerations to guide knowledge building and sense-making can help build meaningful engagement in scientific practices.

While some research has emphasized meaningful engagement in modeling (e.g., Lehrer & Schauble, 2015; Manz, 2015; Schwarz, Passmore & Reiser, 2017), it continues to be important to better understand how teachers can support students' engagement in scientific modeling practices. Critical as teachers are to the enactment of the practice in classroom, they are often unfamiliar with models and what modeling practices entail (e.g., Danusso et al., 2010; Justi & Gilbert, 2003; van Driel & Verloop, 1999). Further, teachers who think of models as repositories of information (e.g.,"models of" approach, Gouvea and Passmore, 2017) focus on the representational nature of models, as opposed to attending to how models are developed and for what purposes. With a "models of" perspective (Gouvea & Passmore, 2017), modeling becomes a procedural exercise where students figure out the right things to include in the models without using models as tools for making sense of phenomena. Similarly, in section 1, I found that teachers' explicit verbal messages about models and modeling regarding the purpose of the practice shaped students' modeling practices (Ke & Schwarz, 2016). In that work, analysis of students' small group work in the classroom of one teacher who framed modeling as "putting what you learned into the models" and emphasized that students to finish the models in a timely manner led to students finishing the task regardless of substance and including particular information in their model, regardless of the relevance of that information.

Knowing that the way a teacher frames and enacts modeling largely impacts the meaningfulness of modeling practice, we pose the question: what are productive ways in which teachers can support students' modeling practices? In this paper, I draw on Epistemologies-in-Practices framework (Berland et al., 2016) and seek to investigate how teachers might support students' engagement in modeling practices in a disciplinarily and knowledge-building way and what effects that support might have on students. In particular, I present a case study of one teacher who used epistemic considerations to support her students' modeling practices to examine what teaching practices she used to support modeling. I also investigate how that interaction might have impacted the nature of students' engagement in modeling.

As such, my research questions are:

1. How does this teacher support students' epistemic considerations development?
2. How does this teacher's support for epistemic considerations seem to influence students' modeling practices?

Presenting this case study will highlight what teacher practices might be critical for meaningfully engaging students in scientific modeling and what the impact of these practices might be for students. Such work will advance knowledge about how to support modeling practices in the classroom using epistemic considerations and the effects on students' modeling practice.

Conceptual Framework

In this paper, I use Epistemologies-in-Practice framework (Berland et al., 2016) to examine students' engagement in modeling practice. This framework has evolved from earlier work that focused explicitly on metamodeling knowledge (e.g., Schwarz & White, 2005) and the subsequent view that metamodeling knowledge is most meaningful in combination with engaging in elements of practices (e.g., Schwarz et al., 2009; Schwarz et al., 2012). The particular epistemic considerations derived from the hypothetical learning progression were helpful in determining how to meaningfully engage students in modeling, explanation and argumentation practices as they unfold over time (e.g., Baek & Schwarz, 2015; Berland et al., 2016). By epistemic considerations, I refer to the purposes and goals of the work in which students are engaged. An important aspect of studying engagement in practices is to understand what epistemic considerations are guiding the work and in what ways those align with the norms and values of science. For example, developing and revising models that address the mechanism of phenomena lies at the core of the scientific endeavor; therefore, considering the degree to which an explanation is mechanistic should guide learners who are engaged in modeling practice.

These epistemic considerations that frame and guide practices are called "epistemologies in practice" (EIP). This EIP framework is important because it can capture the nature of students' engagement in modeling practices and how teachers might be supporting students' development of modeling in the classroom community. It acknowledges the context specificity of considerations in practices and describes how the practices of modeling, explanation and argumentation might become more meaningful from a disciplinary and classroom perspective through epistemic considerations (Berland et al., 2016, see Table 1).

Further, while we know that teachers play a significant role in how practices are established and pursued in classroom communities, much prior research focuses on teachers' understanding of models and the practice of modeling (e.g., Henzi & van Driel, 2011; van Driel & Verloop, 1999) rather than the role of teachers in guiding the epistemic aspects of classroom and how that might impact students' engagement (See Kelly et al. 2014; Lidar et al., 2006). This shift in focus is important as we have found that some elementary teachers who understand more scientific knowledge (content and practice) at the elementary level are sometimes *less* supportive of students engaging in modeling to support their evolving sense-making. In particular, these teachers can be primarily concerned about using their authoritative knowledge to ensure that students have the most accurate information about the systems and are therefore less invested in students' sense-making processes that may lead towards inaccurate ideas. Others have also found that teachers who focused on guiding students towards a particular conclusion offered fewer opportunities for students to discuss and evaluate each other's work (e.g., Vo et al., 2015).

As part of our work in studying how teachers support epistemic work in the classroom, we build on research about the importance of epistemic framing (Berland & Hammer, 2012; Russ & Luna, 2013) and epistemological messaging (Russ, 2017). In particular, this work indicates that teachers frame epistemic aspects of the modeling practice and send messages about the epistemic nature of modeling practices to students (e.g., Gray, 2016; Russ, 2017). We advance this work by studying how a teacher can support meaningful engagement in modeling through epistemic considerations and how epistemic moves impact students' practical epistemologies (Lidar et al., 2006) or engagement in modeling practice.

Method

Research Design. I use a case study design (Yin, 2009) to explore the relationship between the teacher's instructional support on epistemic considerations and students' modeling practices. The case study approach enables us to characterize the complex interactions between teacher and students within a classroom setting over time and to better understand the interactions that lead to meaningful modeling engagement and modeling competence.

Contexts and participants. To investigate our research questions, I analyzed the pedagogical practice of a 5th grade science teacher, Mrs. M, from a Midwest suburban elementary school during the 2012-2013 academic year. The study highlights Mrs. M's teaching and her classroom as our work indicated she was particularly effective at engaging students in epistemically-rich modeling practice in ways that aligned with disciplinary and classroom knowledge-building norms.

The data in this study derive from a 6 to 8-week model-based unit (Baek, et. al, 2011; Kenyon, et. al, 2008) about evaporation and condensation. In the unit, students are asked to address a driving question of whether or not they would drink the liquid from a solar still. To answer this driving question, students constructed an initial diagrammatic model to explain the phenomenon, and continuously evaluated and revised their models using evidence from their empirical investigations and scientific information. In Mrs. M's classroom, we collected data from eight students (called "focus students") and interviewed them before and after the unit for the purpose of evaluating their modeling practices. These eight focus students were selected by Mr. M so that they vary in terms of gender, ethnicity and academic levels.

When we introduced the epistemic consideration framework to her about four years into our nine-year collaboration, she took on the goals of this work as it provided a framework to work towards with students. She thought of it as a way to evaluate whether the models were moving in a good direction. The analysis of Mrs. M's teaching indicated that she particularly emphasized two epistemic considerations - Nature and Generality. Her approach to the Nature consideration was to work with students to figure out "how and why." She also told us that she was going to try to support the Generality consideration this time because she thought it was the most challenging epistemic consideration for students to use. While Mrs. M mentioned Audience and Justification as important aspects to consider when engaging in modeling activities in her instruction, she did not emphasize the two epistemic considerations as much as Nature and Generality. Therefore, the findings focus on how she supported Nature and Generality in her modeling instruction.

Data Collection.

Video-recordings. The primary data for this analysis included video-recordings of modeling lessons in which Mrs. M's students constructed, revised, and evaluated their models of evaporation and condensation. I chose those modeling lessons for our analysis because within those lessons, Mrs. M spent the majority of the class time engaging students in various critical aspects of modeling practices. Those aspects included: helping students make sense of the relevant phenomena their models were supposed to explain, organizing discussion around criteria for developing models, giving specific instructions for model creation, revision and evaluation, facilitating student presentations of their models (both individual and consensus models), and facilitating peer feedback. The video-recordings usually consisted of whole-class discussion and small group work or discussion. For the purpose of this study, I analyzed whole-class discussions led by Mrs. M and did not included analysis of her small group interactions. I did so because I wanted to focus on Mrs. M's instructional support for epistemic considerations which she did not do as explicitly in the small work or conversation among students. Altogether, there were 14 class periods of Mrs. M's instruction and each class period lasted about 45 minutes.

Semi-structured pre- and post- student interviews. To further elicit students' ideas about their models and modeling experience, I also collected semi-structured pre- and post- student interview data from the eight focus students. During our semi-structured interview, we asked students to (1) describe their models and model-based explanations generated in class, (2) describe their rationale for developing and revising those models, and (3) use their models to apply to new contexts. Further, we designed the interview questions for the purpose of eliciting students' responses to the four epistemic considerations. Since I focus on Nature and Generality considerations in this study, I analyzed students' responses to questions that were aligned with the two epistemic considerations. To obtain information regarding students' considerations about Nature, we asked students to use their models to explain how and why evaporation/condensation occurred. Regarding the Generality consideration, we asked students in pre-interview whether they thought their models could apply to other phenomena, and if so how. In the post-interview, we specifically ask students to explain two phenomena related to condensation, "bathroom mirror fogging-up" and "rainfall."

Data Analysis.

Teacher support for epistemic considerations. In order to examine how Mrs. M supported students' use of the Nature of Account and Generality epistemic considerations, I analyzed Mrs. M's talk during the whole-class discussions using the written transcripts of the video-recordings. The unit of analysis is utterance, the smallest unit the function of which could be identified. An utterance could be part of a sentence, a whole sentence, or an dialogic interaction between teacher and student. First, I identified utterances where Mrs. M used Nature and/or Generality epistemic considerations to support her students' modeling practices. Specifically, I looked for instances where Mrs. M talked explicitly about the epistemic considerations ("Mechanism" and "Generality" in Mrs. M's word) concerning what they meant and how students should use them to guide their modeling work. Also, I searched for utterances where Mrs. M was helping students to figure out the mechanistic accounts or explanations of the phenomena (Nature), the connections between phenomena, and how their models were supposed to account for those phenomena (Generality). For example, if Mrs. M asked students about the factors that caused condensation, it would be coded as talk about Nature because it helped students to develop their answers to one of the driving questions of the unit, "how and why do liquids appear on a surface?" Altogether, I identified 128 utterances about Nature and 68 utterances about Generality in Mrs. M's talk that spanned most of the class periods in the video-recordings. Next, for each utterance, I develop codes to categorize the types of talk in which Mrs. M engaged based on the forms of the teacher support (e.g. question, comment, direct instruction, etc.), the aspects of the epistemic consideration that Mrs. M addressed (e.g. making analogy between phenomena for Generality), and the contexts in which the utterances occurred (e.g. student model evaluation). After identifying and coding utterances, I used constant comparative method (Glaser & Strauss, 1967) and split/merged the original codes into new codes that could be applied to different utterances (e.g. asking general "how and why" questions about student work, listing everyday phenomena about evaporation/condensation, etc.). Finally, I reexamined the data with the new codes and generated two themes regarding Mrs. M's support for Nature (e.g. "explain how and why" and "trace water molecules") and one for Generality (e.g. "explain multiple phenomena") that are prevalent in the data.

Students' modeling practices. When analyzing students' modeling practices in the student semi-structured interviews, I characterized how students' use of the Nature and Generality epistemic considerations developed over time. For each focus student, I first identified sections in the interviews where the students responded to questions related to Nature and Generality. In each section, I coded students' responses based on key aspects of the epistemic considerations in the context of a 5th grade evaporation and condensation unit from our current work on Epistemologies-in-Practices (Krist et al., forthcoming; Berland, et. al., 2016). In particular, in terms of Nature, we recorded 1) what students considered as the major factor (e.g. non-visible component such as water molecules or external conditions such as temperature and time), 2) unpacking the factors by characterizing the properties, rules, and behaviors of factors (e.g. molecules bumping into each other and moving faster), and 3) the nature of the reasoning (e.g. causal relationship, connection between micro-level observation to micro-level mechanism, or inclusion of scientific principles such as "the higher the temperature, the faster the molecules move") presented in their model-based explanations. In addition, we also triangulated our coding with analysis of the students' diagrammatic models when available. For instance, if a student did not mention the movement of water molecules in the interview, but he/she drew it on his/her model and made notes about it, we would still code the students' model-based explanation as involving micro-level explanatory process, which was central to the mechanism. In analyzing students' use of Generality, we recorded whether students were able to 1) identify the analogous parts (e.g. cold surface) between phenomena, 2) identify the generalized components/processes (e.g. water molecules slowing down and get together) that can be applied to multiple phenomena, and 3) apply the generalized components/processes to explain new phenomena. In addition to coding students' performances regarding their use of Nature and

Generality, we also noted students' reflective talk about the epistemic considerations throughout the interviews (e.g. "I want to figure out the how and why part so that other people can understand it better"). This reflective or meta-talk about the epistemic considerations helped uncover how the students were using the epistemic consideration in their modeling work. After we coded students' modeling practices in each section, we compared students' pre-interview codes to post interview codes in order to further characterize the development in each focus student's epistemic considerations in modeling.

Findings

In this section, I share the analysis regarding the features of Mrs. M's teaching that seemed to support students' meaningful engagement in modeling practices with respect to the epistemic considerations of Nature and Generality. In particular, I focus on how Mrs. M's teaching supported students epistemic engagement towards developing causal, mechanistic models that could explain multiple phenomena as opposed to procedural aspects of engaging in the practice or rote memorization. I then turn my attention to how students' modeling practices changed over time by presenting one focus students' development with respect to considerations about Nature of Account and Generality. This example will also illustrate how those changes may be connected to and influenced by Mrs. M's instruction.

Instructional support for Engaging in Modeling Practice.

"Remember to explain how and why!" One of the ways in which Mrs. M supported students' meaningful engagement in scientific modeling practice was by emphasizing the nature and purpose of the model (Nature of Account) throughout the unit and in different ways. This idea links to the disciplinary norms of developing and revising scientific knowledge that is explanatory in nature and address both the processes of the phenomena as well as the potential mechanisms of the phenomena. For instance, for every phenomenon of evaporation or condensation that the class generated, Mrs. M would always ask the similar "how and why" questions such as, "how and why does water appear on the cold can?", "How and why does dew form on the grass in the morning?" to reinforce the idea that it was important for students to attend to the mechanism of the phenomena with their models. Below is an excerpt that exemplifies the way in which Mrs. M emphasized explaining "how and why." The conversation occurred in the second lesson when she asked her students to construct their very first model of evaporation.

Mrs. M:	You guys are going to be constructing an initial model [of evaporation]. So what changes did you observe over time? **How and why do you think those changes happen?** Those [questions] are hard to explain, aren't they? In other words, **how and why do you think the liquid seemed to disappear? How and why**, Jack?
Jack:	It's probably just natural.
Mrs. M:	OK, so **how did it happen?**
Emma:	They just evaporated.
Mrs. M:	What does that mean? **Where did it go?**
Emma:	Into the air.

At the beginning of the episode, Mrs. M asked the class "how and why do you think the liquid seemed to disappear?" Note that this conversation happened at the very beginning of the unit before students constructed their initial model of evaporation. Students had known the word 'evaporation' from earlier schooling, but had never unpacked what it meant or how it happened nor had they conducted any investigation to validate their hypothesis of evaporation. Therefore, Mrs. M's questions not only directed students to think about the mechanism of the phenomena, but the question was also open-ended to allow students to share their initial ideas. After Jack's answer "it's just natural," which is a typical answer at the beginning of the unit, Mrs. M problematized the phenomena by asking the class "how did it happen?" Her question sent the message to the class that "it's just natural" was not a sufficient answer and students needed to further unpack the mechanism to figure out the "how and why." As another student, Emma, responded with “it just evaporated,” Mrs. M asked her to clarify what she meant by “evaporated.” She also probed her about “where did the water go?” to scaffold her thinking about the process happening at the microscopic level, which is critical for understanding about the mechanism. In this way, Mrs. M’s question about tracing matter (e.g. water molecules in this case) across levels (macroscopic to microscopic) may have been especially helpful for students who did not think about the process going on at the microscopic level or who failed to make the connection between observable phenomena to non-visible mechanism. In addition, the fact that Mrs. M followed the more general question of “how and why do you think it happened?” with the more specific question of “where did the water go” also conveyed the message to the class that that one way students could achieve the goal of explaining “how and why” was to figure out where the water went in the phenomena. In other words, Mrs. M not only set “explain how and why” as the primary goal of their modeling, she also helped her students think about how to meet the goal by asking them specific questions of tracing water molecules. In this way, “explain how and why” became more meaningful for students as they learned to unpack the mechanism, as opposed to a general abstract goal they do not know how to achieve. In fact, this was a common practice Mrs. M took throughout the unit. Whenever she was addressing the “how and why” of students’ models, she followed up with questions with regard to tracing water molecules, either “where did the water go” or “where did the water come from” for phenomena of evaporation and condensation.

Not only did Mrs. M emphasize “explaining how and why” during model creation, she also prioritized “explain how and why” as one of the most important criteria for evaluating a scientific model since she understood that the goal of models is to explain phenomena. Whenever students showed their models to the class or their group members, she often asked students to show how their models addressed “how and why.” The following episode exemplifies how Mrs. M supported her students to engage in model evaluation with a focus on “explaining how and why.” The conversation occurred in the seventh lesson after students had constructed their initial models of condensation.

Mrs. M: Would you please come up here and share your model with us, Tom? **I'm looking for the how and why pieces. I'm going to be asking you [class] to help Tom to tell us the how and why piece, the mechanism piece.**

Tom: This is my model and this is the mirror and this is the water molecules evaporated from the shower. And then they'll come around to the mirror and there's a fog and there's some water droplets.

Mrs. M: Is there anyone in here who has anything to say about this model? Whether we have any stars, any wishes, anything like that?

Tom: Sarah?

Sarah: I really like how you put that they are attracted to it [mirror], **but I'd like to know why.**

Starting at the beginning of this episode, Mrs. M was explicit about “explaining how and why” as the focus of the activity of model sharing and evaluation. She asked Tom to present his model with special attention to the “how and why” piece of his model. In the meantime, Mrs. M also directed the class as audience to pay attention to the mechanism piece as well. In this way, the class shared the common goal of explaining how and why as Tom began to share his model. He traced the water in the process of condensation, water being evaporated from the shower, coming around to the mirror, and finally turning into fog and water droplets. It is important to note that Tom's presentation was no easy task, albeit brief, as it required him to understand 1) what Mrs. M meant by “how and why”, and 2) what counted as the “how and why” in his own model. The fact that Tom was able to consider explaining how and why condensation occurred when creating the model and communicated how he met the goal of “explaining how and why” to the class indicated that he was engaged in modeling practices in a non-procedural way that aligned with epistemic goals of developing a mechanistic model. We suspect that Tom's mechanistic presentation of his model may be related to Mrs. M's foregrounding of the epistemic consideration of Nature of Account. In particular, Mrs. M's frequent questions about "how and why" in combination with specific matter-tracing questions throughout the unit, may have contributed to his tracing of water molecules in his model.

After Tom's presentation, Mrs. M turned to the class for model evaluation. She asked if anyone had any "stars and wishes." By "stars and wishes," Mrs. M was referring to the norms of evaluating models she had set up in previous lessons. That is, when evaluating models, students were supposed to come up with at least one "star" that they like about the model and one "wish" that they think the model could be improved. More importantly, the stars and wishes should be based on the epistemic considerations of modeling practices. In this conversation, since Mrs. M had made explicit that she was "looking for the how and why, the mechanism piece," the expectation she set up for the class was to provide any "stars" or "wishes" concerning how well Tom's model explained how and why condensation occurred. It is worth noting that this framing of the activity was not only meaningful from the disciplinary perspective, but more importantly, it is also accessible to students since Mrs. M had already set up the norms of evaluating models. As evident in Sarah's comment about "why water molecules are attracted to the mirror," she was familiar with the norms of giving "stars and wishes" based on "how and why." Additionally, Sarah's comment also showed that she had her own understandings of what counted as "how and why" and Tom's model did not address the "why" part. This is another indication of students' meaningful engagement in the modeling practices as Sarah was able to take up the epistemic consideration of "explaining how and why" and use it to evaluate other students' models.

"Your model should be able to explain ALL these phenomena!" Besides emphasizing the goal of "explaining how and why," Mrs. M also highlighted "explaining multiple phenomena" as one of the primary goals when engaging students in modeling practices. For example, when students were revising their models or constructing consensus models, she constantly challenged her students to use their models to explain other relevant phenomena that were familiar to students. Often times after a student presented their models in front of class, Mrs. M would follow up with questions about how that particular model was able to explain other similar phenomena. The following episode is representative of how Mrs. M set up the goal of "explaining multiple phenomena" in the modeling activities. The conversation occurred in lesson six when Mrs. M asked students to construct their consensus models of evaporation with group members.

Mrs. M: "**Generality." A model needs to be used to explain multiple phenomena.** So what are some phenomena of evaporation? Give me some examples of evaporation that your model can explain.
Todd: How hair dries.
Mrs. M: So I would use my model to explain how hair dries. What else?
Cathy: How nail polish dries.
Mrs. M: Nail polish dries. I use my model to explain how nail polish dries.
Sam: How the towel dries.
Mrs. M: So hanging your clothes out to dry. **So your model, needs to be able to, not just be used for one of those things, but your model needs to be able to be used to explain all of those things!** You guys are going to be given a task of creating a consensus model. **You need to decide, as a group, how you are going to create a model that represents the big idea of evaporation that can be used for all of the phenomena we were talking about earlier.** Tomorrow, I'm just gonna draw out of a hat, I'm just gonna say, [with] **your model, you're gonna tell me how you can smell dirty feet. [With] your model, you're gonna tell me, how the paint in Alicia's room dried. [With] your model, you're gonna tell me, how your bathing suit dries.** You have no idea of what I'm going to tell you, but your model is going to have to show me that.

In this episode, Mrs. M started with the overall statement of "a model needs to be used to explain multiple phenomena." Then she asked students to list examples of evaporation that they can use their model to explain. By doing this, Mrs. M provided scaffolding to help students better understand what Generality meant in terms of students' own models and what specific phenomena their models should account for. Towards the end of the episode, Mrs. M made "explain multiple phenomena" as the primary goal of consensus model construction, "You need to decide, as a group, how you are going to create a model that represents the big idea of evaporation that can be used for all of the phenomena we were talking about earlier." I argue that this framing of the activity was epistemic in nature, and fundamentally different than some other instructional goals teachers may have when engaging students in consensus model building. For instance, other teachers might be worried about student participation or group dynamics under such circumstances. Therefore, their framing of the activities might be something like "everyone should contribute" or "make sure you are nice to each other." While those are important things to consider as teachers organize small group activities, the goals are not as scientifically meaningful or meaningful for a learning community building knowledge as "explaining multiple phenomena." The nature of students' engagement of modeling may look vastly different if those goals were set up as the primary goals of consensus model building.

Similar to how she helped her students to contextualize the goal of "explaining how and why," Mrs. M also provided scaffolding in her instruction to help her students better understand the epistemic consideration of Generality. In particular, Mrs. M frequently asked her students to compare different phenomena so that they could recognize the connection between phenomena that share similar mechanisms and then figure out what aspects of the mechanism could be generalized to account for different phenomena. The following episode illustrates how Mrs. M scaffolded students to see the connection between two phenomena, "fog on the mirror" and "cold can." The conversation occurred in lesson seven when students were first introduced to condensation.

Mrs. M:	I'm going to give you one minute to answer the question. **How are these two phenomena different?** The Coke can and the fog on the mirror. **Think about how they happen, think about where it came from.** There's enough room to explain your ideas so please do that. (after students working on the responses for 2 minutes)
Mrs. M:	**Now think how they are similar then.**
Mrs. M:	Jack, **tell me how they are different.**
Jack:	The Coke can is cold and the bathroom is hot and steamy.
Mrs. M:	OK. So **what is the same**, Anna?

Anna: Well, on the mirror, you will find more than just fog, you will find droplets of water. So those droplets of water are very similar to what's on the can.

At the beginning of the episode, Mrs. M first asked students to identify the similarities and differences between the two phenomena, "cold Coke can" and "fog on the mirror in the bathroom." She further directed students to think about the "how and why" piece, "think about how they happened" and "where it came from." As demonstrated in the previous section, Mrs. M often asked general "how and why" question in combination with specific matter-tracing mechanism-oriented question such as "where did the water come from." In this case, by focusing on the similarities and differences of the two phenomena in terms of "how and why," Mrs. M intended to guide students to not only identify the analogous parts in the two phenomena, but also extract the aspect of the mechanism that can be applied to both scenarios. We argue that Mrs. M's emphasis on identifying the similarities and differences between two phenomena concerning the mechanism may potentially help students shift from not recognizing generality should/can happen, to mapping components to another context, and eventually to applying generalized mechanism to different contexts. While Anna's response did not address the mechanism of the two phenomena, she identified that the liquid water seemed to be appearing in both contexts. It is understandable that Anna did not identify the generalized process/mechanism that could explain both phenomena, since the activity occurred at the beginning of the condensation unit when students were just starting to make sense of phenomena of condensation without having learned much content knowledge.

As shown from the excerpts above, Mrs. M prioritized "explaining multiple phenomena" as one of the primary goals of modeling practices. She also scaffolded students to achieve the goal by comparing the similarities and differences between phenomena. Further, it is interesting to note that the scaffolding Mrs. M provided often involved examining the "how and why" piece of the phenomena, which may help students recognize and generalize the key components and processes that can be applied to various phenomena.

The development of students' modeling practice. From the above analysis, we see how Mrs. M prioritized the epistemic considerations of Nature of Account and Generality for modeling activities in class. However, how did this emphasis on "explaining how and why" and "explain multiple phenomena" impact students? It is important to look at the nature of students' modeling practices to examine whether Mrs. M's instructional support was productive in engaging students in the practice, and if so, in what ways. In particular, I analyzed all eight focus students' pre- and post- interviews in Mrs. M's class to determine how they engaged in modeling and what role the epistemic considerations played as they discussed/recalled their modeling experiences in the class activities. While each focus student was unique in terms of their development in the epistemic considerations, I identified general patterns concerning shifts in students' epistemic considerations that were shared by the majority of the focus students, which may be attributed to Mrs. M's instruction.

In terms of Nature of Account, the analysis of interview data shows that towards the end of the unit, all but one focus student developed increasingly mechanistic models that could explain phenomena. Among those seven students who made progress, two of them shifted from describing the phenomena at the macro-level towards providing a full explanatory process of how and why condensation happens. The other five focus students improved their model-based explanations and had a more complete mechanisms at the end of the unit. The only focus student who remained at generating a partial explanatory process of how and why phenomena occur at the end of the unit had been absent for a whole week because of a cold.

In terms of Generality, I found that five out of the eight focus students generalized key elements or processes that could be applied to multiple phenomena by the end of the unit. The other two focus students also shifted from not seeing the connections between phenomena at the beginning of the unit towards identifying the analogous parts of two similar situations at the end of the unit.

In the following section, I present one focus student, Jeanette, to illustrate how her modeling practices developed over the course of the unit with respect to Nature of Account and Generality. I chose Jeanette's example because she was clearer in expressing her ideas and she also represented other students' modeling practices development under Mrs. M's instructional support. In particular, the ways in which she developed model-based explanations as well as model application to different phenomena was similar to several other focus students.

The following excerpt was from Jeanette's pre-interview, which occurred after she had constructed her initial model of evaporation in lesson two. She chose the two-cup experiment, an investigation the class observed at the beginning of the unit, as the phenomenon of her model. The excerpt was highlighted because in the excerpt Jeanette was answering questions in relation to how her initial model could explain phenomena of evaporation that she chose and whether her model was general so that it could explain other phenomena.

Interviewer:	**Could you explain to me how your model shows evaporation?**
Jeanette:	Well, in the uncovered cup the water goes out and it goes everywhere. But in the covered cup it goes up and can't.
Interviewer:	**So how do you know that in the uncovered cup the water will go outside and in the covered cup the water will stay here?**
Jeanette:	Because when we actually did this experiment, I saw that the water in this cup went down and the water in that cup did not.
Interviewer:	**Could you use your model to show how and why evaporation happens?**
Jeanette:	No.
Interviewer:	**Why do you think your model cannot show that?**
Jeanette:	Because it just doesn't show it here. It just shows that the water is going somewhere. *It doesn't show how or why.*

…

Interviewer:	**Do you know other example of evaporation?**
Jeanette:	Well, when I first got my ears pierced I had to clean them with alcohol and I would leave the cap open and the alcohol in there would evaporate.
Interviewer:	**And do you think the alcohol example is similar to what you have in this model?**
Jeanette:	Yeah. When the cap was closed, the alcohol did not evaporate. But when the cap was open, it did evaporate.

At the beginning of the excerpt, when Jeanette was asked how her model showed evaporation, her response focused on where the water went in both scenarios, “go out and go everywhere” when the cup was uncovered, and “go up and can’t [go out]” when it was covered. Jeanette’s focus on where the water went reflected Mrs. M’s instructional emphasis on tracing matter to figure out “how and why.” In other words, Mrs. M’s constantly asking questions such as “where did the water go?” may have influenced what components/elements students chose to prioritize as they constructed their models to explain phenomena. While thinking about non-visible components such as water molecules may have helped lead students to the hidden mechanism, Jeanette did not further unpack the mechanism by describing what happened at the molecular level as “water goes out and goes everywhere.” Instead, she attributed the evaporation to the condition of whether or not the container was covered. In her diagrammatic model, she wrote, “The water in this cup will evaporate because it’s open.” While Jeanette’s hypothesis was scientifically incorrect, it was understandable since the interview took place at the beginning of the unit where students’ have not collected much evidence about evaporation such as experimental data on humidity and simulation of particle movement. However, it is interesting to note that Jeanette was well aware that her model did not fully explain the phenomenon. When asked if her model could explain how and why evaporation happens, she was firm about her model not being able to show “how and why,” “it’s just doesn’t, it doesn’t show how or why.” The quote indicated that Jeanette had her own standard of what counted as “how and why” and simply showing water going somewhere was not enough. Furthermore, Jeanette also jotted down questions and notes on her model (Figure. 3) that may help her further develop her model. For example, next to the open cup, she wrote, “water goes up and away, because what?” At the bottom of her model, she wrote down the epistemic consideration specifically, “M, how and why” (M stands for Mechanism). All those side notes further suggest that Jeanette was actively using “explain how and why,” which Mrs. M emphasized throughout the unit, to guide her model development. I argue that what Jeanette demonstrated in this excerpt speaks to how productively Mrs. M was able to engage students in meaningful practice from both a scientific and classroom knowledge-building perspective. The practice could have become proceduralized or rote memorization if Jeanette had responded with “I put water going up into the air to show evaporation because Mrs. M asked us to include water molecules in our model.”

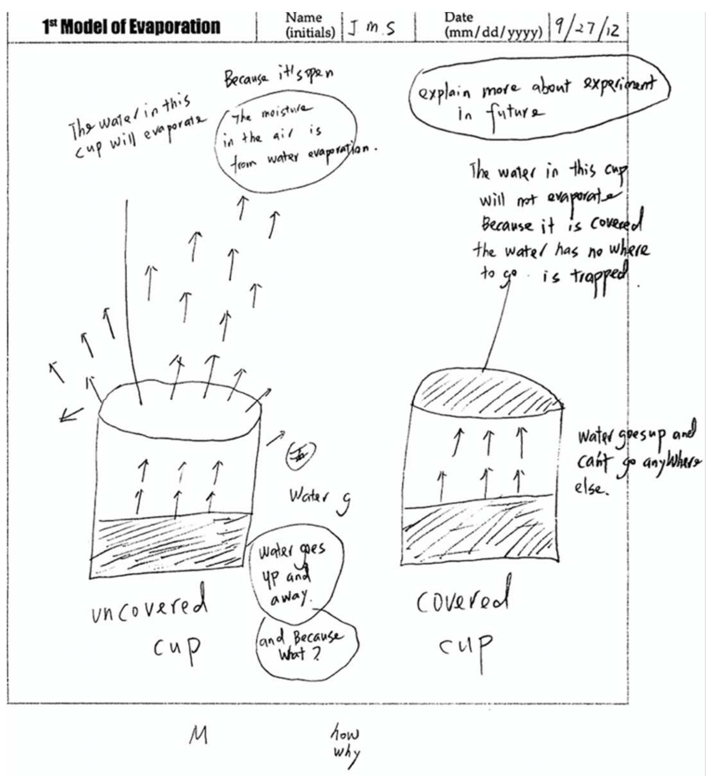

Figure 3. Jeanette’s initial model of evaporation

In terms of generality, later in the pre-interview, Jeanette was asked if she could identify other phenomena about evaporation and whether it was similar to what she had in her model.

Jeanette was able to come up with an example of alcohol evaporating and gave the reasoning why the two phenomena were similar, that in both situations evaporation happens when the container is not capped. In other words, Jeanette was able to see the connection between phenomena and identify the analogous part of the phenomenon. I suspect that Jeanette's recognition of the similarity between phenomena may have been affected by how Mrs. M scaffolded students thinking about Generality, as Mrs. M often asked students to identify the similarities and differences among every-day phenomena when introducing evaporation and condensation. However, Jeanette was not able to generalize the key process that could be applied to explain different phenomena, which I argue may be limited by her lack of content knowledge and understanding of the mechanism.

In comparison, during her post-interview after she revised her model of condensation and constructed a consensus model of model with her group member, she was not only able to explain phenomena at a mechanistic level with her model, but she could also generalize key processes of that mechanism and apply them to different phenomena. The excerpts below highlighted what her modeling practices looked like with respect to the epistemic considerations of Nature of Account and Generality.

Interviewer: **Can you use your model to explain how condensation happens?**

Jeanette: So these are the water molecules in the air and they're flying around. But when they get closer to the can they slow down. And then they begin to clump together on the can and then more and more of them clump together and we see the fog.

Interviewer: **Why do they come to the cold can and come together?**

Jeanette: Because heat makes them go really fast. And when they get near a place that's colder, they lose the heat that makes them go fast and so they slow down.

Interviewer: **So what changes did you make to revise your initial condensation model?**

Jeanette: Well, in my first model there was no *how and why*. It didn't say *why* the molecules were doing that and *how* they were doing that.

…

Interviewer: **Let's try to use your model to explain some situations. For example, can you explain the phenomenon of why and how does the mirror in your bathroom fog up when you fill the bathtub with hot water?**

Jeanette: When you fill up a bathtub, the water is hot. And so that water evaporates and since the mirror is colder than the water molecules are, they will move around by it and slow down and form water droplets on it.

Interviewer: **OK, can you use your model to explain how and why rain falls? Do you think it's related or not?**

Jeanette: I don't think rainfall is related to condensation. Because when rain happens, it goes into a cloud and there's nothing solid or anything colder that they would actually go to and form on.

When asked to use her model to explain how condensation happens, Jeanette again focused on the water molecules, similar to how she did in the pre-interview. However, this time she was able to describe the hidden mechanism at the molecular level. With her model, she identified an explanatory process, water molecules first "flying around in the air," and then "slowing down when they get closer to the can," and finally "clumping together on the can." She also made the connection between micro-level molecular movement (e.g. "clump together") to macro-level phenomena (e.g. "we see the fog"), which is challenging for students to conceptually comprehend, especially for young learners. In addition, Jeanette also made a chain of reasoning to further explain why water molecules slowed down, "when they get a place that's colder, they lose the heat that make them go fast and so they slow down." Altogether, Jeanette's model-based explanation included an explanatory process at the molecular level to show how water condensed onto the cold can, a chain of reasoning to explain why the process happened, and a connection between micro-level molecular movement and the macro-level phenomena. Compared to what she said in the pre-interview, it is evident that Jeanette's model-based explanation became more mechanistic over the course of the unit.

It is also worth noting that, similar to what she said in the pre-interview, she was again not satisfied with her initial model of condensation as "there was no how and why." Further, she elaborated on what she thought as "how and why," that is "why the molecules were doing that [condense on a cold surface] and how they were doing that." In contrast, in her revised model, Jeanette had both “how they were doing that” (water molecules slowed down and clumped together) and why they were doing that (water molecules lost heat as they come near a cold object). I argue that Jeanette was taking up the goal of “explaining how and why,” which Mrs. M prioritized as the primary goal of modeling, and used the epistemic consideration to guide her revision of her initial model of condensation.

Later in the interview, Jeanette was asked to use her model to explain two other phenomena, “mirror in the bathroom” and “rainfall” (The phenomenon of her model was cold Coke can). When trying to use her model to explain how and why the bathroom mirror fogged up, Jeanette successfully generalized the key process going on in her own model, “water molecules slow down because of a colder object and form water droplets,” and applied it to the new phenomenon. When asked to use her model to explain rainfall, although she did not think her model was able to, it was evident that Jeanette was again trying to apply the same generalized process as she was looking for a colder solid object where water can go to. Compared to what she did in the pre-interview, in the post-interview, Jeanette was not only able to identify the analogous parts in both situations, she also went beyond the macro-level elements of the phenomenon. I argue that Jeanette’s shift with respect to Generality may have been influenced by Mrs. M’s instructional emphasis on “explaining multiple phenomena” as one of the primary goals of developing models.

Summary of Jeanette’s development in modeling competencies. As shown in the above section, Jeanette’s modeling practice developed from pre-interview to post-interview to better explain phenomena as well as to account for different phenomena. With respect to Nature of Account, her model-based explanations became more mechanistic, shifting from focusing on the macro-level conditions (e.g. whether the container was capped or not) under which the phenomena occurred to describing the explanatory process at the microscopic level that accounted for how and why the phenomena happened. In the meantime, I also found that in both interviews, Jeanette was consciously using the goal of "explain how and why" to navigate her modeling process despite her lack of content knowledge about the topic in the pre-interview. In terms of Generality, Jeanette shifted from identifying similar components in different phenomena to using generalized process to account for multiple phenomena. Her development in both areas may have been influenced by Mrs. M's instructional emphasis on the two epistemic considerations.

Discussion

While teachers sometimes struggle with how to enact scientific modeling in their classroom, Mrs. M's case shows evidence that there are disciplinarily productive ways in which teachers can engage students in modeling practices to potentially support the development of students' modeling competencies. In particular, I found that Mrs. M's prioritizing the epistemic considerations of Nature and Generality as the primary goals of modeling practices seemed to productively influence students' modeling work. We see evidence from both classroom interactions (e.g. Sarah's question about why) and student interviews (Jeanette's self-evaluation about her own models) that Mrs. M's students had developed a strong sense of examining the "how and why" piece of phenomena, and used that to navigate their own modeling work to create a more mechanistic model to better account for the phenomena. We also see evidence from student interviews that students applied their models to explain new phenomena by generalizing the key components and processes of the hidden mechanism. The findings are consistent with and build on prior work around how teachers' "framing" and "epistemological messages" (Berland & Hammer, 2012; Russ & Luna, 2013; Russ, 2017) of activities in science classroom affects student participation and learning. While those studies examined the instant teacher-student dynamics in terms of their expectations of the activities, the results demonstrate that the ways in which a teacher's "framing" of modeling activities may also have a continuing effects on students' practices that goes beyond in-the-moment interactions between teacher and students. In other words, we see evidence that this framing impacts students' expectations about the goals and purpose of modeling as well as the actual process and product of modeling (e.g., to develop and revise mechanistic models that can be generalized to other phenomena).

Moreover, the findings also suggest that simply emphasizing the epistemic considerations (e.g. "models should be able to explain and predict phenomena") is not likely to be sufficient. The analysis of Mrs. M's teaching indicates that, in order to productively engage students in modeling practices in a meaningful way, a teacher also needs to provide scaffolding (e.g. asking students to trace water at the molecular level for Nature; asking students to compare between two similar phenomena for Generality) to help students contextualize the epistemic goals with their own models. In that way, students may have a better sense of how to achieve those abstract epistemic goals within the learning context that is relevant to them. I find that Mrs. M's blend of foregrounding the overarching goals and providing specific scaffolding consistently throughout the unit seem to be particularly productive in supporting students' development in modeling competencies. The result echoes with what Litar and her colleagues (2006) found regarding the interplay between teachers' epistemological moves and students' practical epistemologies. In their study, they conjectured that some of the teacher's epistemological moves were not taken up by students probably because they were too challenging for students. The study showed evidence that students were able to take up the "epistemological move" as Mrs. M's epistemological message was appropriately scaffolded and contextualized in a way that was approachable for students.

In addition to emphasizing epistemic considerations consistently throughout the unit, our analysis indicated that Mrs. M was successful in setting up the norms of modeling activities (e.g. “stars and wishes” for model evaluation) as well as the social interactions among students (e.g. consensus model building within groups). This seemed to be another critical aspect of Mrs. M’s instruction that may potentially influence students’ modeling practices. Setting up social norms around modeling practices is critical because it facilitates engagement with epistemic ideas across students. While the analysis did not specifically focus on how Mrs. M set up the norms of different modeling practices (e.g. how to give each other feedback about models, how to make a consensus model with group members, etc.), during the data analysis, I often found that the norms had already been set up in the background of the activities as Mrs. M engaged students in the epistemic aspects of modeling. I point out that this is not a common practice shared by all teachers. The findings indicated that, in order to engage students in modeling in a disciplinarily meaningful way, it is necessary for students to be familiar with the norms of practice. The finding is also consistent with what Colley and Windschitl (2016) found, that higher-rigor sense-making talks often occurred in association with conditions where the teacher was successful in engaging students in the social practice of talking to a partner or commenting on each other’s ideas. More research needs to be done to further unpack the relationship between the social and epistemic aspects of engaging students in productive scientific practices.

Overall, the findings suggest that the combination of the following three elements are critical for supporting students in meaningful engagement in modeling practice, 1) prioritizing epistemic considerations as the primary goals of model development and revision, 2) providing scaffolding to contextualize epistemic considerations in concrete and approachable ways for students, and 3) setting up the norms of modeling practices within a community to support the development and revision of modeling practice/and ideas. In other words, there may not a universal, but rather a suite of concerted instructional supports that teachers need to employ in order to productively engage student in modeling practices in a meaningful way. While this study is just one case in a particular learning context, the findings may also apply to other learning environment with careful consideration of the context under which such learning occurs.

Conclusions

As the research community studies modeling competencies, our work contributes towards understanding how scientific modeling can productively unfold in classroom environments. In particular, the teacher's role and interactions are paramount for how modeling takes place and whether it becomes proceduralized school science or meaningful for a knowledge-building classroom community. This is particularly important given the "practice turn" envisioned by the Framework and the epistemic nature of this critical practice.

What role do teachers play, and how does this matter? This study and those of others (e.g., Lehrer & Schauble, 2010, Vo et al., 2015) indicates that teachers' enactments of modeling have real ramifications on students' modeling practices and whether modeling is taken up as a school practice or as a disciplinarily meaningful one. As such, these findings move beyond documenting teachers knowledge of modeling and towards understanding how the practice unfolds in the classroom. Mrs. M guided students by highlighting and scaffolding epistemic messages while engaging them in the social work needed to do so. Most importantly, students took up these messages as they engaged in scientific modeling.

The work illustrates how one teacher productively engaged her students in modeling to support them in developing mechanistic models that generalized to other phenomena. Her teaching scaffolded students in developing modeling competencies using epistemic considerations. There is still much more to be learned about how to meaningfully engage students in scientific modeling and how to support teachers in doing so. Understanding the interactions of teaching and learning along with supporting teachers to enact these productive interactions will be critical to advancing the field. In this way, all learners will be able to engage meaningfully in scientific modeling to make sense of the world.

Research Study 3: Examining Teachers' Scaffolding Strategies for The Development of Students' Model-based Explanations Using a Web-based Modeling Tool: A Case Study

Recent reform efforts (Duschl, Schweingruber, & Shouse, 2007; National Research Council, 1996) in science education have shifted from engaging students in learning a wide range of disciplinary knowledge to making sense of the natural world through appropriation of scientific and engineering practices, similar to what scientists and engineers do in the discipline. In the recent release of Next Generation Science Standards (NGSS; NGSS Lead States, 2013), scientific modeling is highlighted as one of the eight core scientific practices in which students should engage in order to make sense of the world. Modeling is also pedagogical useful for science learners because "models serve the purpose of being a tool for thinking with, making predictions, and making sense of experience" and it can help them "establish, extend, and refine their knowledge" (National Research Council, 2012). Thus, it is critical to productively engage students in scientific modeling to achieve the new vision of science teaching and learning. Here I use the term "productive" to refer to student engagement that is making progress towards the disciplinary norms, goals, and practice of science, borrowing from Engle and Conant (2002)'s notion of "disciplinary productive engagement".

There is ample evidence in the literature suggesting that students are capable of engage in modeling practices in a productive way (Lehrer & Schauble, 2006; Metcalf, Krajcik, & Soloway, 2000; Schwarz et al., 2009; (Windschitl et al., 2008). Studies found that when students were given the opportunities to engage in model-based instruction, their model-based reasoning as well as understanding of the content knowledge improved (Louca, Zacharia, & Constantinou, 2011; Manz, 2012; Passmore, Gouvea, & Giere, 2014). For example, Manz (2012) found that a classroom of third-graders were able to develop their ecological understandings and modeling practices through a series of social situated modeling activities in a yearlong investigation about plant reproduction at a wild backyard area. The study showed how conceptual understanding and engagement in scientific practices such as modeling are in service of each other. On one hand, modeling activities provide opportunities to problematize, broaden, and deepen students' conceptual understanding (e.g., plant reproduction); on the other hand, shared knowledge disciplinary core ideas support students' modeling work and what it means to model.

Meanwhile, a growing body of research has focused on the design of appropriate learning environments such as computer-based modeling tools to support students' productive engagement in scientific practices (Stratford, Krajcik, & Soloway, 1998). For instance, Stratford and his colleges (Stratford, Krajcik, & Soloway, 1998) used a computer-based modeling tool called "Model-it" to support students in developing dynamic models to explain ecological phenomena. In particular, the modeling software designed included scaffolding features such as asking students to identify factors, to create both "immediate" and "rate" relationships, and to test models by running simulation. They found that most students (ninth-graders) were able to come up with working models employing a range of factors and relationships, to justify the relationship they set up in the model, and to test their models, though not many of them kept fine-tuning their models to meet their expectations. The study showed that using a computer-based modeling software had great potentials in supporting students' modeling practices in the context of learning disciplinary ideas.

While it is a promising sign that students can be engaged in scientific modeling at different grade level similar to what scientists do with the support of curriculum materials and innovative modeling software, methodologically, most studies relied on instruments such as clinical interviews and student models to elicit student understandings about their models and modeling experience. How did students' modeling practice develop, and more importantly, why? As in all classrooms, it is likely that the teacher plays in guiding student practice within the classroom communities. Yet, few modeling studies have investigated the role of teachers in classroom interactions to support students' modeling practices.

It is well-documented that, despite the increasing emphasis on scientific modeling in the field of science education, teachers struggle with enacting reformed-based science teaching such as engaging students in scientific modeling. For instance, teacher often lack a deep understanding of what modeling practices entail as well as the purpose of modeling (Crawford & Cullin; Justi & Gilbert, 2003). One common pitfall of engaging students in scientific practices in the context of school and classroom cultures is to focus mostly on the *product* of learning, as opposed to the *process* of learning. For instance, teachers who think of models as repositories of information (e.g.,"models of" approach, Gouvea and Passmore, 2017) focus on the representational nature of models, as opposed to attending to how models are developed and for what purposes. With a "models of" perspective (Gouvea & Passmore, 2017), modeling becomes a procedural exercise where students figure out the right things to include in the models without using models as tools for making sense of phenomena.

The proceduralization of modeling practices speaks to the importance of addressing the epistemic learning goals related to the modeling practice in the classroom settings. Sandoval (2005) argues that having a better understanding about the epistemic purposes or goals of science inquiry can lead students towards better doing science. With respect to the practice of modeling in particular, Pluta, Chinn, & Duncan (2011) also found that students leveraged their understandings of the explanatory goals of models to guide their modeling building. More recently, Berland and her colleagues (2016) proposed Epistemologies-in-Practices (EIP) framework to highlight several epistemic considerations, the purposes of student work that aim to help students engage in the practice of modeling, explanation and argumentation practices. The epistemic considerations in the EIP framework were based on earlier work on students' metamodeling knowledge (Schwarz & White, 2005) and a hypothetical learning progression of scientific modeling (Schwarz et al., 2009). While these studies presented potential fruitful direction for future study in order to better support students' productive engagement in modeling, it is still unclear how teachers can leverage the epistemic aspects of practice to promote student learning with respect to scientific modeling. Much prior research in this line so far focuses on teachers' own understanding about the nature of modeling practices (van Driel & Verloop, 1999; Henzi & van Driel 2011) rather than the role of teachers in guiding the epistemic aspects of modeling practices and how that might impact students' engagement.

Furthermore, while computer-based modeling tools have advantages in supporting students' modeling practices that is otherwise impossible with traditional paper-and-pencil models, it also adds to the complexity level that teachers need to navigate within the classroom community. Puntambekar & Kolodner (2005) argues that a distributed scaffolding framework is useful in examining teaching and learning in a complex system of scaffolds. However, few studies have focused on scaffolding for modeling practices in the field of education (Fretz et al., 2002). Most of the work done so far using a scaffolding framework investigates student learning in the area of science inquiry in general (Quintana et al., 2004), constructing scientific explanation (Delen & Krajcik, 2018; McNeill & Krajcik, 2009; Reiser, 2004), and argumentation (Belland, Glazewski, & Richardson, 2011).

As such, the goal of this study is to address the research gap and explore how teachers can scaffold for student engagement in scientific modeling in a productive way, to "trace moment-by-moment development of new ideas and disciplinary understandings as they unfold in real time settings" (p.403). In particular, I focus on one key aspect of modeling practices, using models to explain phenomena. There are two reasons I chose to study the practice of using models to explain phenomena. First, developing model-based explanations or reasoning lies at the heart of the practice of scientific modeling. Developing models to explain phenomena is also deemed as the most important aspect of modeling practices in the NGSS through Performance Expectations that students are expected to achieve by the end of the grade level. Second, while the explanatory power is the key element in what defines scientific modeling, most teachers do not know how to unpack it in the curricular contexts in a way that is accessible to students. By focusing on teachers' scaffolding strategies towards students' development in model-based explanation, this study aims to shed light on how teachers can do so in a productive way.

In particular, I ask the following two research questions,

1. What scaffolding strategies does the teacher use to support students' model-based explanations? In what ways?
2. How might the teacher's scaffolding strategies influence students' in developing their model-based explanations?

Theoretical Framework

Scaffolding Student Learning. The concept of scaffolding has been broadly used to study the process of learning in education research over the past few decades. The construct was first introduced by Wood, Bruner, and Ross (1976) as "adult controlling those elements of the task that are essentially beyond the learner's capacity, thus permitting him to concentrate upon and complete only those elements that are within his range of competence" (p. 90). By this definition, one key feature of scaffolding is this idea that the support provided by the more knowledgeable other is within the learner's capacity to complete the task that is otherwise impossible. As Cazden (1979) pointed out, the concept of scaffolding is associated with what Vygotsky (1978) called the Zone of Proximal Development (ZPD) defined as "the distance between the actual developmental level as determined by independent problem solving and the level of potential development as determined through problem solving under adult guidance or in collaboration with more capable peers" (p.86), an important concept in sociocultural theory. Therefore, the scaffolding metaphor distinguishes itself from other forms of educational support in that it "brings with it a great deal of theoretical baggage" (Stone, 1998) within the field of developmental psychology.

In terms of what constitutes the scaffolding process, Wood et al. (1976) argue that it is an "interactive system of exchange" and they have identified six "scaffolding functions"- recruiting the child's interest, reducing the degree of freedom of the task, maintaining the direction of the task, marking critical features of the task, controlling the frustration level of the child, and demonstrating the solution to the task. Underlying the six functions are two key processes intrinsic to the concept of scaffolding, dynamic assessment and adaptive support. Dynamic assessment involves constantly diagnosing the learner's current understanding as the instruction progresses. Adaptive support is related to a "careful calibration of support" (Stone, 1998) in response to the result of the dynamic assessment. Additionally, the adaptiveness of the support also suggests a process of gradually removing the scaffolds so that the learner is responsible for his/her learning, which Collins et al. (1989) later labeled as "fading" of scaffolding. The transfer of responsibility allows the learner to "internalize" the learning (Vygotsky, 1978), a term Vygotsky used to describe the cognitive process moving from an interpsychological plane to an intrapsychological plane. However, the detailed mechanisms of fading in the scaffolding framework are not clearly understood (Stone, 1998).

While there seemed to be a consensus on the theoretical underpinnings of the concept of scaffolding, researchers varied in their descriptions of what scaffolding process entails. As Pea (2004) points out, “the concept of scaffolding has become so broad in its meaning that it has become unclear in its significance”. This is partly so because over time the knowledgeable other in the scaffolding framework has been expanded from tutors/parents (Cazden, 1979; Wood et al., 1976) to teachers in classroom (Palinscar & Brown, 1984), peers (Hogan, Nastasi, & Pressley, 1999; Pata, Lehtinen, & Sarapuu, 2006), computer software (Fretz et al., 2002; Quintana et al., 2004; Reiser, 2004), and curriculum materials (Davis, 2003) with the advances in sociocultural theory and distributed cognitions. Meanwhile, the concept of scaffolding has also been expanded from one-to-one interaction to supporting multiple ZPDs with multiple supports (Puntambekar & Hubscher, 2005; Tabak, 2004). The notion of distributed scaffolding was introduced by Puntambekar and Hubscher (2005) to recognize classroom as a complex system of scaffolds in which a collection of curricular materials, teacher instruction, activity structure, peer feedback can work together to support learners. Building upon this work, Tabak (2004) argued that distributed scaffolding can occur in three different patterns, differentiated, redundant, and synergistic. Differentiated scaffolds is when multiple supports each address a different learning goal; redundant scaffolds refers to multiple supports addressing the same learning goal; synergistic scaffolds is when multiple supports interact and work in concert to guide a particular learning goal, especially for complex learning tasks involving “a mélange of knowledge, skills, and values that few if any individual mediums or agents exist that would be able to support the development of these practices” (p.318).

In this study, I draw on the notion of distributed scaffolding as my theoretical lens as I explore how teacher provides scaffolds to supports student in using models to explain phenomena, a complex learning task with other types of scaffolds (e.g., a model-based curriculum unit and an online modeling tool) available in the learning context. It is also important to note that, as I examine teacher instruction as scaffolds, I seek to adhere to the tenet of the original scaffolding framework with its "theoretical baggage" in sociocultural learning theory. In particular, I will highlight the aforementioned key features of scaffolding, namely dynamic assessment and adaptive support, that many recent studies on scaffolding "surprisingly" failed to address (see the review by Belland, 2014). I will describe further what I mean by scaffolding strategies and how I identify them in the following section.

Method

Research Design. I use a case study design (Yin, 2009) to explore the relationship between the teacher's scaffolding strategies to support model-based explanation and students' modeling practice. The case study approach enables me to better understand the complex interactions between teacher and students within a science classroom over time that lead to student's development in model-based explanation.

Participants. Mrs. A is an experienced science teacher in a Midwest public middle school where more than half of the student population are eligible for free or reduced lunch. Mrs. A has a bachelor degree in biology and she has taught middle school science for over 20 years. In terms of pedagogical approach, Mrs. A was particularly effective in eliciting student ideas and making connections between classroom science learning and student daily life. Before this study, Mrs. A collaborated with our Building Models Research Team to implement a unit on ocean acidification using our web-based modeling tool (SageModeler) in the spring of 2016. Mrs. A had also participated in a 3-day professional development session on developing modeling-based NGSS-aligned curriculum materials using SageModeler in the summer of 2016. In that session, since Mrs. A was planning to implement an IQWST unit (Krajcik, Reiser, Sutherland, & Fortus, 2012) for her 7th grade classes during the academic year of 2016-2017, I worked with her to adapt the earth science unit in order to provide students with more opportunities to engage in the practice of scientific modeling.

During the data collection of this study, I also conducted semi-structured interviews with five focus students before, in the middle, and after the enactment of the unit for the purpose of eliciting ideas about their modeling experiences. The focus students were chosen by Mrs. A so that they differed with respect to their science achievement levels.

Curricular Contexts. This study took place in the context of an 8-week modeling-based IQWST earth science unit (weather unit, see Table 4) that Mrs. A and I adapted over the summer of 2016. In the weather unit, students were expected to create, revise, and evaluate models to answer the driving question, "How and why does a storm form?" Students drew on their everyday experiences to create their initial storm model. They then draw on their knowledge about energy to analyze what happens to matter and energy to cause surface air to be heated. Students then investigate what happens to the air after it is heated. They had the opportunities to collect additional evidence from a series of empirical investigations to attempt to explain why hot air rises and revise their storm models accordingly. While trying to make as fewer changes to the original curriculum as possible, Mrs. A and I decided to make the following two primary adaptations, 1) asking students to develop models in our web-based modeling tool, SageModeler, after each time they created or revise their diagrammatic models of storm, and 2) asking students to develop an initial model, both diagrammatically and on SageModeler, to explain how storm forms at the beginning of the unit. The goals of the adaptation are two folds. First, we wanted students to have the opportunities to use different types of models when explaining the same phenomena so that they could see the merits and limitation of each type of model. Second, we hoped students would develop semi-quantitative reasoning skills with the support from the modeling tool (SageModeler) that diagrammatic models do not afford students with. We hypothesized that the semi-quantitative feature of the modeling tool might be more accessible to middle school students if they had a chance to use diagrammatic models to explore the mechanism of the same phenomenon first.

With respect to the timeline of the study, this study was conducted in the spring of 2017 and the enactment spanned from mid-March towards the end of May. During the two and half months, Mrs. M's 7th grade classes also had one-week spring break during the first week of April and took a state-level assessment for three consecutive days towards the end of April. Prior to the study, Mrs. A implemented an 8-week unit on energy transfer that was part of a multi-year NSF-funded research projects. Therefore, students in her class also had experience using energy transfer and conservation of energy as a lens to explain phenomena. In addition, at the beginning of the academic year 2016-2017, Mrs. A had enacted the IQWST 7th grade chemistry unit with a focus on chemical reactions ("How Can I Make New Stuff from Old Stuff?). In the unit, students had multiple opportunities to create diagrammatic models to explain relevant phenomena. Given the reform nature of those curricular units, by the time Mrs. A enacted the weather unit, she already built up a classroom community where students felt comfortable asking questions, expressing their ideas, and working collectively to develop knowledge products (e.g., scientific models, scientific explanations, etc.).

Table 4. Outline of the Adapted Modeling-based Weather Unit

	Title of Learning Tasks	Performance Expectation of Learning Tasks
Lesson 1: What is weather?	Activity 1.1 Identifying Weather Conditions Around the World Activity 1.2 Creating Initial Storm Models* Activity 1.3 Setting Up the Driving Question Board	● Generate questions about the cause of weather phenomena in terms of transfer of energy and flow of air and water ● Develop models to explain how different weather conditions contribute to a storm.
Lesson 2: What makes air hot?	Activity 2.1 It Is Heating Up Activity 2.2 A Little Heat from Me to You Activity 2.3 Heating Up Model*	● Construct and defend a model of how air is heated by the sun that includes the conversion of solar energy to thermal energy in Earth's surface and the transfer of energy via conduction from Earth's surface to air.
Lesson 3: What happens to the hot air?	Activity 3.1 How Do Differences in Temperature Affect Air Masses? Activity 3.2 What Happens When Air Is Heated or Cooled? Activity 3.3 Why Heat Rises	● Construct and defend a model of convection that explains why hot air rises and cold air sinks in terms of movement of air masses due to density differences ● Apply a model of convection to explain one cause of wind
Lesson 4: Where does the energy come from in a storm?	Activity 4.1 Temperature Difference and Movement of Air Masses Activity 4.2 Is a Storm Cloud Different from Other Clouds Activity 4.3 Creating Revised Storm Models*	● Revise storm models to explain the cause of energy flow, precipitation, and air movements in convective storms.
Lesson 5: What can weather maps tell us?	Activity 5.1 What Can Weather Maps Tell Us? Activity 5.2 Creating an Isobar Map	● Analyze weather maps to identify and track movement of high- and low- pressure areas
Lesson 6: Does the storm model fit data from a storm?	Activity 6.1 Can We Identify Patterns in Data? Activity 6.2 Can the Storm Model Explain the Data? Activity 6.3 Creating Final Storm Models*	● Apply storm models to explain patterns in weather ● Evaluate the fit of the model against the data

(* indicates the adaptation part of the curriculum)

Web-based Modeling Tool. In this study, students used SageModeler (Damelin, et. al, 2017), an open source web-based modeling tool to explain how and why storm forms. SageModeler is designed to support students using models to explain phenomena, especially regarding those complex systems such as eco-system and weather patterns. It also provides scaffolding features including 1) visual representation of variables and relationship customized by students, 2) ability to define functional relationship without having to write equations, 3) an exploratory data-analysis environment designed for students.

In particular, with respect to model-based explanation development, SageModeler embedded scaffolding features into a separate window (e.g., "relationship box") that helps students to identify the relationship between different factors or variables that are relevant for the system or to explain the phenomenon. In the relationship, students are prompted to choose appropriate semi-quantitative relationship between variables and provide evidence and/or reasoning ("why do you think so?") to support their choice (see Figure 4).

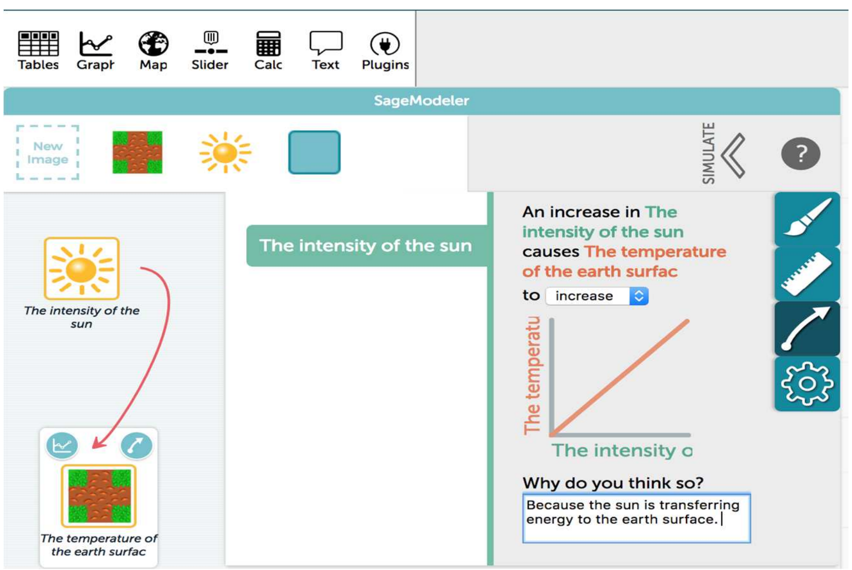

Figure 4. The interface of the relationship box in SageModeler

Data Sources.

Video-recordings. The primary data for this analysis included video-recordings of key modeling lessons in which students constructed, revised, and evaluated their storm models. The video-recordings usually consisted of both whole-class discussion and small group work or discussion. Altogether, there were 12 class periods of Mrs. A's instruction with each class period lasting about 50 minutes (see Table 5).

Table 5. Video-recorded modeling lessons in the weather unit

Lesson #	Dates	Curricular Learning Activities	Description of the Modeling Activities
L1, L2	3/21, 3/23	Activity 1.2 Creating Initial Storm Models	● Create initial storm model on paper ● Share initial storm model ● Create initial storm model in SageModeler
L3	3/30	Activity 2.1 It Is Heating Up	● Create heating up model on paper
L4, L5	4/10, 4/11	Activity 2.3 Heating Up Models	● Revise heating up model on paper ● Create heating up model in SageModeler
L6, L7	4/18, 4/19	Activity 3.3 Why Heat Rises	● Create group model of convection on paper ● Share group model of convection on paper ● Create class model of convection on paper
L8, L9	4/25, 4/27	Activity 4.3 Creating Revised Storm Models	● Create revised storm model in SageModeler ● Share revised storm model in SageModeler
L10, L11, L12	5/12, 5/15, 5/18	Activity 6.3 Creating Final Storm Models	● Create final storm model in SageModeler ● Share final storm model in SageModeler

I chose those modeling lessons for our analysis because within those lessons, the teacher spent the majority of the class time engaging students in various aspects of modeling practices. Those aspects included: helping students make sense of the relevant phenomena their models were supposed to explain, organizing discussion around criteria for developing models, giving specific instructions for model creation, revision and evaluation, facilitating student presentations of their models (both individual and group models), and facilitating peer feedback.

Semi-structured teacher interview. In order to better understand Mrs. A's teaching goals and strategies as well as to triangulate my analysis of Mrs. A's instructional practices, I conducted a semi-structured teacher interview with Mrs. A at the beginning of the enactment that lasted about 20 minutes. In the interview, I asked Mrs. A to talk about 1) her overall vision of science learning and modeling practices in particular, 2) her goal for the weather unit and any scaffolding strategies or to help achieve the goal, and 3) how she planned to implement the modeling tool (SageModeler) in the unit.

Semi-structured interviews of focus students. To elicit students' ideas about their models and modeling experience, I collected semi-structured student interview data from five focus students in Mrs. A's class three times over the course of the unit. The pre-interview took place at the beginning of the unit after students having constructed their initial storm model. The mid-interview and the post-interview were conducted after students had created their revised storm model and final storm model respectively. During the semi-structured interviews, I asked students to (1) describe their models and model-based explanations generated in class, (2) describe their rationale for developing and revising those models. The interview questions are designed to specifically address how well students' models are able to answer the driving question as well as any evidence students use to justify that their models are correct. In addition, in the post interviews, I also ask the focus students to create a model to explain a new phenomenon-how and why hurricane forms and why it often weakens when it hits the land. The task is designed to assess if students are able to use what they learned in the weather unit and apply it to a closely related new context. The problem also calls for semi-quantitative reasoning skills as students need to explain why the strength of the hurricane decreases in addition to accounting for the mechanism of the hurricane.

Focus students' models. In order to analyze the five focus students' development in model-based reasoning, I collected their initial, revised, and final models of storm, both diagrammatic and on SageModeler over the course of the unit. It is also important to note that the student models are analyzed together with the semi-structured student interview as the two data sources are complementary to each other in order to characterize students' modeling practices.

Data Analysis.

Teacher scaffolding strategies. When examining the teacher's scaffolding strategies, I analyzed the teacher's talk during the whole-class discussion using the written transcripts of the video-recordings of the 12 key modeling lessons. I define scaffolding as supports that a teacher provides students to achieve the target practice without which students would be unable to achieve. In accordance with the original tenet of scaffolding framework proposed by Wood and his colleagues (1976), I emphasize the two key features in my data analysis associated with scaffolding, dynamic assessment and adaptive support.

First, I identified all scaffolding episodes where Mrs. A attempted to scaffold student learning with respect to model-based explanations. The unit of analysis is episode as scaffolds is dialogic in nature. When searching for a scaffolding episode, the conversation had to meet the following requirements in order to count as a scaffolding episode:

1) The focus of the episode is a sub-component of the practice of using models to explain phenomena (e.g., what causes a storm);

2) The teacher should have a sense of where the student/class is at before making any scaffolding move. This is often done when the teacher asks questions to assess student understanding.
3) The feedback/instruction/question that the teacher provides should potentially help students to advance their understanding or practice with respect to developing their model-based explanation.

It is worth noting that sometimes a scaffolding episode did not include the process of explicitly evaluating students' prior knowledge. However, for those instances, it was clear from reading the transcripts that the teacher already had a good sense of where students are at (e.g., the teacher did the evaluating process in the previous lesson) and made specific scaffolding moves accordingly. On the contrary, if the episode was mainly about assessing or reviewing students' understanding, as oppose to helping students advance their thinking, it should not be qualified as a scaffolding episode. It is also important to note that, based on my definition of scaffolding, I did not make the assumption that teachers' scaffolding is inherently meaningful. Rather, my definition of scaffolding focuses on whether it helps student to achieve certain aspects of the target practice. In other words, teacher scaffolds could be either procedural or epistemic, as long as it helps student to appropriate the target practice (e.g., developing model-based explanations) that students were unable to do without such support. Once I identified all scaffolding episodes, I summarized what aspects of model-based explanations the teacher was scaffolding for each episode.

Second, in order to unpack how Mrs. A's scaffolding approach supported students' development in model-based explanations, I identified her scaffolding moves that advanced student understanding or practice concerning model-based explanations. For this study, I define a scaffolding move as the part of teacher talk that functions as advancing student thinking and potentially building towards the target practice, using models to explain phenomena. Note that the unit of analysis for scaffolding moves is an utterance, the smallest unit the function which could be identified. An utterance could be part of a sentence, a whole sentence, or a dialogic interaction between teacher and student. From the preliminary analysis of the data, Mrs. A's scaffolding moves could be sorted into two broad categories, questioning and teacher-centered guided instruction. I define teacher-centered guided instruction as the teacher being the authoritative source in guiding students' participations in knowledge building.

Once I identified all the scaffolding moves for each episode, I used a constant comparative approach (Glaser & Strauss, 1967) to develop codes to further categorize the types of questions Mrs. A used to scaffold students towards different aspects of model-based explanations. After identifying and coding utterances, I split and/or merged the original codes into new codes that could be applied to different utterances. In Table 6 below, I listed the codes I developed for teacher questioning approaches. When developing codes, I referred to Pea (2004)'s idea of "channeling" as one way of scaffolding and Chin (2007)'s three sub-categories (e.g., pumping, reflective toss, and constructive challenge) for teachers' Socratic questioning approach that stimulates productive student thinking. The feature of each type of question and a corresponding example from the classroom videotaped data are also provided.

Finally, I reexamined the data with the new codes and generated themes to characterize how the teacher used questions to scaffold the development of students' model-based explanations.

Table 6. Developed codes for teacher questioning approaches

Types of Questions	Features	Examples
Channeling	Questions that direct students towards certain feature of the learning task	Mrs. A: *What do we know about molecules when they get energy?* (L7)
Pumping	Questions that encourage students to provide more information via explicit request	Mrs. A: *What else do we need to have in here?* (L10)
Reflective toss	Questions that respond to a prior utterance made by the student to throw back the responsibility of thinking	Mrs. A: What else should be on our model? Student: Wind. Mrs. A: *So what causes wind?* Student: Differences in the low and high pressure. (L9)
Constructive Challenge	Questions that stimulate student thinking instead of giving direct corrective feedback	Mrs. A: How is the sun exactly heating up the air? Student: It gives energy to the atmosphere and then atmosphere then transfers it to the air. Mrs. A: Okay, so here's a question for you guys. *Is the air at the top of the atmosphere, like at the top of our Troposhere gonna be warmer or colder than down here?* (L4)
Students-to-consider	Questions that do not require students' immediate response, but for students to consider	Mrs. A: You can compare your temperature readings to what Oslo has, what Belem has, what Atlanta has. *Does your model explain what's happening in those (cities)?* Because if it does, then we should be able to use your models to predict what's happening. If it isn't, then make revisions. (L5)
Information-seeking	Questions that require students to recall information or give a predetermined short answer	Mrs. A: So they are going to spread out as they bump into each other. *What does this whole thing then become?* Student: Hot air mass. (L7)

Development of Students' model-based explanations. In order to answer my second research question, I analyzed the student interviews with a focus on students' generated model-based explanations. For each focus student, I first identified sections in the interviews in which the students responded to questions related to model-based explanations. In each section, I coded students' responses based on the coding rubrics (see Table 7) that I developed to capture 1) what students considered as the major factors of the phenomena examined, 2) how students unpacked the factors or the relationship between those factors or variables, 3) the nature of reasoning presented in their model-based explanations, and 4) the source of evidence students used to support their model-based explanation.

Table 7. Coding rubrics for model-based explanations in the weather unit

	Range of Ideas that Students are Expected to Have to Explain the Driving Question: What Causes the Storm?
Factors	1a. The sun/energy source 1b. Humidity/water vapor/water molecules/precipitation 1c. Air mass/air molecules 1d. Temperature/air temperature/heat 1e. Wind/wind speed/wind strength 1f. Pressure
Processes/Relationships	2a The sun transfers energy to the earth surface, and the earth surface transfers part of the energy it absorbs to the air above it. (sun-earth's surface-air) 2b. Liquid water on the earth surface evaporates into the air to become water vapor, and as they transfer energy to the surroundings, they condense into clouds or precipitations. (evaporation-condensation) 2c. Hot air rises, and cold air moves in to take its place (convection). 2d. Air masses move when high-pressure air pushes into the space of low-pressure air. Higher differences in pressure result in stronger wind. (Pressure difference-wind)
Sources of evidence	3a. Teacher 3b. Peers 3c. Personal experience 3d. Prior knowledge 3e. Empirical investigations/experiments

It is important to note that the coding rubric is content-specific as it is developed based on what students are supposed to have learned in the context of the weather unit. In addition, as mentioned in the previous section, when coding student interviews, student models are used as an essential complementary piece to help understand students' modeling practices. I made the decision rule that any time students included a relevant component (e.g., factors, processes, sources of evidence) into their models, but was not explicit about it in the interview, it should be captured as part of students' model-based explanation as students can be implicit about their reasoning and skip things that they think obvious in the context of a semi-structured interview. For instance, if a student drew the sun as the energy source in the diagrammatic model or included the sun in the SageModeler without explicitly mentioning it in the interview, 1a would still be coded as part of the student's model-based explanation.

In addition to coding students' performances regarding their model-based explanations, I also noted students' rationales about their model-related decisions throughout the interviews (e.g. "I want to add in the energy transfer piece so that other people can understand my model better"), which helped uncover the purposes or goals that drive students' modeling work that may not be captured by looking at the student models alone. After I coded students' model-based explanations, I then compared students' pre-interview codes, mid-interview codes, to post interview codes in order to characterize the development in each focus student's model-based explanations. Constant comparisons were also drawn between Mrs. A's scaffolding strategies and focus students' development in model-based explanations to reveal patterns that might indicate how the teacher's scaffolding strategies influence student practice.

Findings

In this section, I organize the findings around my analysis about the teacher's scaffolding strategies and the development of students' model-based explanations in order to answer the two research questions. First, I describe an overview of Mrs. A's scaffolding episodes across the unit. I then show how Mrs. A used different types of questions to provide scaffolds for students to develop their model-based explanations, both with respect to content and epistemology. With respect to student practice, I present my analysis of student interviews to demonstrate the patterns I found in terms of developing model-based explanations among the five focus students. I then focus on one particular student, Linda, to further illustrate how she developed proficiencies in constructing model-based explanations and in what ways her modeling work might be influenced by Mrs. A's scaffolding strategies.

Teacher Scaffolding Strategies. My analysis of Mrs. A's scaffolding episodes across the unit showed that Mrs. A had provided scaffolds for various aspects of model-based explanations throughout the unit (see Figure 2). In Figure 5, I presented the number of scaffolding episodes found in each video-recorded key modeling lessons as well as the focus of the scaffolds. It is important to note that for each key modeling lesson, I only identified a small number (0-3) of scaffolding episodes. This does not imply that Mrs. A did not provide additional scaffolds to support students' modeling practice. Rather, because of 1) the dialogic nature of scaffolds, 2) the restricted definition of scaffolds, 3) the fading of scaffolds as the unit progresses, it is not uncommon to only find a couple of scaffolding episodes for each lesson.

Altogether, I found Mrs. A provided scaffolds for seven aspects of the practice of using models to explain what causes a storm. These seven aspects fell into two main categories, content scaffolds and epistemic scaffolds. While content scaffolds support students in developing content knowledge related to the phenomena (e.g., what causes a storm), epistemic scaffolds are mainly about scaffolds that advance students' epistemic ideas about models and modeling (such as models are used for explaining phenomena). With respect to content knowledge, Mrs. A scaffolded all four key processes or relationships that I identified in Table 7, which are essential for explaining the phenomena, 1) Sun-earth surface-air, 2) Convection, 3) Evaporation-condensation, and 4) Pressure difference-wind. Mrs. A's scaffolds for content knowledge development started in L4 (sun-earth surface-air) and continued towards to end of the unit (L11). In terms of epistemic scaffolds, Mrs. A had provided scaffolds for the following epistemic ideas about models and modeling, 1) models are used to explain phenomena and evidence is used to support model, (Explain phenomena & Use Evidence), 2) data generated by model could be compared with external/empirical data to see whether the model is correct or not (Compare data), and 3) in order to make a runnable model with a semi-quantitative modeling tool, identified key components of the system need to be set up as variables as opposed to objects (Variable set-up in SageModeler). Mrs. A's scaffolds for epistemic ideas were scattered through the unit, with "explain phenomena & use evidence" at the beginning of the unit (L1), "compare data" in the middle of the unit (L5), and "variable set-up in SageModeler" four times throughout the unit (L2, L5, L8, L10).

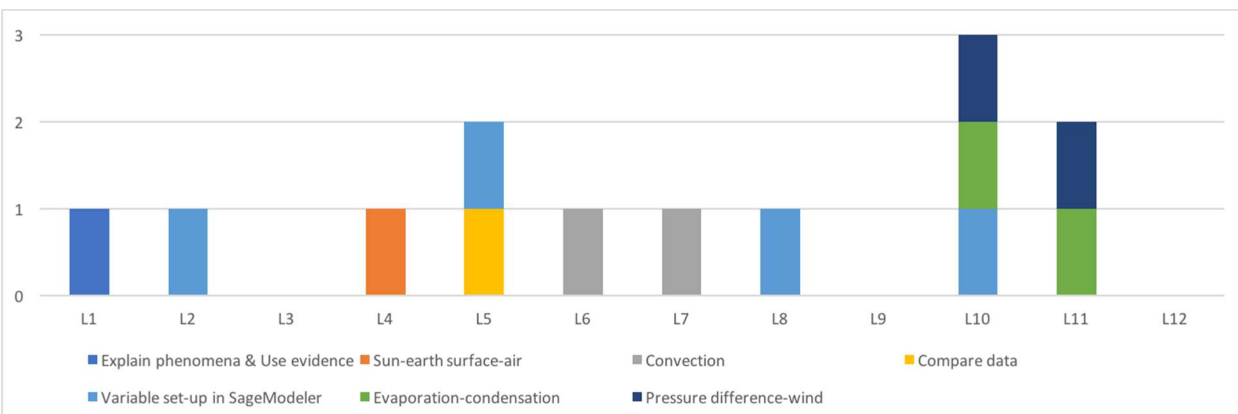

Figure 5. Mrs. A's scaffolding Episodes across the weather unit

While it is useful to see what aspects of the practice Mrs. A scaffolded, the ways in which Mrs. A provided these different types of scaffolds are also important to better understand her overall scaffolding strategies. From the analysis of the video-taped data as well as the teacher interview, it appeared that Mrs. A used a lot of questioning to support students in developing model-based explanations. The following excerpt from the teacher interview that took place at the beginning of the unit highlighted Mrs. A's view on her scaffolding strategies.

> **Interviewer: What scaffolding strategy did you use to help them (students) learn science?**
> Mrs. A: *I tend to ask them a lot of questions.* I don't tell them the answers always, *but I try and get them there by asking questions about what are they noticing.* Like, even in the lab today, "Okay, what's going on here? Okay, metal's a conductor." They have the words, but they don't always pull in the idea. "Okay, what does it mean if something can thermally conduct?" "Because it's a metal." "Okay, yeah, so why? What's going on inside of that?" So, *I think I just keep asking them questions, until they start making the connections in their own brains.*

As shown in the transcript, Mrs. A thought that asking question, instead of giving answers right away, is the key to help "get them there" and "make connections in their own brains." The example she gave also illustrated that she used questions to elicit students' ideas and help them advance their understanding (e.g., what conduction means at the micro-level) about the phenomena.

The analysis reveals that Mrs. A used six types of questions when scaffolding for students' development in model-based explanations. Among the six types of questions, "information-seeking" questions are thought to be counterproductive to students' articulating and advancing thoughts and ideas about the topic, similar to the beginning stage of the Initiation-Response-Evaluation (IRE) pattern of discourse (Mehan, 1979). In Figure 6 below, I present how Mrs. A used a combination of different questioning approaches to scaffold for various aspects of the practice model-based explanation. Note that the scaffolding move categorized as "teacher-centered guided instruction" is also included in Figure 6 as it is the other major scaffolding move besides questioning.

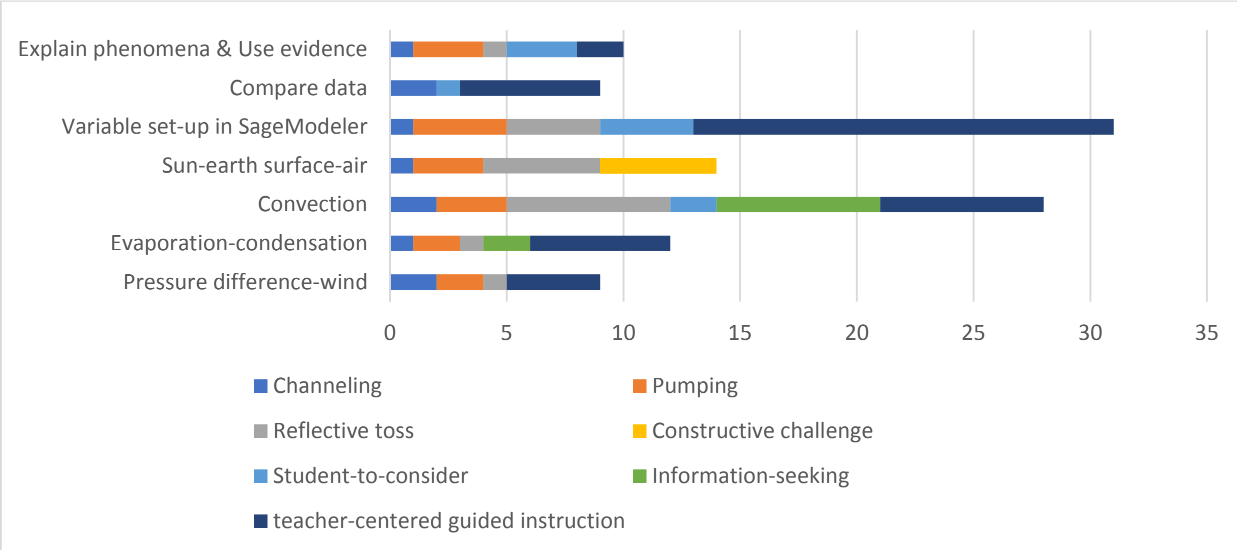

Figure 6. Mrs. A's scaffolding moves across the weather unit

From Figure 6, two general patterns emerged with respect to Mrs. A's scaffolding strategies. For the first pattern, which I call scaffolding for sense making, Mrs. A used a combination of questions (e.g., channeling, pumping, and reflective toss, constructive challenges, student-to-consider questions), which functioned as eliciting students' ideas and advancing student thinking, to provide scaffolds for students' development in both content understanding and epistemic ideas about models. For the second pattern, which I refer to as scaffolding for task completion, Mrs. A used teacher-centered guided instruction as the primary scaffolding moves for "compare data" and "variable set-up in SageModeler," which were related to student using SageModeler. In the next section, I further describe the two emerging patterns with examples from the classroom video data.

Pattern 1: Scaffolding for sense-making. The first pattern, scaffolding for sense-making, describes how Mrs. A used a combination of different questions that encouraged students to articulate their ideas, to advance their thinking, and to reconsider their ideas when they do not align with available evidence. In other words, the combination of Mrs. A's scaffolding questions served the purposes of helping students make sense of the examined phenomena that is essential for the practice of developing model-based explanations. In this section, I present a couple of excerpts from Mrs. A's classroom videotape data that were representative of her scaffolding approaches to illustrate how Mrs. A provided scaffolds for students' sense-making.

The first excerpt occurred during the learning activity 2.3 (L4), where students were expected to revise their initial model of "what makes air hot?" on paper.

T: We are going to revise our heat-up model. ***So what's heating up the air? Where does the energy come from?*** [Channeling]
S: The sun.
T: The sun, okay. ***So how is the sun exactly heating up the air?*** [Reflective toss]
S: It gives energy to the atmosphere and then atmosphere then transfers it to the air.
T: Okay, so here's a question for you guys. ***Is the air at the top of the atmosphere, like at the top of our Troposhere, gonna be warmer or colder than down here?*** I'm talking about the first layer where all of our weather occurs. [constructive challenge]
S: I personally say warmer.
T: ***Why is that?*** [Reflective toss]
S: Because it's closer to the sun.
T: Then I have a question for you guys, ***if the top of the troposphere is warm, because the sun is hitting that, then how come the mountains are cold, like Tennessee there is snow on the top of the mountains?*** [constructive challenge] When I drive up, I'll start at the bottom of the mountain, and I'll go driving up to the top of the mountain and there's snow up there. ***If that's hotter because it's coming from the sun, would that be the case?*** [constructive challenge]
S: Because there's not a lot of oxygen?
T: I can still breathe. I don't need any special mask, it's not like Mount Everest or anything like that, but it's definitely cooler. ***Shouldn't it be warmer out there?*** [constructive challenge] But it's not.

At the beginning of the conversation, Mrs. A started with a channeling question about the energy source, "where does the energy come from?" to guide students towards thinking about how energy was involved in the phenomena (e.g., what makes air hot?). She then made a reflective toss move to ask the student how the energy transfer from the sun to their air occurred. These two questions successfully elicited students' understanding about the phenomena, that the sun transfers energy to the air via the atmosphere. When coding for scaffolding episodes, the two exchanges made between teacher and students was coded as the evaluating phase, to get a sense of where students are at, which is the dynamic assessment stage of scaffolding. Next, instead of correcting students' alternative idea, Mrs. A used the "constructive challenge" approach to prompt students think about a scenario (e.g., Trophosphere) that might work against their ideas. However, either students did not know the fact that Trophosphere is colder or had no prior experience (outside temperature reading on the entertainment system during a flight), the student came up with an answer that could actually be supported by his idea ("because it's closer to the sun"). Apparently, the first constructive challenge made by Mrs. A was not effective. Mrs. A then used another "constructive challenge" to tell students the fact that it was cold on mountains, with which students might be more familiar. This time, she was explicit about the student's idea not being able to explain the fact that it was cold on mountains.

It is important to note that Mrs. A's use of "reflective toss" questions to get a better sense of the student's alternative idea as well as her adjustment in her "constructive challenge" question to make it more accessible to students reflect the dynamic nature of scaffolding, that teacher needs to provide scaffolds appropriate to student current level of understanding. It is also evident from the episode that Mrs. A was trying to help students advance their understanding about how energy is transferred from the sun to the air through sense-making as opposed to rote memorization. Instead of telling students that the sun transfers to the earth's surface via air first, Mrs. A used the student's own idea as the starting point of her scaffolds. By asking two "constructive challenge" questions, Mrs. A attempted to provide evidence that the student can use to reject his idea, which is a key epistemic practice of the discipline of science. The excerpt below is the continued conversation following the previous excerpt.

T: Here's another question. It's summer time we don't have school, we go to Lake Michigan, my favorite lake in the world. It's a nice sunny day, some poofy clouds every once in a while, but a very beautiful day. We've got our sunblock on, so we don't end up with skin cancer or anything like that. So, we decide to leave our shoes in the car because this is what I always do, I love being barefoot in the summer time. The sand is hot, right? Okay, ***how is it getting hot?*** [constructive challenge]

S: Because there's more sun.

T: So the sun is heating it, ***is that what you're saying?*** [pumping]
S: Yes.
T: Alright, ***yeah Betsy?*** [pumping]
S: The reason the sand would be hotter in the summer, is because sand is normally out in the open like Lake Michigan. That's also why at night it's colder.
T: ***So sand cools down at night?*** [pumping]
S: It would cool down at night because there's less energy from the sun.
T: ***Where did that energy from the sand go then?*** [reflective toss]
S: It would transfer either to the air or something near it.
T: Okay, so it could transfer to the air.

In this episode, Mrs. A proposed another "constructive challenge" question, "how is the sand getting hot?" She also embedded the question within a more engaging scenario that was related to student everyday life, going to the beach near Lake Michigan in the summer. The purpose of the "constructive challenge" question was the same as the previous one, to provide evidence that could be used to reject the idea that the sun transfer energy to the air directly. Mrs. A then used "pumping" approach twice to elicit students' ideas about how sand gets hot before one student mentioning about the energy loss of the sand at night. As if Mrs. A was anticipating the answer, she followed up with a "reflective toss" question about where the energy of sand transfer to. This "reflective toss" question is non-trivial, but key to Mrs. A's scaffolding approach. By answer this question, students finally reached the conclusion based on their own experience that energy could be transferred to the air from the earth's surface such as sand. Again, this episode demonstrated that the key to effective scaffolding is to provide an appropriate amount of support depending on student current understanding or prior knowledge. In this case, each of Mrs. A's scaffolding moves including engaging "constructive challenge" scenario, the "pumping" approach, and the "reflective toss" question with a focus on energy transfer, served its particular purpose for helping students to reject their original idea and to reconsider alternative ones that align with the evidence given.

The previous two excerpts demonstrated how Mrs. A used a combination of questioning approaches and provided scaffolds for students' content knowledge about how the sun transfer energy to the air through sense making. Over the course of the unit, Mrs. A also used similar scaffolding strategies for helping students develop other key content ideas (e.g., convection, evaporation-condensation) and epistemic ideas. The following episode was an example of how Mrs. A provided scaffolds for students' development in epistemic ideas about models and modeling. It took place at the beginning of the unit (L1) before students were asked to construct their initial storm model on paper.

T: ***Why do we make models? What is the purpose?*** [channeling]
S: How to better understand what's going on.
T: Okay, to understand what's going on. ***What else, do you think?*** [pumping]
S: To make it simpler. Pretty much to understand it better with just making it more simple, so you understand pretty much what's going on.
T: Okay, yeah, so that you could understand it and also that you could explain it to somebody else so they could understand it. That would be a good use. ***What else could we use our model for?*** [pumping]
S: We could show energy transfer.
T: Okay, to show how energy is being transferred in there. ***Do you think it's possible that energy is transferred in a storm?*** [reflective toss]
S: Yes.
T: Okay, so maybe that's in there. ***What else?*** [pumping]
S: It can describe and explain how things work.
T: Yeah, we should be able to do a claim evidence reasoning from that. For a good model, we should be able to use that to actually justify what we're saying, to explain what we're saying. OK, our driving question is what's causing a storm, or how does a storm happen? I want you to start making a model. ***As you're making a model, I want you to think about, "Okay, does my model explain what causes a storm? How do I know that's the way it happens? What knowledge or evidence do you have that supports that model?"*** [student-to-consider]

Mrs. A started the conversation with the channeling question related to the purpose of the modeling practice, "why do we make models? What is the purpose?" She then continued with a couple of "pumping questions" to elicit more ideas from students, "what else, do you think?" and "what else could we use models for?" Once a student mentioned "models could show energy transfer," she followed-up the response with a "reflective toss" to help students make the connection between a statement about models in general and the particular model (initial storm model) that students were expected to construct. After another student brought up that “it [models] can describe and explain how things work,” Mrs. A elaborated this student’s idea with her own view on models modeling, that a good model could generate explanations justified by evidence and reasoning. It is interesting that Mrs. A referred to “claim, evidence, reasoning,” the scaffolding structure for constructing scientific explanations (McNeill et al., 2006; McNeill & Krajcik, 2009) highlighted in the IQWST units. While obviously there are differences between the practice of constructing explanations and developing models, the two practices share common goals such as accounting for how and why things occur in the natural world. By making the connection between “claim, evidence, reasoning” and constructing models, Mrs. A highlighted the explanatory feature of modeling and drew on students’ prior knowledge as a valuable resource at the same time. Mrs. A ended the conversation with her instruction for making an initial storm model. Specifically, she asked students to think about how to explain the driving question “what causes a storm?” as well as what evidence or prior knowledge to draw from with. By using “student-to-consider” questions to guide students’ initial modeling work, Mrs. A provided scaffolds for the epistemic aspects of model-based explanations.

Similar to the previous two examples, in this episode, Mrs. A started with assessing students’ understanding via the “channeling” and “pumping” questions. She used “reflective toss” and “student-to-consider” questions to further scaffold students towards applying the epistemic ideas to constructing the initial storm model on paper. Note that Mrs. A’s scaffolding from “models in general” to “students’ own models” was particularly important in that it helped students to contextualize these abstract epistemic ideas into the goals of their own work.

Pattern 2: Scaffolding for task completion. The second pattern, scaffolding for task completion, characterizes how Mrs. A used mainly teacher-centered guided instruction when scaffolding for students' work in SageModeler (e.g., comparing external data and model output, setting up variables). For instance, throughout the unit, Mrs. A emphasized the importance of setting up measurable variables in SageModeler as many students started with using objects. This was actually common practice among students because before constructing or revising models in SageModeler, they had constructed the corresponding models on paper first, which does not require them to identify the key components in the system as variables. However, in order to make a "runnable" model in SageModeler, one has to define each factor that contributes to explaining the phenomena as a variable. The "relationship box" where students are expected to set up the semi-quantitative relationships among factors also prompts students to do that for the purpose of promoting students' quantitative reasoning skills. The following excerpt took place in Activity 4.3 (L8) where students were asked to revise their initial storm model in SageModeler.

T: Okay, Carlos, ***what do you notice about your model now that you might change?*** [channeling]
S: A lot of things.
T: ***What might you start with?*** [pumping]
S: Like adding the energy transfer from the sun to the earth's surface.
T: Okay, so you might add an energy transfer. ***Would you leave it as just sun? What would you change it to?*** [information-seeking]
S: Sun's temperature?
T: Okay, but ***what do we kind of measure here? What do we know about what's happening at the equator?*** [constructive challenge/information-seeking]
S: There's more direct sunlight.
T: More direct sunlight, so the intensity is a lot higher, right? ***So we need to include something like that.*** [direct instruction] Look back at your model right now before you do any changes to it, ***did you have a lot of objects there?*** [information-seeking]
S: Yeah.
T: Okay. ***So we need to think in terms of variables. Things that can be measured. Things that can change that we can increase and decrease. Go ahead and make those revisions to your model.*** [direct instruction]

At the beginning of the conversation, Mrs. A called on a student and asked him about revising his initial model, "what do you notice about your model that you might change?" After

Mrs. A's "pumping," the student mentioned adding energy transfer from the sun to the earth's surface. Instead of following up with questions about why he wanted to adding energy transfer to elicit students' rationale of model revision, Mrs. A asked a specific "information-seeking" question about what the student could change the label of sun into. This scaffolding move indicated that Mrs. M prioritized students changing objects into variables in SageModeler when revising models. She also had a "target answer" for her "information-seeking" question, which is "the intensity of the sun." However, the student did not come up with the "correct answer." Mrs. A then asked two "constructive challenge" questions, "but what do we kind of measure here? What do we know about what's happening at the equator?" expecting students to reconsider his response. The questions referred to the activity in the previous lesson in which students participated when the idea of "the sun's intensity" and "direct sunlight" were first introduced. After the student said "there's more sunlight," which is close to the scientifically correct answer, Mrs. A gave the guided instruction that the student needed to include something like "the sun's intensity." Mrs. A ended the episode with a mini-lecture about what variables meant (e.g., "things that can be measured and increase or decrease") and students needed to change objects to variables in their models.

The above episode demonstrates that, while using different types of questioning approaches to help students came up with the ideas that she targeted, Mrs. A did that mainly through information-seeking questions and teacher-centered guided instruction. Throughout the process, the student did not have opportunities to explore why he needed to make things into variables other than it was the teacher who requested that change. Since the conversation occurred after students were introduced to how to run simulations and generate model outcomes, the scaffolding would make more sense for students if the teacher had made the connection between setting up variables in SageModeler and the overall goal of model construction (e.g., to explain and predict phenomena); Making factors into variables afforded students with the opportunities to manipulate those variables to explore the relationships among them through running simulations and then making predictions about the examined phenomenon based on their own models.

In fact, I argue that the teacher might fail to see the connection between setting up variables and the overall purpose of models herself. Instead, she viewed it as a necessary procedural step to construct models in the modeling software. When guiding students to set up the relationship statement in SageModeler, Mrs. A mentioned multiple time throughout the unit that, if using objects instead of variables, the relationship statement would read "funny," such as "an increase in sun causes the earth to increase." That would be the main reason why students wanted to make variables in SageModeler. Mrs. A also talked about this in the interview that she used the scaffolding feature in the relationship statement ("an increase in _____causes _____to increase/decrease") as a way to make sure students have variables in their models.

> "One thing I like about SageModeler is that it helps students to know what are the independent variables and what are dependent variables, while on paper, that's hard for them to understand. In the relationship statement, at first they'll start out with objects, and then they realize that that statement doesn't make any sense at all. You know, an increase in sun causes the car to increase. That doesn't make any sense. So we're talking about the car's temperature. So I like them having to come up with that relationship statement, and seeing that, 'If I label this an object, then it's gonna say an object here.'"

It was apparent from the teacher interview that reading the relationship statement was Mrs. A's way of scaffolding for variables set-up in SageModeler, while the intent of the design of the "relationship box" was mainly towards promoting students' semi-quantitative reasoning skills. The discrepancy may result in the approach Mrs. A used to introduce variables when developing models in SageModeler. Thus, setting up variables in SageModeler became a procedural practice as students were trying to make sure that the modeling tool did not read "funny" as opposed to trying to figure out how to set up variables in a way that could lead to predicting phenomena. In other words, Mrs. A's scaffolding approach made the goal of the modeling activity mainly about the operation of the software, instead of the practice of modeling which the software is designed to support.

In addition to setting up variables in SageModeler, Mrs. A was also observed using primarily teacher-centered guided instruction as scaffolds towards advancing students' knowledge about how to run simulations and compare the result to external data. Similar to setting up variables, Mrs. A's scaffolding moves were mostly focusing on how to run simulations in the software (e.g., what button to hit, what mode to choose, how to show graphs of the simulated results). While these are important procedural aspects of the modeling practice that students need to master in order to get the result of their computer-based models, the lack of the instructional emphasis on helping students realize how running simulations connected to the overall goal of the modeling practice made the practice task-oriented.

Summary. Overall, Mrs. A had provided various scaffolds towards different aspects of the practice of using models to explain phenomena over the course of the unit. Her scaffolds ranged from advancing students' content knowledge about the examined phenomenon to supporting students in developing epistemic knowledge about models and modeling. In particular, Mrs. A used a combination of questioning approaches to provide the appropriate amount of scaffolds after assessing students' current level of understanding. However, with respect to students' modeling work involving the web-based modeling tool, SageModeler, her scaffolds tended to be mostly focused on procedures in that she used direct instruction to scaffold students towards completing the tasks. I hypothesized that this might be due to the teacher's lack of understanding about the intent of the design of the tool. While the modeling tool was designed to promote students' semi-quantitative understanding about the relationship between variables, the teacher did not provide scaffolding that could helping students understand what variables meant and why they needed to set up variables in the software in the first place. Without connecting it to the overall goal of modeling practice, the scaffolds Mrs. A provided became task-oriented as opposed to focused on sense-making.

Student Practice. In order to answer my second research question, I analyzed all five focus students' pre-, mid-, and post- interviews to look for the patterns with respect to how they developed their model-based explanations across the unit (see Table 8 below). The coding (see Table 7 for the coding rubrics) of each focus student across the three time points are listed in Table 8 below. The number in each coding corresponds with one of the three categories that I use to code students' model-based explanations, factors (1), relationship/process (2), and source of evidence (3). The letter in each coding indicates the specific factor, relationship/process, or source of evidence that was included in the model-based explanation. Also, I linked the coding for source of evidence to the key factors or relationships/processes that students use the evidence to justify. For instance, a 2a (3c) code suggests that the student used her personal experience to justify the process that the sun first transfers energy to the earth surface and then to the air. In addition, it is interesting to note that, all five focus students have the same codes for both types of models at any point of time. I hypothesize that this may be due to Mrs. A's instruction on developing models in SageModeler. I will elaborate on this in the discussion section.

Table 8. Focus students' coding scores for model-based explanations

	Initial Storm Model	Revised Storm Model	Final Storm Model	Interview Hurricane Model
Linda	1a, 1b, 1d, 1e;	1a, 1c, 1d, 1e, 1f; 2a (3c), 2c, 2d;	1a, 1b, 1c, 1d, 1e, 1f; 2a, 2b, 2c, 2d;	1a, 1b, 1c, 1d, 1e, 1f; 2a, 2b, 2c, 2d;
Emily	1a, 1b, 1c, 1d, 1e;	a, 1b, 1c, 1d, 1e, 1f; 2a, 2b, 2c (3e), 2d;	1a, 1b, 1c, 1d, 1e, 1f; 2a, 2b, 2c (3e), 2d;	1a, 1b, 1c, 1d, 1e, 1f; 2a, 2b, 2c (3e), 2d;
Betsy	1a, 1b; 2a, 2b;	1a, 1c, 1d, 1e, 1f; 2a, 2c (3e);	1a, 1b, 1c, 1d, 1e, 1f; 2a, 2b, 2c	1a, 1b, 1c, 1d, 1e, 1f; 2a, 2b, 2c;
Cindy	1a, 1b, 1d;	1a, 1b, 1c, 1d; 2a, 2b, 2c (3a);	1a, 1b, 1c, 1d, 1e, 1f; 2a, 2b;	1a, 1b, 1c, 1d; 2a, 2c;
Carlos	1a, 1c, 1d, 1e;	1a, 1b, 1c, 1d, 1e, 1f; 2a, 2b, 2c (3a);	1a, 1b, 1c, 1d, 1e, 1f; 2a, 2b	1b, 1c, 1d, 1e, 1f; 2b, 2c;

The coding indicates that, at the beginning of the unit, all five focus students were able to identify some key factors/conditions that contribute to how a storm is formed. For example, they all have the sun as the energy source of the storm (1a). Four out of the five focus students were able to identify water molecules (1b) as the key factor, which is the source of matter in the formation of storm. In addition, the focus students also identified temperature, wind, and air molecules as the other key factors that contributed to the storm. However, only one of the focus students (Betsy) was able to identify the relationships or processes for the sun and water molecules. The finding is not surprising as at the time students had not learned much about the examined phenomenon. They constructed their models, both on paper and in SageModeler, mainly based on their prior knowledge or personal experience.

In the mid-interview, all five focus students included not only key factors, but also the key processes/relationships among those key factors into their model-based explanations. In particular, all five students chose to add how energy was transferred to the air from the sun (2a) and how warm air and cold air interacted (2c) in their models, which were the two aspects of the practice of model-based explanations for which Mrs. A provided scaffolds. The findings indicate that Mrs. A's scaffolding strategies may have been effective towards helping students advance their understanding in the two areas mentioned above. It is also interesting to note that while students chose to include these two key processes into their models, how they justified it differed. For example, in terms of the convection movement of air (e.g., hot air rises), Emily and Betsy both referred to the two experiments (3e) with convection box and said they were really helpful for them to visualize how air moves when heated or cooled down. In contrast, both Cindy and Carlos mentioned Mrs. A as the authoritative source (3a), saying that they made sure they had all the warm air going up because in class Mrs. A told them that hot air rose.

In the post-interview, the focus students were asked to reflect on their experience with developing their final storm models and to construct a new model to explain the phenomenon of hurricane. Table 4 showed that the focus students made some small adjustments (except Emily), but mainly kept what they had in their revised storm models. For Linda and Betsy, they added water molecules as the key factor as well as the process of evaporation and condensation. This might be attributed to Mrs. A's scaffolding moves towards this idea later in the unit (see Figure 2, L10 & L11). For Cindy and Carlos, they did not include convection into their models and they were not able to apply all the key processes/relationships they identified in their storm models to explain the new phenomenon (e.g., how hurricane forms). Given the fact that both Cindy and Carlos cited the teacher as the source of their evidence, it was possible that they relied too much on Mrs. A's instruction rather than trying to make sense of the phenomena themselves.

Overall, all five focus students made progress in developing model-based explanations, shifting from only including key factors in their models at the beginning of the unit, to adding in key relationships and processes at the middle of the unit, and they maintained the same level of towards the end of the unit. They were also able to apply what they learned from the weather unit to explain a new phenomenon through modeling, at least partially (for Cindy and Carlos).

In the next section, I further analyze how students developed their proficiencies in model-based explanations and how that might be attributed to Mrs. A's scaffolding strategies by focusing on particular student (Linda). Specifically, I focus on the aspects of the modeling practice that may not be captured by my coding rubrics, such as students' meta-talk about their modeling experiences and the rationale of model revision. Because Linda was fairly reflective about her modeling experience, I chose her case to illustrate my analysis.

Linda's case. Similar to the other four focus students, Linda's model-based explanation at the beginning of unit focused primarily on identifying factors that contributed to the formation of storm. The following transcript is about Linda's thought process when she constructed her initial storm model on paper (Figure 7). I also included the coding for her model-based explanations.

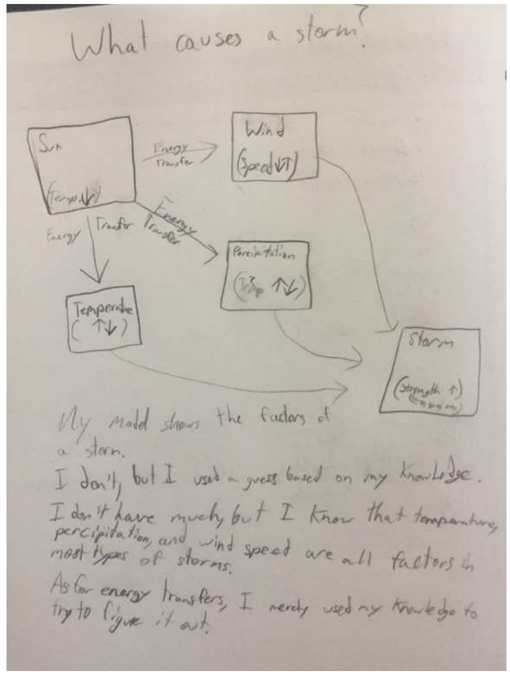

Figure 7. Linda's initial model of storm on paper

Interviewer: **Can you walk me through your initial (storm) model?**

Linda: When I was making the model, I was thinking of where a storm would get its energy from. And I was thinking of the sun because that's usually where most things get energy from [1a]. So I had the sun, the first thing I put down. *And then I kind of thought of, what were the factors of what causes a storm?* So I have wind [1e], precipitation [1b], and temperature [1d]. *I thought all of these kinds of combine to increase the storm's strength.*

The transcript shows that, in addition to successfully identifying the key factors, Linda was also cognizant of the epistemic idea that it was important to identify the relationship between key factors that cause the phenomena, even though she was not sure about the exact relationship at this stage. Linda mentioned that she used the epistemic question of "what were the factors of what causes a storm?" to guide her modeling work. She identified wind, precipitation, and temperatures as the key factors that were involved in a storm system and thought "all of these kind of combined to increase the storm's strength." It is worth noting that Linda also leveraged the idea of energy transfer to help her identify the energy source (e.g., the sun) of the storm as her starting point.

When constructing the initial storm model in SageModeler (see Figure 8), Linda used the similar approach and "have pretty much the same thing." She again had the sun as the energy source and transferred energy to the three key factors in a storm system-temperature of air, wind speed, and precipitation level. While she was unsure about the relationships between the key factors that cause a storm, she attempted to illustrate them in her model that they somehow "go back to this (storm's strength)" with multiple arrows pointing towards the icon of "storm's strength." She also had two arrows between "temperature of air" and "humidity percentage" because again she was not sure about the relationship between the two, but hypothesized that they might affect each other.

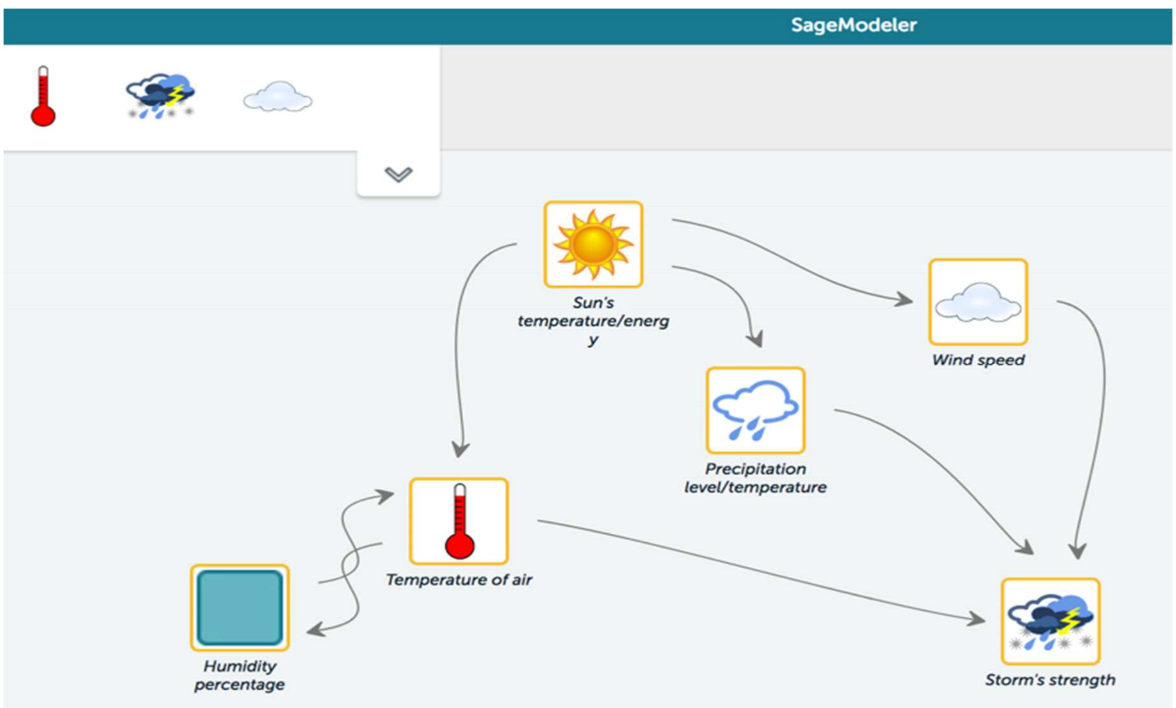

Figure 8. Linda's initial storm model in SageModeler

The analysis of Linda's pre-interview suggested that Linda's modeling approach leveraged the epistemic idea that key factors in a system and the relationships among them cause the phenomena to occur. While she had not learned much about the content knowledge, she used the idea trying to figure out the relationships among key factors to guide her modeling work. In addition, Linda also leveraged the idea of energy transfer when creating the initial model. Linda's attention to energy transfer may be influenced by the energy unit that took place before the weather unit as well as Mrs. A's instructional emphasis on energy transfer in the weather unit. In the interview, when Mr. A was asked about her goal for the unit, she mentioned that she wanted her students to understand the storm system from the lens of energy and matter conservation,

> "I want them to understand where energy and matter fitting into the whole storm. What is the source of energy that drives a storm. Because we've done so much with energy, they're focusing on that right now, but I want them to also understand that matter's involved in that, too. There's air molecule, there're water molecules, and how do those then become part of making a storm."

In the middle of the unit, Linda added many key processes to her revised storm models that were essential in answering the driving question, "what causes a storm?" Figure. 9 below is Linda's diagrammatic revised storm model followed by the coded transcript of her talking about the model in the mid-interview.

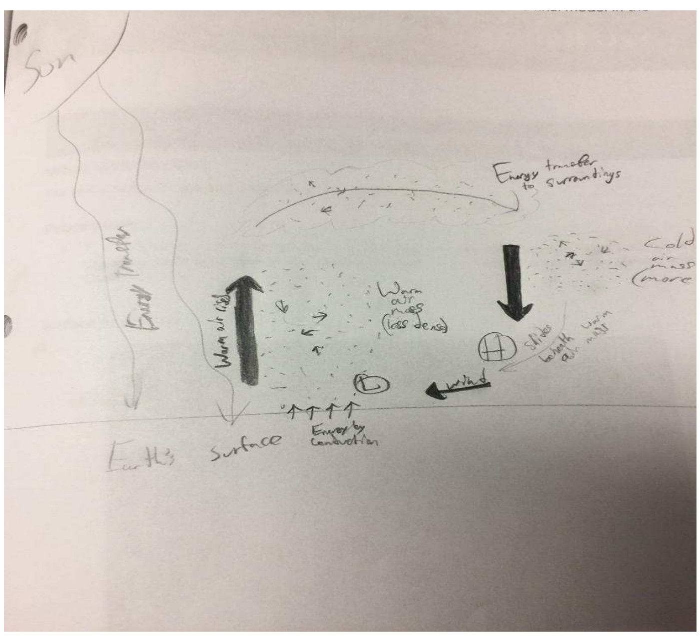

Figure 9. Linda's revised storm model on paper

> "So first off I have the sun, and it transfers energy to the earth surface. The air molecules [1c] above the earth surface, the earth surface transfers energy to them. [1a, 2a] They warm up and they become less dense. The molecules speed up so they become less dense and they rise. Then the molecules transfer energy to the surroundings, then they cool down and they become more dense, so they sink. It becomes cold air mass. [1d, 2c] So that side meets with the new warm air mass, that creates wind because of the high pressure where the warm air masses there's low air pressure." [1e, 1f, 2d]

We saw from both the transcript and the diagrammatic model that Linda included the process of the sun transferring energy to the earth's surface first, and then the earth's surface transferring energy to the air molecules above it. She also connected this idea to the convection movements of the air masses as warm air rises and cold air sinks. In the end, she talked about how the differences of pressure created wind. In fact, instead of recreating the model, Linda added those key processes and relationships based upon her hypothesis in her initial model that the sun would somehow affect the temperature of air and pressure and wind are two key factors in a storm system. I argue that the addition of the key processes and relationship may also be contributed to Mrs. A's scaffolding strategies. By the time of the mid-interview (before L10), Mrs. A had used different types of questioning approaches to help students make sense of the target phenomenon (e.g., what causes a storm?) and provided scaffolds for both "sun-earth's surface-air" (in L4) and "convection" (in L6 and L7).

Similarly, in her revised storm model in SageModeler (see Figure 10 below), Linda also added those key relationships among the factors. When asked to describe the model, she said,

> "Since I have to have variables, I have the sun's intensity [1a]. So the greater that is, the earth's surface temperature will increase as this increases, and that kind of make the molecules' speed increase and the air above earth's surface temperature [1d, 2a]. When that air [1c] rises, that caused the amount of clouds to increase. The molecules will slow down and they become more dense [2c], and that causes the air pressure to increase. As the air pressure [1f] increases, the bigger difference between the higher pressure and lower pressure, causing the wind speed [1e] to increase." [2d]

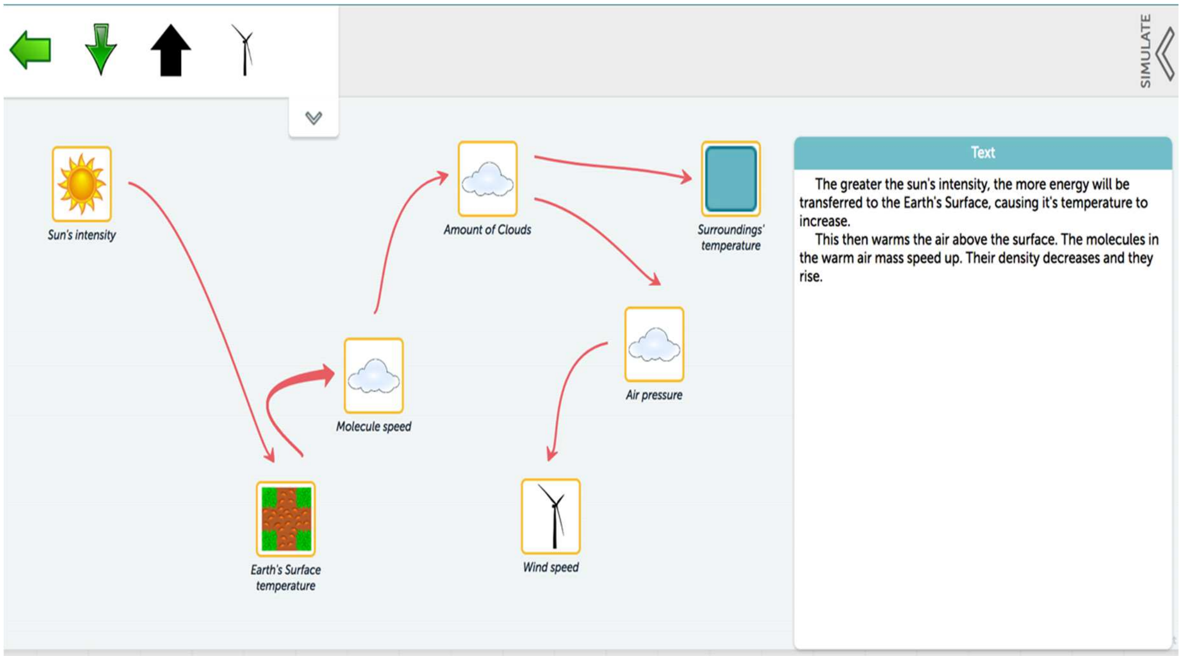

Figure 10. Linda's revised storm model in SageModeler

It is interesting to note that one of the changes Linda made was to make objects into variables. In the interview, she was probed to elaborate on why she "has to have variables." Her response was as follows,

> "For the relationship statement. So when you read it, if you just have objects, it doesn't really make sense. If you read it, "an increase in the sun's intensity causes earth surface temperature to increase by about the same", that makes a lot more sense than just saying "an increase in the sun causes the earth surface to increase".

As shown in the transcript above, Linda referred to the "relationship statement" as the main reason why she put variables in her model, "because it (relationship statement) doesn't really make sense if you just have objects." This approach was exactly what Mrs. A. mentioned in the teacher interview as illustrated in the prior section. In class, she also emphasized a couple of times that if students had objects in their models, their relationship statement would read "funny." While this might be an effective approach in directing students to set up their variables in SageModeler, as evident in Linda's case, I argue that it was disconnected to the overall goal of modeling practice, and thus made the practice task-oriented as opposed to meaningful that is aligned to the disciplinary norms and value. Rather than trying to figure out how to construct a model in a way that the identified components/variables and relationships are able to explain and predict the phenomena, the goal of the modeling activity now became making the relationship statement read right.

Compared to her revised storm model, Linda changed the "amount of clouds" to "water molecules speed" to indicate the process of evaporation and condensation at the micro-level in her final model (see Figure 11) while keeping the other parts of her model intact. She also included a more complete written explanation about the mechanism of how storm forms in her final model.

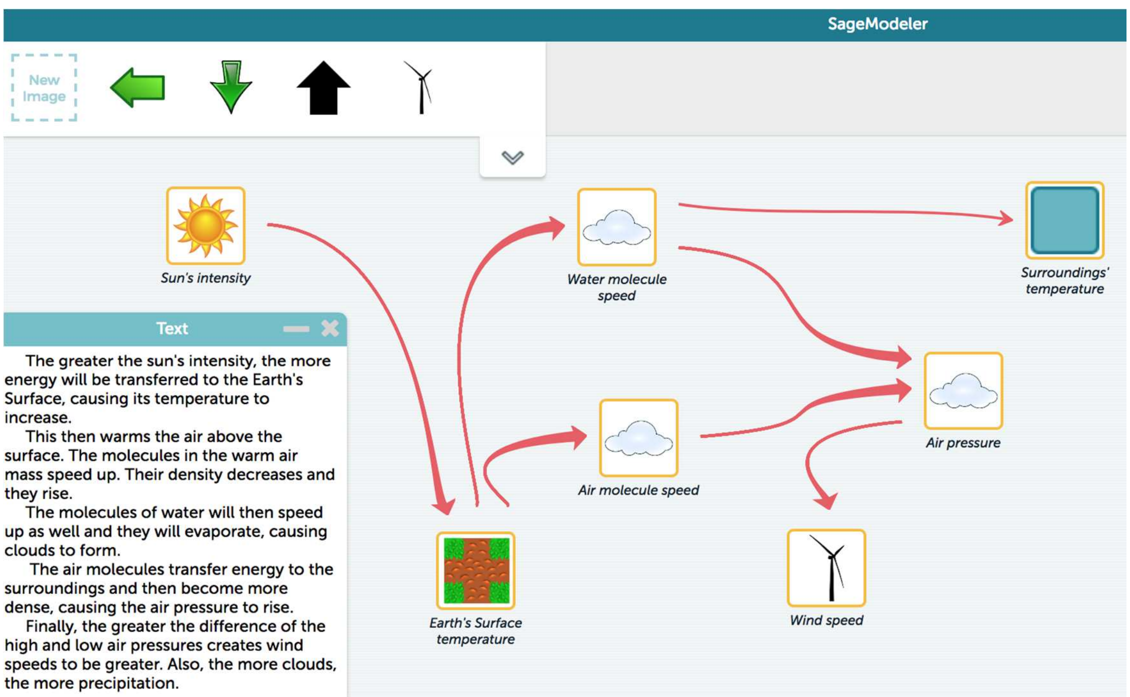

Figure 11. Linda's final storm model in SageModeler

While Linda maintained her focus on identifying the key relationships and processes in her final storm model, she was also able to apply all the components (1a, 1b, 1c, 1d, 1e, 1f) and relationships (2a, 2b, 2c, 2d) in her storm model to create a model to explain a closely-related new phenomenon, what causes a hurricane. Below is the transcript with coding of Linda's model-based explanation about the new phenomenon.

> "So first off, the hurricane mostly forms around the equator, and that's where the sun's intensity [1a] is at its greatest, so that probably would be a good thing to add. So the sun transfers energy to the ocean's surface, then that would cause the water to evaporate [1b, 2a]. As the water evaporates, it becomes less dense, then it will rise into clouds [2b]. The air [1c] is becoming less dense as well, and that whole process is happening when it will rise, and then it will cool down, become more dense [1d, 2c], so the difference in high and low pressure [1f] causes the wind [1e] speed to be greater [2d]. Although I'm not exactly sure about this. That's just what I think based on my knowledge."

Similar to how she started constructing the storm model, Linda first identified the sun as the energy source and energy being transferred from the sun to the ocean. She then included the process of water evaporation into clouds and how the convection movement of air masses created wind. In the following transcript, Linda further explained why hurricane often weakened as it hit the land. The question was designed to elicit students' semi-quantitative reasoning skills involving key components/variables in a system.

> "I think as it (hurricane) hits the land, it will weaken because there's so much precipitation coming down, but then there's no more water underneath it to keep evaporating, and to have more and more clouds forming, and that's I think why as hurricane move across an ocean, it has more energy because there's more clouds, more precipitation, and when it hits the land, there's no more water to cause more clouds to form, that's why it weakens."

The transcript showed that Linda used the idea of water evaporating into clouds and then coming down as precipitation as the foundation of her semi-quantitative reasoning; because there's less water evaporating into clouds and turning into precipitation, the hurricane weakened. It is interesting to note that Linda added this part into her model in her final storm model, which is also one of the key aspects of the practice of model-based explanation that Mrs. A provided scaffolds for later in the unit (in L10 and L11). I argue that the fact that Linda was able to identify to the relationships among key factors and apply them to explain a new phenomenon may be contributed to Mrs. A's scaffolding move towards those relationships.

Summary. With respect to focus students' model-based explanation development, most focus students started their initial storm model with a focus on identifying the key factors in the storm system. In the middle of the unit, they added key relationships/processes that contribute to explain the examined phenomenon into their revised storm models. In particular, all focus students included the convection movements of air masses and the energy transfer process from the sun to the earth's surface and then to the air above it, the two areas in which Mrs. A used different types of questioning approaches to help students make sense of and advance their understandings. Towards the end of the unit, all focus students maintained their attention to identifying the relationships among the key factors in the storm system and were able to apply at least part of their storm models to explain a close-related new phenomenon. The analysis of a particular focus student together with her reflection on her modeling experience further indicates that Mrs. A's scaffolding strategies may play a key role in influencing students' model-based reasoning, both on paper and in the web-based modeling tool.

Discussion

The analysis of Mrs. A's instruction and students' modeling practices suggests that teachers' scaffolding strategies were effective when the scaffolds were built towards students' sense-making processes. In the unit, Mrs. A used different types of questioning approaches (e.g., pumping, reflective toss, constructive challenge, etc.) to provide the appropriate amount of support in advancing students' understanding towards the relationships between the key factors in a storm system. In turn, the focus students seemed to take up the scaffolded ideas when revising their storm models. Another key finding of this study is that, Mrs. A used primarily teacher-centered guided instruction to provide scaffolds when students were developing their models within the web-based modeling tool. The scaffolds provided were task-oriented in nature and focused mainly on the technological aspects of the modeling tool. In this section, I will discuss the results in terms of their implications for how teachers should provide instructional scaffolds with different types of scaffolds available in the classroom and how dealing with different types of models adds to the complexity and challenges in teaching scientific modeling for teachers.

Different types of scaffolds. Classroom are complex systems in which different types of scaffolds need to work coherently with each other in order to productively support student learning towards to the target goal. In the context of this study, there are primarily three types of scaffolds (e.g., teacher instruction, computer software, and curricular materials) at play. While my research questions did not focus specifically on the interactions between those different types of scaffolds, my analysis lent myself to investigate how teachers' instructional scaffolds interact with the curricular scaffolds and the scaffolds provided by computer-based modeling software. I found that the interaction between the teacher's instructional scaffolds on developing diagrammatic models and scaffolding features in the curricular materials was synergistic in nature. As the first pattern (e.g., scaffolding for sense-making) suggested, Mrs. A. used different types of questioning approaches to elicit and advance students' idea about models and the phenomena while engaging students in the modeling activities in the curriculum. In particular, Mrs. A had provided instructional scaffolds for all the key relationships and processes involved in a storm system, which is coherent with the learning goals identified in the teacher edition of the curriculum materials. The synergistic nature of the interaction may also be contributed to the adaptation of the curriculum by Mrs. A and myself. During the adaptation, we went over the curriculum and discussed the goals of each modeling activity to have a better understanding of the intent of the curriculum materials and how it is designed to support student learning. We then decided which activities should be abbreviated, deleted, or added based on Mrs. A's knowledge of her students' prior experience in the topic so that her students can have a more coherent learning environment to engage in the practice of scientific modeling.

On the other hand, the interaction between the teacher's instructional scaffolds and the computer-based scaffolds was not disciplinary productive in terms of supporting students' model-based explanations in SageModeler. As illustrated above, Mrs. A used the "relationship statement" feature as a check point (e.g., whether it reads funny or not) so that students can change the objects into variables for the sake of being able to run the simulation later in the unit. Also, the focus of Mrs. A's instruction centered around the specific technological features of the software, as opposed to having an overall understanding about the goal of modeling with connection to the scaffolding features of the modeling tool. As I argued earlier, Mrs. A's approach to the modeling software reflected her lack of understanding of the intent of the software from the designer's perspective. In particular, she was not able to make the connection herself between the purposes of setting up models with semi-quantitative variables and testing models by running simulations. Furthermore, from the student interview data, it seems that Mrs. A's oversimplified approach to SageModeler in turn influenced her students' modeling practices. While all five students have the same codes for their model-based explanation with both types of models, students' rationales for their decisions made in SageModeler might not align with the disciplinary practice (see Linda's example of changing objects into variables).

The result of this study is consistent with Tabak (2004)'s view on what makes synergistic scaffolds effective. She argued that "for productive synergy to occur… different materials need to share semiotic features, and these features need to be consistent not only with the designers' but with the teacher's conception of the task, goals, and discipline" (p.329). It also aligns with what McNeill and Krajcik (2009) found regarding the interaction between the teacher's instructional scaffolds and curricular scaffolds for supporting students' construction of scientific explanation; they found that teachers who provided a modified definition of scientific explanation resulted in less student learning in terms of their ability to include appropriate reasoning in the scientific explanation. They argued that this was so because there existed a "discontinuity between the initial intent of the designers and the resulting enactment of the explanation framework in the teachers' classrooms" (p.449). In this sense, effective synergy can only be achieved when different scaffolds are congruent with each other across all dimensions of the target practices including the epistemic aspect of the practice.

Different types of models. According to the National Research Council's report, *A Framework for K-12 Science Education* (NRC, 2012) and the Next Generation Science Standards (NGSS; Lead States, 2013), by grade 12, students should be able to "represent and explain phenomena with multiple types of models – for example, represent molecules with 3-D models or with bond-diagram – and move flexibly between model types when different ones are most useful for different purposes" (p.58). It was towards this modeling-related learning goal that Mrs. A and I decided to adapt the IQWST curriculum to incorporate the computer-based modeling tool so that students have the opportunity to use different types of models to explain the phenomenon of a storm. The finding of this study demonstrated that Mrs. A had two distinct scaffolding strategies when engaging students developing the two types of model. When supporting students in developing their diagrammatic models of storm, Mrs. A used a variety of questioning approaches as scaffolds to support students in making sense of the phenomenon and developing model-based explanations. In contrast, she used primarily teacher-centered guided instruction with information-seeking questions when engaging students in developing computer-based models in the online modeling tool. However, it is worth noting that the discrepancy in Mrs. A's scaffolding strategies towards the two types of models should not be viewed in isolation. Rather, it should be understood in light of the instructional sequence of the unit, that the development of the diagrammatic models always proceeds the development of computer-based models on the same phenomenon. In other words, focusing on the technological aspects of the modeling tool does not necessarily indicate Mrs. A's neglect on the other aspects of the practice. On the contrary, it is possible that Mrs. A based her on her previous instruction concerning diagrammatic models and her evaluation of her student.

Nonetheless, it is evident that Mrs. A did not fully understand the affordances and constraints of the two types of models in explaining the same phenomena. While Mrs. A had engaged students in conversations a couple of times to compare the two types of models, the discussions were mainly focused on the user experience, instead of the epistemic features embedded within each type of model. For example, at one time the class came to a consensus that the paper-and-pencil diagram is easier to navigate the layout of model components, but model revision is less convenient compared to the computer-based models. In fact, during instruction, Mrs. A used the word "copy" in multiple occasions when asking students to create or revise their models in the modeling tool based on their diagrammatic models. This reflected Mrs. A's view about computer-based models, that the web-based modeling tool is a form of new technology that provides the platform for students to transfer their diagrammatic models to. The instructional focus on the technological aspects of the online modeling tool may also result from Mrs. A's own experience interacting with the tool. From the informal conversations I had with

Mrs. A during the professional development as well as the adaptation process, Mrs. A mentioned it in multiple occasions that it took her a considerable amount of time to get familiar with the software (e.g., where the icons and labels are, how to run a simulation, how to test models with changing variables, etc.) before she felt comfortable trying it out in her own classrooms. Therefore, it was not totally surprising that she spent the majority of her time walking through the technological aspects of the modeling tool and providing scaffolds along the way to help students come up with a runnable model that they can later share with other people. In other words, the primary instructional goal related to the modeling software became getting the product done, as opposed to using the software as a sense-making tool to explore the phenomenon further with the scaffolding feature of semi-quantitative reasoning embedded in the tool.

Despite the increasing attention to scientific modeling in the science education community and the growing number of modeling and simulation tools (e.g., SageModeler, NetLogo, StarLogo, etc.) available for teachers to implement in classroom, little research has been done to date to investigate the process of how students move between different types of models to explain phenomena and/or how teachers could help smooth the transition. As the result of this study suggests, teacher instruction with respect to modeling can be unproductive if they do not understand the affordances and constraints of different types of models. More research needs to done in this particular area if we aim to achieve the learning goals set up by the NGSS.

Limitations

Due to the explorative nature of the study and the limited number of teacher and students involved, the result of the study is not intended to be generalized to other complex learning contexts without carefully examining the boundaries of the Mrs. A's case. One limitation of the study is related to the data sources that I use to characterize the teacher's scaffolding strategies. In the study, I used videotapes of key modeling lessons (12 lessons in total) and pre-unit teacher interview as my primary data sources. However, it is likely that Mrs. A also provided additional instructional scaffolds during the lessons in which the major learning goal is for students to conduct empirical investigations that I did not capture in my data analysis. In particular, Mrs. A might have provided additional instructional supports to help students make the connections between the empirical data students collected and the key factors or relationships students included in their models, which is key to development in the practice of model-based explanation (e.g., the "source of evidence" dimension in the coding rubric). Without that piece of data, it is important to note that my analysis of Mrs. A's scaffolding strategies only applied to part of her instruction for the unit. Future studies should consider classroom investigations as an essential piece of data collection in order to better characterize teachers' instructional practices to support students' engagement in scientific modeling.

Implications

Engaging students in modeling practices in a disciplinarily productive way is challenging as teachers need to navigate through a complex system of scaffolds that may not be inherently coherent with each other. This study highlights the importance of scaffolding for students' sense-making process with dynamic assessment techniques and customized supports, both with respect to epistemology and content. In addition, while computer-based modeling tools have great potentials in promoting students' productive engagement in scientific modeling, the result of the study also suggests that it is insufficient for teachers to only master the technological aspects of the software. In order to make the modeling practices productive, teachers should not only be cognizant of the affordances and constraints of the computer-based modeling tool, but they should also have a thorough understanding of the intent of the software (e.g., scaffolding features) as well as how it connects to the overall goal of the practice. This study also has significant implications in terms of how to design professional development programs to better prepare teachers for enacting modeling practices with computer-based modeling tools. In retrospect, while we as a research team spent a fair amount of time introducing SageModeler and its different scaffolding features in the teacher workshop sessions, we did not make explicit the epistemic goals embedded within the software from the designer's perspective and how teachers can foreground those goals with appropriate instructional strategies. As illustrated by the Mrs. A's case, even for experienced teachers who are adept at enacting domain-general teaching practices such as eliciting student ideas and using questions to advance student thinking, the practice of modeling is still challenging for them as they need to attend to and balance different aspects of the practice (e.g., social, epistemic, cognitive, technological). Future professional development programs should take into account the challenges in doing so and help teachers envision effective ways to productively engage students in scientific modeling.

Synthesis

In this dissertation, I present three research studies to explore how teachers' instructional practices can help student's meaningful engagement in scientific modeling across different learning contexts. In this section, I summarize the findings of each research paper and discuss the common themes that I find cutting across the three research papers. I conclude this section with possible directions for future research in light of my dissertation study.

Summary of Findings

In research paper 1, I compared and contrasted two elementary teachers' messages about modeling in a model-based evaporation and condensation unit and how their messages may influence students' modeling practices. The findings suggest that each teacher is sharing complex messages about the importance of various aspects of the modeling practice in a combination of ways. Mrs. M's students frequently attended to the Nature of Account (e.g., How and why do phenomena happen?) and Generality (e.g., How does my model apply to other phenomena?) epistemic considerations when they were constructing their consensus models of evaporation and condensation. I argue that there may be a combination of reasons why students in Mrs. M's students took up the practice in this way. First, Mrs. M prioritized "explain how and why" and "explain multiple phenomena" as the primary goals of modeling practices. Second, Mrs. M also contextualized the abstract epistemic goals in students' modeling work and make those goals specific enough for students to operationalize (e.g., can your model explain how you smell your dirty socks?). Third, Mrs. M was able to set up the norms of modeling practices (e.g., "stars and wishes" activity for model evaluation) and hold students accountable to them. In comparison, students in Mr. H's class approached modeling in a procedural way when engaged in consensus model building. In the focus group, students in Mr. H's class worked mainly on listing out the things they learned in the unit and were concerned about finishing the model in time. I argue that this may attributed to Mr. H's emphasized messages about "finish in time" and "put information into model." While Mr. H also brought up the messages about "explain how and why" and "explain multiple phenomena" in the unit, he did not foreground them as the primary goals and only introduced these epistemic ideas sporadically across the unit.

In research paper 2, I focused on how Mrs. M supported students' epistemic considerations in *Nature of Accounts* and *Generality*. I found that Mrs. M frequently unpacked the two epistemic considerations to scaffold students' understanding. For Nature of Account, Mrs. M often asked mechanistic questions about tracing matter (e.g., Where did the water come from?). For Generality, Mrs. M often asked students to compare the similarities and differences between phenomena before students were able to generalize the mechanism to different phenomena. I argue that Mrs. M's scaffolding strategies may have a profound influence on students' uptake of the epistemic considerations. In terms of *Nature of Account*, the analysis of focus students' interview revealed that students' model-based explanations became more mechanistic, shifting from focusing on the macro-level conditions under which the phenomena occurred to describing the explanatory process at the microscopic level that accounted for how and why the phenomena happened. Students also made progress in Generality, shifting from not seeing the connections between phenomena at the beginning of the unit towards identifying the analogous parts of two similar situations at the end of the unit. In addition, the interview analysis of one focus students also suggests that the student was consciously using the goal of "explain how and why" to navigate her modeling process despite her lack of content knowledge about the topic in the pre-interview.

In research paper 3, I investigated an experienced middle school teacher's scaffolding strategies aimed at supporting students' model-based explanations in a model-based weather unit. The findings suggest that Mrs. A's strategies fell into two categories, scaffolding for sense-making and scaffolding for task completion. When scaffolding for sense making, Mrs. A used a combination of questioning approaches (e.g., pumping, reflective toss, constructive challenge, etc.) to provide appropriately responsive scaffolds after assessing students' current level of understanding. However, with respect to students' modeling work involving the web-based modeling tool, SageModeler, her scaffolds tended to be mostly focused on procedures in that she used teacher-centered guided instruction to scaffold students towards completing the tasks. I hypothesized that this might be due to the teacher's lack of understanding about the intent of the design of the tool. In terms of the teacher's influence on student practice, the analysis of student interviews indicated that all focus students were able to identify the key components and relationships for which Mrs. A provided scaffolds during instruction. The analysis of a particular focus student (Linda) together with her reflection on her modeling experience further indicates that Mrs. A's scaffolding strategies may have played a key role in influencing students' model-based reasoning.

Common Themes across Three Studies

In all three research studies, teachers' instructional practices seemed to have influenced how students engaged in the practice of modeling accordingly. But what aspects of the teaching practices may have contributed to this seemingly simple correlation? In this section, I present two common themes cutting across the three studies that I argue are essential for us to better understand how to meaningfully engage students in scientific modeling.

Theme 1: How teachers support epistemic aspects of modeling matters. We know from the case of Mr. H (he emphasized both "explain how and why" and "explain multiple phenomena") that simply emphasizing certain epistemic ideas about modeling may not be sufficient to influence student practice. It is the ways in which teachers emphasize the epistemic aspects of the practice that matters. For example, Mrs. M foregrounded Nature and Generality and prioritized them as the primary goals of modeling practices. She also unpacked what those epistemic considerations meant and contextualized them in a way that students could use them to guide their own modeling building. Similarly, for Mrs. A in study 3, the ways in which she used questioning approaches may determine whether her scaffoldings strategies are working towards sense-making or task completion. All these approaches (e.g., unpacking, contextualizing, and scaffolding for sense-making) seem to contribute to students' meaningful engagement in the modeling practices.

Theme 2: Connection to other dimensions of practice. Lehrer and Schauble (2006) and Duschl (2008) describe scientific practices as being consistent of four dimensions: conceptual, epistemic, social and material. While the main focus of this dissertation study were epistemic aspects of modeling practices, the findings also indicate that it was important for teachers to connect the epistemic aspect of the practice with other dimensions for the purpose of meaningful engagement in the practice. In particular, the epistemic and conceptual dimensions seemed to work closely in service to each other. For instance, when emphasizing the message of "explain how and why," Mrs. M always followed with questions asking students to trace matter in the system (e.g., where did the water go? Where did the water come from?). In this way, students know that one productive way to address the "how and why" question is to trace the matter in the system. Similarly, when scaffolding for content understanding about how energy transfers from the sun to the earth surface and then to the air, Mrs. A used “constructive challenge” approach to help students reject an alternative idea that the energy transfers directly from the sun to the air above ground. In the process, Mrs. M leveraged a key epistemic idea about modeling concerning using evidence to support or reject models. In this sense, students are no long learning about the content for the sake of learning content. Rather, they learned the content as justified knowledge that they can use in their models to explain phenomena.

In terms of connections with other dimensions, in study 1 and 2, Mrs. M was able to set up the norms of model critique (e.g., “stars and wishes” activity) and hold each other accountable to the disciplinary norms. In particular, she combined the epistemic and social dimensions of modeling practices by emphasizing the importance of “explain how and why” when giving each other feedback. Also, a counter example arises in study 3 when Mrs. A focused mainly on the material dimension of the practice without connecting it to the epistemic dimension. She centered her instruction on the technological aspects of the computer-based modeling tool when engaging students in modeling practices in SageModeler. Without taking into account the epistemic feature of the modeling tool, Mrs. A’s scaffolding became task-oriented that does not align with the disciplinary norms.

Implications for Teacher Professional Learning

This dissertation study has significant implications for how to better prepare teachers to enact modeling practices in a meaningful way. In particular, it emphasizes the importance of prioritizing the epistemic goals of scientific modeling that are accessible to student. Below I discuss two key areas that may be productive for teacher educators to address in future professional development programs in order to support teacher learning in this regard.

First, it is important to help teachers recognize and make explicit the epistemic goals of modeling activities, which are often neglected or implicit in most traditional classrooms. For instance, as the findings of study 3 demonstrated that when Mrs. A mainly focused on the technological aspects of modeling practices, students were not sure why they needed to include variables into their models, which made the practice procedural as opposed to meaningful. Epistemic goals can vary across different activities depending on which goals teacher want to prioritize. For example, a teacher may emphasize "explain how and why" when students are constructing models while highlighting "using evidence to support models" when asking students to revise their models based on empirical evidence. It is thus at the teacher's discretion to determine what epistemic goals of modeling to emphasize under what circumstances. Furthermore, when making decisions about which goals to emphasize, teachers also needs to take into considerations of those non-epistemological goals associated with the constraints of the school classroom settings to which they need to attend to (e.g., covering the curricular materials in a certain timeframe). As study 1 suggested, teachers needs to balance those goals in order to support students' meaningful engagement in scientific modeling.

Second, the central argument of this dissertation study is that how teachers support the epistemic aspects of modeling practices matters. Therefore, it is crucial for teachers to develop strategies to unpack, contextualize, and scaffold those epistemic goals so that they are appropriate for students to take up and guide their own work. In particular, the findings of this dissertation study suggest that it is fruitful if teachers connect the epistemic aspects of modeling with other dimensions (e.g., conceptual, social, material) of the practice. For instance, combining the "explaining how and why" goal with specific mechanism questions related to tracing matter and energy seem to be productive for both Mrs. M and Mrs. A. It also seems critical for Mrs. A to set up the norms of model evaluation while focusing on "explain how and why" at the same time. In addition, study 3 indicates that using different types of questioning approaches to scaffold student sense-making while taking student ideas into account seemed fruitful for advancing student thinking and meaningful engagement. As such, it is important for future professional programs to center around helping teachers develop those strategies within their own content areas and topics.

Direction for Future Research

This dissertation study provides a rich account of how teacher may meaningfully engage students in scientific modeling through highlighting the epistemic aspects of modeling practices. Methodologically, I use different types of data sources as indicators to characterize the interaction between teachers' instructional practices and students' modeling practices. However, due to the limited number of participants involved in this study the nature of design of the study, more work involving more teachers under different learning contexts needs to be done in order to better generalize and expand the findings of this study. In this section, I discuss possible directions for future research based on this dissertation study.

First, as the findings of my dissertation suggest, it is important for teachers to connect the epistemic aspects of modeling practices with other dimensions of the practice in order to make modeling practice meaningful. Future work can investigate the particular interactions among the four dimensions and how that contributes to students' meaningful engagement in modeling practices. For example, I found in study 1 and 2 that Mrs. M was able to set up the norms of model evaluation with an emphasis on "explaining how and why" emphasizing social and epistemic considerations. However, it remains an empirical question concerning how teacher can support students in both aspects of the practices in a way that is appropriate to students' ways of knowing.

Second, in study 1, the messages about modeling I identified in Mrs. M and Mr. H's instruction could be further categorized into domain-general epistemological messages (e.g., give each other feedback) and domain-specific epistemological messages (e.g., use evidence to support model). Previous research suggests that both domain-general and domain-specific epistemologies could impact student learning (Hutchison & Hammer, 2010; Sandoval & Çam, 2011). In Russ's (2018) recent paper, she advocated for starting with domain-general epistemological messages about knowledge instruction to "disrupt the school game." While it remains an empirical question in terms of whether that is the better approach, I argue that it is more important to better understand how domain-general and domain-specific epistemological messages interact and how they in turn affects how students take up those messages and use them to guide their own work.

Third, we know from study 1 and 3 that, teacher often have to balance different goals as they engage students in the modeling practices. Same is true for students as they go through the meaning making process and "privilege" (Wertsch, 1993) certain epistemological messages. A closer look at how that process takes place can advance the field in thinking about how teacher and student co-construct the meanings related to what counts as valuable knowledge when engaging in scientific modeling.

In the end, this dissertation and on-going work will be important for helping teachers and their students meaningfully engage in modeling and other scientific practices to advance student learning and scientific literacy in the world.

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