J Sci Educ Technol (2015) 24:216–233
DOI 10.1007/s10956-014-9532-6

The Influence of Curriculum, Instruction, Technology, and Social Interactions on Two Fifth-Grade Students' Epistemologies in Modeling Throughout a Model-Based Curriculum Unit

Hamin Baek · Christina V. Schwarz

Abstract In the past decade, reform efforts in science education have increasingly attended to engaging students in scientific practices such as scientific modeling. Engaging students in scientific modeling can help them develop their epistemologies by allowing them to attend to the roles of mechanism and empirical evidence when constructing and revising models. In this article, we present our in-depth case study of how two fifth graders—Brian and Joon—who were students in a public school classroom located in a Midwestern state shifted their epistemologies in modeling as they participated in the enactment of a technologically enhanced, model-based curriculum unit on evaporation and condensation. First, analyses of Brian's and Joon's models indicate that their epistemologies in modeling related to explanation and empirical evidence shifted productively throughout the unit. Additionally, while their initial and final epistemologies in modeling were similar, the pathways in which their epistemologies in modeling shifted differed. Next, analyses of the classroom activities illustrate how various components of the learning ecology including technological tools, the teacher's scaffolding remarks, and students' collective activities and conversations, were marshaled in the service of the two students' shifting epistemologies in modeling. These findings suggest a nuanced view of individual learners' engagement in scientific modeling, their epistemological shifts in the practice, and the roles of technology and other components of a modeling-oriented learning environment for such shifts.

Keywords Scientific practice · Scientific modeling · Epistemology in practice · Epistemology in modeling

Introduction

In the past decade, reform efforts in science education have increasingly attended to engaging students in scientific practices such as scientific modeling. This focus on scientific practices has emerged out of the confluence of several factors including varying interpretations of prior science education reform documents around the definition and meaningful enactment of scientific inquiry. The lack of consensus around scientific inquiry sometimes led to interpretations of inquiry as primarily 'discovery' or 'hands-on' learning without supporting conceptual development, or as a way to teach skill-based procedural aspects of the "scientific method" (e.g., Windschitl et al. 2008) rather than meaningfully engaging students in authentic activities of science to make sense of phenomena. To help educators better understand and enact richer forms of science in the K-12 classroom, scientific practices are now highlighted as one of the three major dimensions of *A Framework for K-12 Science Education* (National Research Council 2012) and the *Next Generation Science Standards* (National Research Council 2013).

Engaging in any disciplinary practice is not just learning a new skill or procedure. It is participating in a disciplinary "community of practice" (Lave and Wenger 1991), which involves changing one's way of knowing, communicating,

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H. Baek (✉)
Handong International School, Namsong-ri, Heunghae-eup,
Buk-gu, Pohang-si, Gyeongsangbuk-do, Seoul 791-941,
Republic of Korea
e-mail: haminbaek@gmail.com

C. V. Schwarz
Michigan State University, Erickson Hall, 620 Farm Lane,
Room 349, East Lansing, MI 48824, USA

and working with others, as well as one's discursive identity. Therefore, engaging students in a scientific practice as a science education approach should include providing them with rich learning environments that foster students' gradual yet productive transitions from relying strictly on their own epistemologies, discourses, and norms to appropriating some important aspects of scientific epistemology, discourse, and norms.

Among scientific practices, scientific modeling has been considered particularly important and pedagogically useful for science learners for several reasons. First, enabling students to participate in and understand scientific modeling is important because it can help them "establish, extend, and refine" their knowledge (National Research Council 2012, p. 26) by making the processes of doing science and advancing ideas more explicit and testable. In addition, scientific modeling can advance content knowledge by making invisible processes, mechanisms, and components visible. Furthermore, as with all scientific practices, engaging students in scientific modeling can help them understand the way that science functions through sharing, evaluating, and revising ideas. Finally, scientific modeling can help students develop their epistemologies by allowing them to attend to the roles of mechanism and empirical evidence when constructing and revising models.

In this article, we focus on this last aspect of scientific modeling—allowing students to attend to the roles of mechanism and evidence—and report on how students' epistemologies in modeling changed over time. In particular, while scientific models and modeling has already been a consistent object of inquiry in science education for more than two decades (Halloun and Hestenes 1987; Gilbert 1991; Mellar et al. 1994; White and Frederiksen 1998; Harrison and Treagust 2000; Lehrer and Schauble 2006), we focus on students' epistemologies as an important aspect of students' engagement in modeling. By epistemologies, we refer to students' implicit epistemological ideas they employ as they engage in a scientific practice to make sense of the world as well as their explicit notions about the purpose and goals of the practice (e.g., Sandoval 2005). While epistemic aspects are implicit in some of the modeling research and explicit in others (e.g., Pluta et al. 2011), they are essential for productive and meaningful engagement in the practice. In particular, we argue that students need to understand and use epistemic considerations such as developing and revising models with respect to empirical evidence to address mechanism of phenomena. These particular epistemic considerations are essential for sense-making, and they lie at the core of the scientific endeavor because they enable prediction and explanation. Furthermore, our prior research indicates that if epistemic considerations of classroom modeling are not addressed and supported, modeling can become a procedural activity in which learners produce drawings for their teachers with the goals of providing correct information (whether or not it makes sense), as much detail as possible (whether or not it is necessary), and with maximum aesthetic qualities (to gain peer approval) (Baek et al. 2011).

In order to better promote students' meaningful engagement in scientific modeling, we call attention to students' epistemologies in scientific practices as an important dimension of science learning. If one is to take seriously this aspect of practice, the questions then become: What aspects of epistemologies in modeling are important and how can they develop over time? While some researchers have found that students can productively attend to criteria such as the explanatory function of models, the role of evidence, appropriate details, and accuracy (Pluta et al. 2011), our prior work indicates that students can attend to and productively engage in epistemologies in practice that focus on several overlapping, though somewhat different considerations. Those considerations include attending to (a) the specificity or generality of knowledge, (b) how the knowledge product addresses a particular audience, (c) how the knowledge product can be justified (with respect to evidence, among other things), and (d) the goal or nature of the knowledge product, including the nature of students' mechanisms used to explain the phenomena. We have been involved in in-depth work to determine whether students can develop their epistemologies in practice over time and across contexts, how they might develop, and what might support them in doing so. Our work indicates the importance of instructional and curricular supports such as engaging students in evaluating and revising their models as well as developing consensus models in which student can argue among competing models using empirical evidence.

In addition to our theoretical work outlining these epistemic considerations of modeling practice, our prior work indicates instructional and curricular components can impact students' scientific modeling practices. For example, we have found that several aspects of a model-based instructional sequence—empirical investigations, computer simulations, and social interactions—positively impacted students' attention to empirical evidence, to invisible objects as an explanatory feature, and to audience and communicative features of models (Baek et al. 2011). In particular, the technology used for collecting empirical data and the computer simulations played critical roles in supporting and expanding students' epistemologies in modeling with respect to empirical evidence and mechanistic aspects of the phenomena. Other research has also shown that technology can play a critical role in student modeling (e.g., Mellar et al. 1994; Khine and Saleh 2011). However, our earlier work and those of others do not indicate how and why such tools and other aspects impact students' developing epistemologies in practice.

In order to advance our knowledge of how and why such epistemologies in practice can develop over time, this article presents an in-depth case of two students' epistemologies in modeling related to explanation and empirical evidence from participating in the enactment of a technologically enhanced model-based curriculum unit. The goal of this research is to illustrate how various components of the learning environment contributed to the shifts of the students' epistemologies in modeling. Such work is critical for determining how to develop and enhance learning environments that best help engage students in modeling with technology for advancing their own epistemologies with respect to evidence and mechanism.

Conceptual Underpinnings

In this section, we briefly outline our definitions of scientific model and modeling and then present our construct of students' epistemologies in modeling. Subsequently, we discuss the role of technology in research on students' engagement in scientific modeling.

Scientific Model and Modeling

We use the term scientific model to stand for an abstract, simplified representation of a system that makes its central features explicit and visible (cf. Ingham and Gilbert 1991; Schwarz et al. 2009; Lehrer and Schauble 2006; Harrison and Treagust 2000; Gobert and Buckley 2000). Scientific models can refer to the mental or internal models that people might have for a system as well as the conceptual or expressed models that people might generate to talk about, keep track of, and advance their understandings of a system (Gobert and Buckley 2000; Ingham and Gilbert 1991). Some common examples of expressed or conceptual models in science include the particle model of matter, water cycle models and food webs, computational models of the atmosphere, and natural selection models. Scientific models can be implicit or explicit and exist in a variety of forms and tools such as diagrams, language, mathematics, and computation simulations and programs. The most critical aspect of a model is that it embodies central aspects of a theory of a system in order for model users to predict and explain the natural world. We define scientific modeling as a scientific practice that entails various modeling activities such as developing, evaluating, revising, and using scientific models to predict and explain the world (Schwarz and White 2005). It should be noted that as scientists engage in scientific modeling, they do not carry out these constitutive activities in a certain order (Nersessian 1995). Depending on needs and situations, scientists conduct these activities in an iterative and dynamic manner. Note also that these modeling activities are so interlocked with activities of other scientific practices such as argumentation and empirical investigation.

Students' Epistemologies in Modeling

The outcome of students' engagement in modeling that this article focuses on is students' epistemologies that reflectively guide and are shaped by their modeling performances, which we call students' *epistemologies in modeling* (EIMs, hereafter). We use epistemology broadly to refer to both explicit knowledge and tacit beliefs about a range of topics about knowledge and knowing (cf. Chinn et al. 2011). Some examples of such topics include the nature, structure, sources, and justification of knowledge, beliefs, and knowledge-related products (e.g., explanation and models). Next, we distinguish one's epistemology used in performing a certain practice from one's epistemology constructed out of the practice, in agreement with those who recently called attention to the distinctiveness of students' epistemologies embedded in their scientific practices (Sandoval 2005; Baek 2013; Berland et al. 2013). Students' EIMs are their epistemologies in practice in the context of performing scientific modeling. Therefore, we hold that students' EIMs are not necessarily the same as their epistemologies about modeling captured in the context of reflecting on the practice in general. Detecting students' EIMs requires researchers to analyze various sources of data including utterances and artifacts they made in situ. Finally, we do not claim that students' EIMs are primarily coherent, theory-like cognitive structures that learners maintain across diverse contexts or that they are only facets of beliefs and ideas drawn on in situation-specific contexts (Elby and Hammer 2010). Rather, the data and our theories indicate that EIM is likely a combination of an individual's various epistemological resources that may be coherent or fragmented across contexts and distributed among tools, social norms, and environment in which the individual is situated. At the same time, while EIMs are contextually bound and situationally triggered by such factors as prior knowledge and experiences as well as the cultural and classroom norms, they may be supported over time in a way that enables individuals to develop more coherent ideas or knowledge as well as consistency across actions in contexts.

In this article, we pay special attention to two considerations of students' EIMs. First, we focus on students' ideas of explanation within their models. Scientific explanations bear distinctive values such as generality and parsimony and often take the form of mechanism, among others, which explains a phenomenon using dynamics and relationships among multiple microscopic or theoretically constructed components of the phenomenon system. However, elementary students' views of explanation vary and are different from those of scientists (McNeill 2011). Therefore, tracing students' ideas of explanation through their actions while modeling provides an indicator of how their EIMs might change. Next, we are interested in students' ideas of how to justify their models and, more particularly, their ideas about using empirical evidence. Ways of justifying knowledge or beliefs vary in different social communities. In the scientific community, provision of empirical evidence is one of the most valued ways of validating a claim. Tracing students' ideas about justification using empirical evidence through their actions while modeling, therefore, can also provide indications of their shifting EIMs. The importance of these two components of scientific epistemology is manifested in the current science education framework's inclusion of explanation and argumentation as stand-alone scientific practices (National Research Council 2012).

Technology in Research on Students' Participation in Scientific Modeling

Researchers identified multiple roles and affordances of technology in fostering students' learning in various forms and contexts. In their account of how technology supports project-based learning, Blumenfeld et al. (1991) identified several roles of educational technologies for project-based learning: fostering students' interest in project-based learning, making information more accessible, offering active representations, structuring the process and providing tactical and strategic support, diagnosing and correcting errors, and managing complexity and aiding production. Van Joolingen and Zacharia (2009) state that technologies have been used around what they identify as four major ingredients of meaningful inquiry in science: (1) a mission that motivates learners and clarifies the goal of the activity, (2) various sources of information including data resources from simulations or lab experimentations, (3) tools such as models, reports, arguments, and explanations to express what they have learned, and (4) cognitive and social scaffolds. In their chapter on the role of technologies in science learning, Kyza et al. (2009) provide a sociocultural perspective on the subject. They argue that learning technologies support learners' acculturation into scientists' sociocultural world where technologies are indispensable mediating artifacts by giving them multiple tools (e.g., scientific visualization tools, databases, data collection and analysis tools, simulations, and models) and scaffolds to facilitate their engagement in scientific practices.

In research on scientific modeling in education, technology has also been one of the major objects of investigation, particularly in the early 1990's. As technological development enabled scientists to develop and use scientific models to an unprecedented level, some researchers attended to the affordances and utility of computer simulations that incorporated scientific models for science learning (e.g., White 1993; Feurzeig and Roberts 1999; Stewart et al. 1992). Typically, these researchers developed or employed computer- or web-based microworlds in which students can change conditions, run simulations, and collect data. In these cases, technological tools were used to provide students with virtual environments that fostered students' active participation in science learning with great ownership (Spitulnik et al. 1999; Schwarz and White 2005; Gobert and Pallant 2004, Quintana et al. 2004).

While these studies provided evidence that technology can have some positive effect on students' understanding or performance of modeling, few of them offered an in-depth process or mechanism of how it happens. More particularly, little is known about how technology interacts with other components of a curriculum, contributing to the improvement of individual learners' modeling practices. This article aims to further advance our knowledge in the field by providing an in-depth case study that focuses on this aspect.

Methods

Contexts

This research was one of the several studies administered under a larger research project called Modeling Designs for Learning Science (MoDeLS), which had a goal of developing a "learning progression" (Smith et al. 2006) for scientific modeling that represents successively sophisticated levels of performance and understanding of scientific modeling. A learning progression for a scientific practice is a hypothetical model of learners' engagement in the practice. Ours focuses on the epistemological aspects of the practice that outlines visible or critical phases or aspects of learners' engagement in the practice. It does not imply a particular model of learning or development or a particular progression for how learners may develop competence in the epistemological aspects of the practice. This article aims to contribute to the knowledge of the field by determining how learners can make epistemological shifts in particular contexts that use technology or develop their epistemologies in practice over time. The learning progression for the larger project was developed as a tool for guiding and assessing K-12 students' engagement in and understanding of modeling. To accomplish this goal, the MoDeLS researchers used design experiment methodology (Cobb et al. 2003).

In employing this methodology, the two authors of this article developed a model-based curriculum unit on evaporation and condensation. To create this unit, we first developed a model-based instructional sequence by building on the findings of prior studies. Our goal was to make

Table 1 The designed model-based curriculum unit and technological tools used within the unit

Phase	Elements of the model-based instructional sequence	Details	Main technological tools involved
Beginning	Being introduced to an anchoring phenomenon and driving questions	A main phenomenon: the appearance of liquid in a bottle cap within a solar still Driving questions: "Would you drink the liquid in the bottle cap that came from this dirty water? Do you know what that liquid is and how it got there?"	
Evaporation	Being introduced to an anchoring phenomenon and driving questions	Anchoring phenomena of evaporation: Water shrinking on a plate/in a humidifier Driving questions: "What happened to the water on the plate/in the humidifier? Where did it go? How? Why?"	
	Constructing initial models	Constructing initial models of evaporation	
	Conducting empirical investigations	Conducting empirical investigations about evaporation	Digital probes (for humidity)
	Evaluating/revising their initial models	Evaluating/revising their initial models of evaporation to construct second models of evaporation	
	Evaluating others' models	Evaluating others' second models of evaporation	
	Being introduced to scientific ideas and related models	Being introduced to scientific ideas about evaporation and related models	Computer simulations about state changes
	Evaluating/revising their second models	Evaluating/revising their seconds model of evaporation to construct a third model of evaporation	
	Constructing a consensus model	Constructing a consensus model of evaporation	
	Using the consensus model for other phenomena	Using the consensus model of evaporation to explain/predict other phenomena of evaporation	
Condensation	Being introduced to an anchoring phenomenon and driving questions	Anchoring phenomena: Water drops forming on plastic wrap/a cold bottle Driving questions: "What are things on the plastic wrap/the cold bottle? Where did they come from? How did they get there?"	
	Constructing initial models	Constructing initial models of condensation	
	Conducting empirical investigations	Conducting empirical investigations about condensation	Digital probes (for humidity) A digital scale (for weight)
	Evaluating/revising their initial models	Evaluating/revising their initial models of condensation to construct second models of condensation	
	Evaluating others' models	Evaluating others' second models of condensation	
	Being introduced to scientific ideas and related models	Being introduced to scientific ideas about condensation and related models	Computer simulations about state changes
	Evaluating/revising their second models	Evaluating/revising their second models of condensation to construct third models of condensation	
	Constructing a consensus model	Constructing a consensus model of condensation	
	Using the consensus model for other phenomena	Using the consensus model of condensation to explain/predict other phenomena of condensation	
Conclusion	Answering the driving questions	Using the models of evaporation and condensation to answer the driving questions about the solar still phenomenon	

scientific modeling pedagogically accessible by organizing its key features and other activities into a general instructional framework (White and Schwarz 1999; Schwarz and Gwekwerere 2007; Clement and Rea-Ramirez 2008; Windschitl et al. 2008). Afterwards, we used this sequence to develop a model-based unit on evaporation and condensation. In developing this unit, we included several technological tools (e.g., digital probes and computer simulations) to help students advance their knowledge and practice within the unit. Table 1 outlines the sequence of this unit with constituent activities and the technological tools employed.

Two kinds of technology tools were used throughout the unit: digital probes for measuring humidity in the air and computer simulations that showed states of matter and how the state of matter changed with respect to the temperature. The primary roles of these tools were, respectively, to provide information (i.e., data) that was otherwise impossible to obtain and to dynamically represent how matter behaves on both macroscopic and microscopic scales.

Participants

The data presented in this article are a portion of the data generated when a class of elementary students and their teachers from a public school located in a Midwestern state enacted the model-based unit of evaporation and condensation in the fall semester of 2008. The participants consisted of a female teacher (Mrs. M) who had been teaching for 6 years, her intern teacher (Ms. H), and 24 fifth graders. In this article, we focus on two students, Brian and Joon, who belonged to a focus group consisting of four students that consented to be studied in this research. Brian was a European American boy whose academic level was high according to Mrs. M's report. While he was not the leader of the focus group during the unit enactment, he actively participated in most of the time and generally his ideas were recognized by teachers and other students alike. Joon was an English-learning student from South Korea yet could communicate well enough in English and performed moderately academically. He was a somewhat active participant in classroom activities, but primarily responded to others' ideas rather than articulated his idea or proposed a new idea. Part of the reason that we analyze and present Brian's and Joon's work for this article is that they were among a few students whose classroom artifacts and discourse data were available throughout the unit implementation to illustrate how their modeling practices developed over time. Moreover, we were interested in determining how similarly or differently these two racially, linguistically, academically, and culturally different students developed their ideas and practices of modeling over the time.

Data Sources

Our research team collected data from multiple sources including written pre- and post-tests, students' artifacts from notebooks, and classroom audio and video recordings. Data analyzed and presented in this article are derived from transcriptions of video recordings of class conversations and activities during the unit enactment. We also analyzed students' notebooks for their models and notes.

Research Questions

For this article, we analyzed the data mentioned above to address the following research questions:

1. How did Brian's and Joon's EIMs related to explanation and empirical evidence change over time as their engagement in a technologically enhanced model-based curriculum unit of evaporation and condensation accumulated?
2. How did various components of the enacted curriculum, including technology, potentially influence the changes of Brian's and Joon's EIMs related to explanation and empirical evidence?

Analysis of Students' EIMs Related to Explanation and Empirical Evidence

To analyze how students' EIMs related to explanation and empirical evidence changed over time, we used a coding scheme developed on the basis of our prior work (Schwarz et al. 2009, 2012) as well as the work of others in the field. This coding scheme targets four considerations of students' epistemologies in practice and has gone through extensive and multiple iterations and refinement. For brevity, we describe a version of that coding scheme related to two considerations of students' epistemologies in practice and illustrate how they are tailored to the work in this context.

Analyzing Students' EIMs Related to Explanation

Students know that they need to offer an explanation of a target phenomenon in their models. But, their ideas and actions regarding explanation vary with respect to constituents of and values to be sought in an explanation. The following levels typically capture the variation in what students focus on in their explanations. We noted that there was extensive variation between level 2 and 3. Hence we added in level 2.5 to help distinguish some aspects of that variation.

Level 1: Identify Explanation with Describing or Depicting a Phenomenon on a Macroscopic Scale Students often have a notion of what may be called "narrative explanation" (Norris et al. 2005). They explain a physical phenomenon in the same way as they explain an everyday event. That is, they may show how their target phenomenon changes over time on a macroscopic scale and often include in their models such features as human characters and background objects, features that often appear in a narrative explanation but are not scientifically relevant. For instance, some of the Mrs. M's students included in their models of evaporation a table on which a cup of water is placed or a human figure, though these were not relevant for explaining how water from the cup evaporates.

Level 2: View Explanation as Identifying Physical Conditions or Factors Involved in a Target Phenomenon Students regard explanation as identifying physical conditions or factors that they think affect a target phenomenon but do not attend to a mechanism underlying the macroscopic event. For example, some models of evaporation showed the sun as a cause of water evaporation. Similarly, some other students identified the air as a factor of evaporation in their models.

Level 2.5: Attending to Invisible Entities as an Explanatory Feature, Yet Without a Clear Understanding of the Meaning of These Entities Students at this level know that scientific explanation involves using some kind of invisible entities to account for a macroscopic phenomenon, but do not hold a firm idea of what such entities are. This means that students have not yet considered how the parsimonious microscopic or theoretically constructed entities contribute to the generality of a mechanism. One of the indicators of this level is that students make up peculiar entities that are not scientifically grounded or parsimonious. For instance, in some of Joon's early models, he used tiny water–air particles as an explanatory feature.

Level 3: View Explanation as Providing a Mechanism Students offer a hidden mechanism to explain a phenomenon. At this level, students attend to how microscopic/theoretical entities behave over time in explaining a target phenomenon. What differentiates this level from level 2.5 is that students' EIMs related to explanation at this level make use of microscopic/theoretical entities that are scientifically valid or at least parsimonious. For example, in their condensation models, a number of Mrs. M's students included tiny bits of water that exist in the air to explain how water drops appear on a cold bottle.

Analyzing Students' EIMs Related to Empirical Evidence

Students also have a range of ideas about how to justify a claim—in this case a model-based explanation. In accordance with such varying ideas, different notions and actions regarding empirical evidence can be distinguished as follows.

Level 1: Do Not Have a Clear Understanding of Empirical Evidence Students do not have a clear understanding of what empirical evidence is and how to use it for model improvement. They often take for granted the accuracy of their models and do not find the need to justify them. One indicator of this level is that even when students obtain empirical evidence that is inconsistent with their models, they do not reflect it in their next models in any way. Most students in Mrs. M's class started with EIM related to empirical evidence at this level.

Level 2: View Empirical Evidence as Just One Source of Information to be Incorporated into a Model Students perceive empirical evidence as one of various sources of information to be reflected in a model but do not know that it has distinctive epistemic authority that other sources of information do not have and can be used to justify or refute a model. One indicator of this level is that when students gain empirical evidence inconsistent with their models, they abstract some information from it and incorporate the information into their next models but leave the discrepancy unaltered. For example, when some of Mrs. M's students obtained a set of data of humidity from an experiment about evaporation that contradicted their models of evaporation, they translated the data into the idea of water particles and included water particles in their next models, but did nothing in their new models to reconcile the inconsistency.

Level 3: View Empirical Evidence as Information That Has Epistemic Authority and Can be Used to Justify or Refute a Model Students recognize the epistemic authority of empirical evidence over other sources of information in justifying or refuting a model and revise a model to be consistent with empirical evidence. This level was particularly indicated by the fact that students, noticing the discrepancy between empirical evidence and their prior models, changed their prior models to resolve the inconsistency. For instance, quite a few students of Mrs. M's included measurement data in their models to indicate that their models are supported by the empirical evidence. In this case, we coded their EIMs related to empirical evidence as level 3 because they attended to the particular epistemic weight of such information.

Analysis of Potential Influences of Various Curriculum Components on Students' EIMs

In order to analyze how the components in our curriculum including technological tools, the teachers' utterances, the curriculum material, and students' interactions influenced students' EIMs shifts over the time, we adopted the analysis procedure developed by the first author (Baek 2013). It drew on social semiotics (van Leeuwen 2005) as a general analytical framework. According to social semiotics, various curriculum components, independently or in concert with one another, function as "semiotic resources" (van Leeuwen, p. 3), that is, resources which convey meanings to participants in the curriculum implementation. Of different types of meanings, we focused on representation or "discourse" (van Leeuwen, p. 3) about scientific modeling that was potentially influential to students' EIMs. Thus, to determine what curriculum components were potentially influential for students' EIMs related to

Table 2 A summary of how Brian's and Joon's EIMs shifted over time and how various curriculum components potentially contributed to those shifts

Curricular events	Brian's EIM related to…		Joon's EIM related to…	
	Explanation	Empirical evidence	Explanation	Empirical evidence
Students constructed their initial models of evaporation (M1)	*Level 1: Brian described evaporation macroscopically and with a human figure*	*N/A*	*Level 1: Joon described evaporation macroscopically*	*N/A*
Mrs. M introduced empirical evidence (O1)		Brian took the ADD notion of empirical evidence		Joon took the ADD notion of empirical evidence
Students conducted empirical investigations about evaporation using humidity detectors (O2)		Brian acquired empirical data of humidity from experiments involving humidity detectors		Joon acquired empirical data of humidity from experiments involving humidity detectors
Mrs. M gave scaffolding to the focus students to help them make sense of the empirical data of humidity (O3)	Brian translated the idea of humidity into the idea of water particles		Joon translated the idea of humidity into the idea of water–air particles	Joon translated the idea of humidity into the idea of water–air particles
Students constructed their second models of evaporation (M2)	*Level 3: Brian showed how water particles behave to explain evaporation*	*Level 3: Brian included empirical data of humidity*	*Level 2.5: Joon showed how water–air particles behave to explain evaporation*	*Level 2: Joon did not resolve the inconsistency between his prior model and some experiments but included water–air particles*
Students saw computer simulations about state changes (O4)				Joon noticed that when a substance changes its status from liquid to gas, the molecules of it spread out into space and do not simply disappear
Students constructed their third models of evaporation (M3)	*Level 3: Brian showed how water particles behave to explain evaporation*	*Level 3: Brian included empirical data of humidity*	*Level 2.5: Joon showed how water–air particles behave to explain evaporation*	*Level 3: Joon revised his prior model to be consistent with the result of an experiment that humidity in the air increases during evaporation*
The focus students constructed their group consensus model of evaporation (O5)			Joon noticed that all the other students in his group had used water particles	Joon adopted Brian's idea of including empirical data
Students constructed their initial models of condensation (M4)	*Level 3: Brian showed how water particles behave to explain condensation*	*N/A*	*Level 3: Joon showed how water particles behave to explain condensation*	*N/A*
Students constructed their second models of condensation (M5)	*Level 3: Brian showed how water particles behave to explain condensation*	*Level 3: Brian included empirical data of humidity and weight*	*Level 3: Joon showed how water particles behave to explain condensation*	*Level 3: Joon included empirical data of humidity and weight*

explanation and empirical evidence, we looked at data where explanation and empirical evidence were represented verbally, pictorially, or performatively.

As we analyzed the data from classroom activities and conversations, we paid particular attention to curricular events that took place right before students' modeling activities from which their EIMs were analyzed. Underlying this decision was our idea, formed between our initial assumption and multiple rounds of data analyses, that students tended to draw primarily on curricular events that preceded their modeling activities in constructing their modeling understandings and performances. Finally, we used the same coding scheme developed to analyze students' EIMs to analyze the meanings of some components of those preceding curricular events for determining the particular influence of certain curriculum components on students' EIMs.

Findings

To address the research questions outlined in the previous section, we organize this section of the article in two parts. First, we present our analyses of Brian and Joon's models and discourse data from some of their modeling activities in order to show how Brian's and Joon's EIMs related to explanation and empirical evidence changed over time. In the subsequent part, we provide analyses of several classroom activities to show how various curriculum components, including technological tools, potentially influenced the shifts of the two students' EIMs. Table 2 provides an overview of the results of our analyses of Brian's and Joon's EIMs related to explanation and empirical evidence in their modeling activities (M1–M5) and of the potential influences of other activities (O1–O5) on their EIMs.

We begin by presenting our analysis of Brian's and Joon's EIMs related to explanation and empirical evidence. For each modeling activity from which their EIMs were analyzed, we provide some information to contextualize the results.

The Shifts of Brian's and Joon's EIMs

Brian's EIM can be characterized by a fairly significant leap to a sophisticated level at a very early stage.

Brian's EIM: Early Leap to Coordinating a Mechanism with Empirical Data

Brian's Initial EIM Brian's initial model of evaporation that he constructed at the earliest stage of the curriculum implementation period indicates that he held a somewhat naïve idea of explanation. After being introduced to two phenomena involving evaporation—water shrinking on a plate and from a humidifier—and then to the idea of scientific model, students followed the written instructions in their notebooks and given by Mrs. M to construct their initial models of evaporation to explain the phenomena (M1 in Table 2). It is worth noting that neither their notebooks nor Mrs. M provided detailed directions about how to construct a model, allowing students to employ their own ideas about modeling and the nature of evaporation to carry out this activity.[1] Brian's initial model of evaporation is shown in Fig. 1.

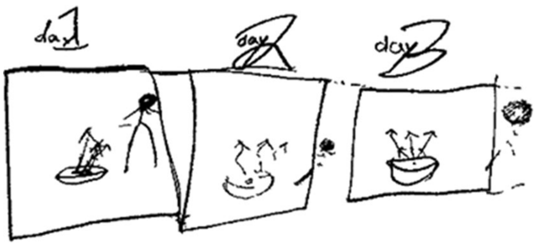

Fig. 1 Brian's initial model of evaporation

It depicts water in a container shrinking over a certain period of time (day 1 → day 2 → day 3) and a "guy who is checking on it every day" (from his explanation given later when a researcher asked about it). Brian's EIM related to explanation, analyzed from this model, is coded as level 1. He did not provide any physical factors or mechanism to explain the phenomenon of water evaporation represented by upward arrows. Instead, he only depicted the phenomenon by showing the size of water shrinking over time. The human figure he included in the model has no role in scientific explanation. However, his EIM related to empirical evidence cannot be analyzed from this data: Because students had no empirical evidence at this time, we do not know for sure what kind of idea Brian had concerning empirical evidence.

Brian's Second EIM Brian's EIM made a noticeable shift in his next modeling activity. After making their initial models of evaporation, students were introduced to the concept of empirical evidence and conducted several sets of empirical investigations about evaporation. Then, students were instructed to construct their second models of evaporation using the empirical evidence they had collected (M2 in Table 2). In this activity, Brian employed a fairly sophisticated idea of explanation and empirical evidence. See his second model of evaporation in Fig. 2.

This model explains how hot and cold water each shrinks from a container and why they shrink at different rates over time by showing that hot and cold water particles move into the air at different speeds. Analysis of this model indicates that Brian deployed a level 3 EIM related to explanation at this time. He utilized water molecules as an explanatory feature. More specifically, he showed how such microscopic/theoretical entities move at different rates in different temperatures to explain why hot water evaporates faster than cold water. This mechanistic

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[1] The only two directions as to how to construct a model that the student notebook provided were to "show how [evaporation] happens over time" and to "capture not just "what happens to the water" but "why or how it happens.""

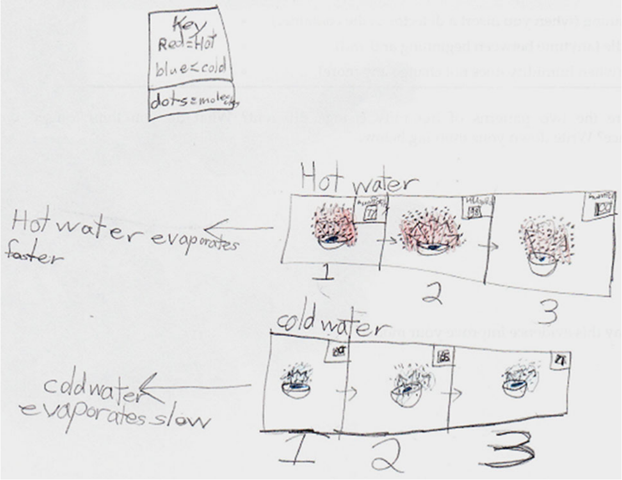

Fig. 2 Brian's second model of evaporation

explanation shows that Brian used a sophisticated notion of scientific explanation. Next, Brian's idea of empirical evidence, analyzed from this model, is coded as level 3. He included data of humidity in this model in such a way that they are consistent with his explanation. This inclusion indicates first that Brian recognized the weight of empirical evidence over other kinds of information in justifying his explanation and also that he was able to coordinate empirical evidence with explanation at this time.

From this activity to the end of the unit, Brian's models had the same characteristics in terms of explanation and use of empirical evidence. He continued to use water particles as an explanatory feature in his models and showed empirical data such as humidity or weight that were consistent his explanations.

Although Brian and Joon engaged in nearly the same classroom activities, their EIMs shifted over time through somewhat different pathways. While Brian's EIM shifted and became stable early on, Joon's EIM changed gradually as he navigated through and appropriated various ideas about models and modeling.

Joon's EIM: Step-by-Step Progress to Coordinating a Mechanism with Empirical Data

Joon's Initial EIM Joon's initial EIM is detected from his initial model of evaporation (Fig. 3) that he created when all students were instructed to do so (M1 in Table 2).

Analysis of the model indicates that Joon's EIM related to explanation was at level 1 at this time. He simply described a target phenomenon on a macroscopic scale with pictures and words. The model shows water on a plate shrinking over time and includes a written description of "water evaporate[*sic*]." Like Brian, Joon failed to explain the phenomenon by identifying physical factors involved or by providing a mechanism at this time. Regarding Joon's EIM related to empirical evidence, however, we cannot analyze it from this model because he did not include any empirical evidence.

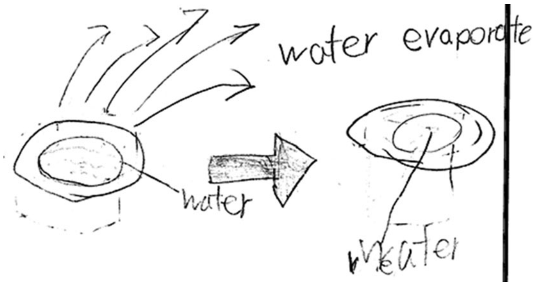

Fig. 3 Joon's initial model of evaporation

Joon's Second EIM Joon's second model of evaporation changed after carrying out multiple empirical investigations about evaporation (M2 in Table 2). His second model of evaporation is illustrated in Fig. 4.

Comparing this model with Joon's prior model, one can notice that Joon's target phenomenon remained the same: water on a plate shrinking over time. In this model, however, Joon introduced unique entities he crafted by putting "little water" in the "air" (which we call "water–air particles" hereafter) and focused on the movement of those water–air particles to explain how water shrinks over time.[2] Note that the water–air particles are microscopic entities but are neither scientifically grounded nor fully parsimonious. Therefore, his EIM related to explanation, analyzed from this model, is coded as level 2.5. Next, analysis of the model indicates that Joon's EIM related to empirical evidence was at a level 2. What empirical evidence about evaporation did Joon incorporate into this model? First, we note that the results of some experiments about evaporation were not consistent with his prior model. For example, one experiment revealed that humidity in the hood covering a cup of water increases as water evaporates over time, which could not be reconciled with his initial model of evaporation in which all the water that has evaporated does not remain in the air. Nevertheless, Joon did not resolve this discrepancy in his second model, indicating that he failed to recognize the inconsistency. However, as we will see in more depth later on, he turned humidity in the air into his idea of "water–air particles." Therefore, his EIM related to empirical evidence was coded as level 2 at this time.

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[2] Although he did not represent these entities fully in the picture, his written explanation that emphasizes the role of the air evidently indicates that he used these entities as a major explanatory feature.

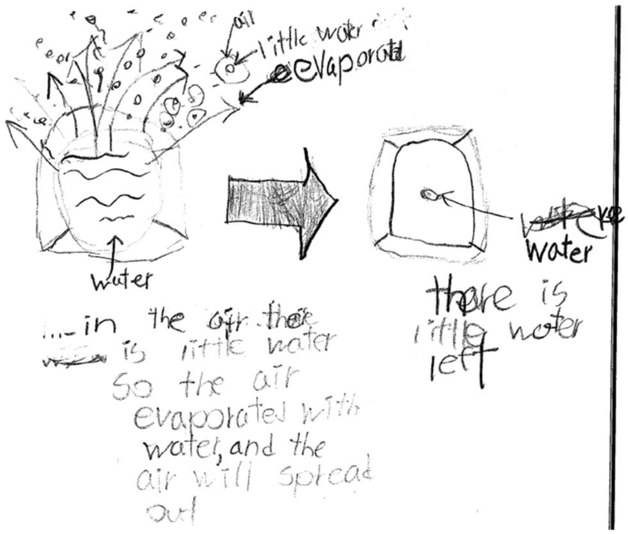

Fig. 4 Joon's second model of evaporation

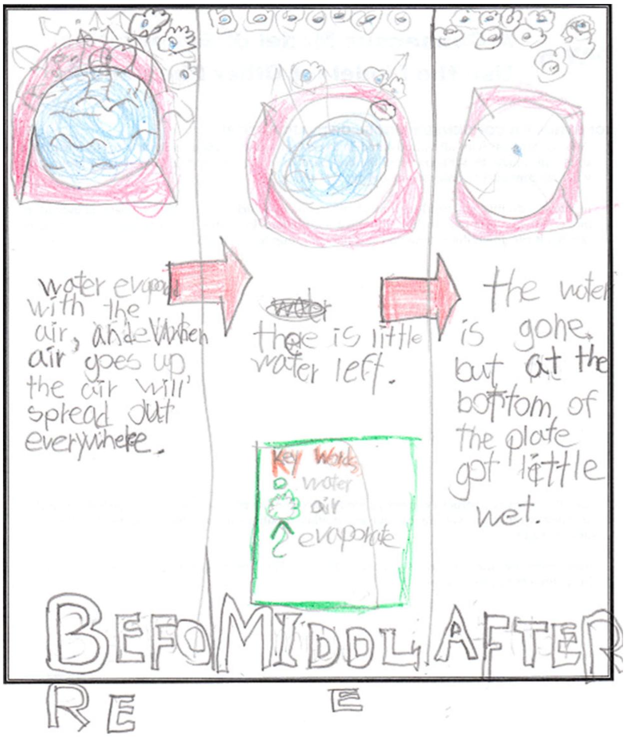

Fig. 5 Joon's third model of evaporation

Joon's Third EIM After watching computer simulations about state changes, Mrs. M told students to construct their third models of evaporation (M3 in Table 2). Joon's third model of evaporation is shown in Fig. 5.

Similar to his previous models, Joon chose to illustrate water shrinking on a plate over time as a target phenomenon. To explain this phenomenon, he showed how water–air particles move into the air as in his prior model. Again, because these entities are microscopic yet not very parsimonious, his EIM related to explanation is coded as level 2.5, as before. On the other hand, he made a noticeable progress in his EIM related to empirical evidence. As mentioned above, his prior model did not show that the number of water–air particles increases over time to make the explanation consistent with one experiment result that humidity in the air increases as water evaporates. However, he did reflect the experiment result by showing more and more water–air particles in the air as water evaporates. This indicates that he took the epistemic weight of the empirical evidence more seriously. Therefore, Joon's EIM related to empirical evidence was scored at a level 3 at this time.

Joon's Fourth EIM After completing their inquiry of evaporation, students moved to studying condensation. Students constructed their initial models of condensation after they were introduced to two cases of condensation (M4 in Table 2) in a manner similar to that of studying evaporation. In his initial model of condensation,[3] Joon showed that the number of water drops appearing on a cold bottle increases over time and explained it by showing that an increasing number of water particles in the air come to the surface of the bottle. One difference between his prior model and this model is that he replaced the water–air particles he had used in his prior model with more parsimonious water particles in this model. Therefore, his EIM related to explanation shifted from level 2.5 in M3 to a level 3 in M4. We could not analyze his EIM related to empirical evidence from this model because he did not have any empirical evidence about condensation at this time.

Joon's Fifth EIM After conducting experiments about condensation, Mrs. M's students constructed their second models of condensation (M5 in Table 2). Joon's second model of condensation is presented in Fig. 6.

In this model, Joon depicted and described how an increasing number of water drops are formed on the surface of a cold bottle as his target phenomenon. Then, he explained it by showing and stating how water particles that he called "water vapor" in the air clump together on the surface of the cold bottle. This is a mechanistic explanation and thus his EIM related to explanation from this model is coded as level 3. Regarding his attention to empirical evidence, Joon included in the model how two sets of empirical data (humidity, weight) change over time to justify his description and explanation of the target phenomenon, indicating Joon's increased awareness of the

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[3] We do not present Joon's initial model of condensation here because it is nearly identical to his second model of condensation (Fig. 6) except that it does not include humidity and weight. Therefore, to better understand the following descriptions, refer to Fig. 6.

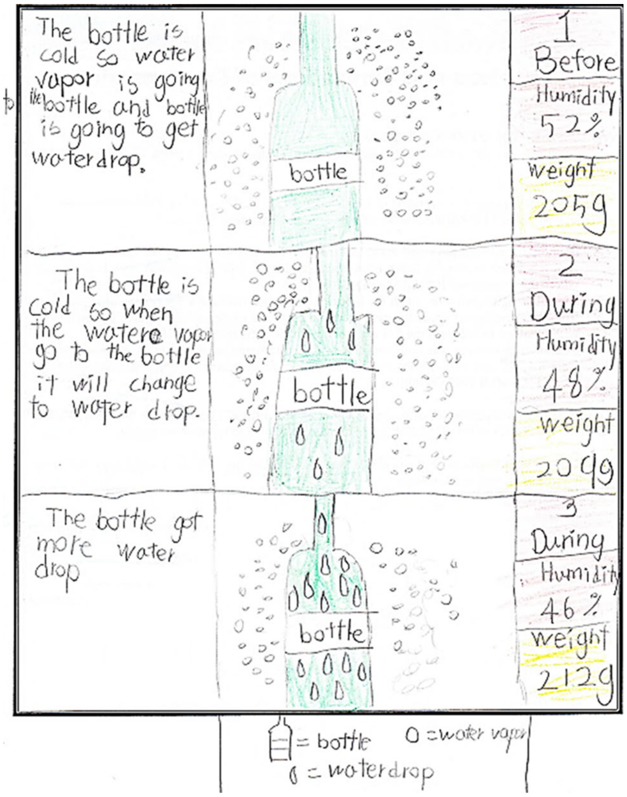

Fig. 6 Joon's second model of condensation

epistemic authority of empirical evidence for a model-based explanation and thus was coded a level 3 for his EIM related to empirical evidence.

We now turn to our second research question: How did various components of the enacted curriculum, including technology, potentially influence the changes of Brian's and Joon's EIMs? In the preceding sections, we showed that Brian's EIM shifted to a fairly sophisticated level at the beginning of the unit, whereas Joon's EIM made multiple shifts from participating in various activities. How and why did Brian's and Joon's EIMs shift in different ways? To address these questions, this section presents our analyses of the potential influences of particular curricular events on the two students' EIMs, with special attention to the role of the technology.

Potential Influences of Various Curriculum Components on Brian's and Joon's EIMs

Table 2 shows that overall, Brian's EIM made one shift (M1 → M2) whereas Joon's EIM three shifts (M1 → M2, M2 → M3, M3 → M4/M5). Correspondingly, the curriculum analysis claims are organized in three parts. First, to examine what potentially affected the shifts of both Brian's and Joon's EIMs from M1 to M2, we focus on three curricular events (O1, O2, O3) that took place between the two modeling activities and analyze how some components of those events potential influenced the two students' EIMs. Second, for the second shift of Joon's EIM from M2 to M3, we investigate the role of an intervening curricular event (O4). Finally, we look at one other curricular event (O5) to understand how Joon's EIM changed from M3 to M4/M5.

The Shifts of Brian's and Joon's EIMs Between M1 and M2

Mrs. M's Introduction of Empirical Evidence (O1) Right after Mrs. M's students created their initial models of evaporation, Mrs. M introduced students to the concept of empirical evidence. To that end, she first read some of the passages from the student notebook that introduce empirical evidence as a criterion for evaluating the quality of models. Then, she added the following comments.

Mrs. M: …Remember what I drew? Just a big circle? And I said, "This is the globe, this is the earth, this is a model of the earth." And you guys were like, "No, it's not." And I said, "Yeah, it is. This is the model of the earth." And you said, "We know, but it's not good." Right? We had to add some different things to that, that's kind of what we are talking about here. Sure, [Reading the student notebook] "…We will conduct a series of experiments about evaporation to improve our model. What you need to do is collect a set of empirical evidence…What you need to do is to collect empirical evidence to test your model with them." Circle "test your model," circle it, put a star next to it. This is exactly what your objective is for the day, alright?

She began by connecting the passages to a previous event when she and her students had talked about a model of the earth and continued to read the remaining passages. It is clear in this excerpt that students were expected to use empirical evidence to improve their models. Yet, how to achieve that goal was not clearly presented. First, no definition of empirical evidence was provided. Second, this introduction provided two somewhat differing ideas of how to use empirical evidence for model improvement. One idea was to *add* empirical evidence to a model (ADD notion of empirical evidence, hereafter). The other was to *test* a model with empirical evidence (TEST notion of empirical evidence, hereafter). There was no information about how to integrate these two ideas of empirical evidence in this introduction.

Conducting Empirical Investigations About Evaporation Using Humidity Detectors (O2) Following Mrs. M's introduction of empirical evidence, students carried out four experiments about evaporation. First, students observed how the initially same level of water in an open cup and in a cup covered with plastic wrap changed over time, finding that the water in the open cup shrank more than the water in the covered cup. Second, students put three dry blue cobalt chloride strips in front of a humidifier each at 5, 10, and 15 cm from the humidifier and measured the time it took each strip to turn pink. They discovered that the farther away a cobalt chloride strip was placed from the humidifier, the longer it took to change colors. Third, students covered a cup of water with a hood and measured humidity inside the hood with a humidity detector over some time, finding that the humidity in the hood increased over the time. Lastly, students covered a cup of hot water and cold water with a hood respectively and measured humidity inside each hood with a humidity detector over time. The result was that the humidity in the first set increased faster than the humidity in the second set.

Note that technological tools students used in conducting these experiments varied in technological sophistication. The most sophisticated technological tool was the digital humidity detector that generated real-time numerical data employed in the third and fourth experiments. This handheld probe made it possible for students to obtain the otherwise unattainable empirical data about evaporation. For example, Brian, Joon, and the other two students who comprised the focus group collected the following measurement data using this device.

- The third experiment: Humidity in the hood increased from 59 to 61% over some time.
- The fourth experiment: Over a similar length of time, humidity in the hood covering hot water increased from 67 to 100% whereas humidity in the hood covering cold water increased from 63 to 65%.

Although empirical data like these were valuable, they did not necessarily secure the development of students' EIMs or their models: Students had to make sense of the data and know how to use them for improving their models of evaporation. We therefore need to examine how students appropriated the empirical data they had acquired using the humidity detectors for their models and what curricular events helped this to happen.

Mrs. M's Scaffolding for Helping Students Make Sense of the Data from the Humidity Detectors (O3) After students carried out the experiments of evaporation, Mrs. M helped them make sense of the empirical data collected and use it to improve their initial models of evaporation. In particular, there was one instance in which Mrs. M's scaffolding potentially impacted Brian's and Joon' EIMs in a significant way. As Mrs. M wrapped up the activity of empirical investigations about evaporation, she asked students, "What do you now understand about evaporation as a result of doing empirical investigations?" and allowed them to spend some time (13 min) to articulate the experiment results in groups. During the time, Mrs. M came to the focus students' group and helped them interpret the result of the experiments involving humidity detectors as follows.

Mrs. M: …What about the humidity detector? What is that telling you?
Brian: That when water evaporates, it's humid?
Mrs. M: What does humid mean?
……
Brian: Water vapor?
Mrs. M: Okay…
……
Adrianna: When water comes in contact with air, it dissolves into the air…
……
Mrs. M: But what does dissolve mean?
Brian: (??) little particles (??)
Mrs. M: ……
Mrs. M: So it doesn't dissolve but it kind of, it kind of gets smaller?

When Brian and Adrianna each came up with ideas of "humid" and "dissolves into the air," Mrs. M pushed them to go further to translate those ideas into the idea of small particles of water. Therefore, Mrs. M's scaffolding here potentially helped students began to attend to microscopic/theoretical entities and thus mechanistic explanation in their modeling activities hereafter. However, this conversation may have left the focus students with an idea that humidity is nothing but an indicator of water particles and likely hindered them from attending to the change of humidity over time as empirical evidence.

Now, consider how these three events potentially affected Brian's and Joon's EIMs respectively.

Brian's EIM Shift What about these events possibly helped Brian shift his EIM? First, considering that it was not until Mrs. M offered scaffolding to the focus students that Brian turned the idea of humidity into the idea of water particles (O3), it is safe to say that his EIM related to explanation shifted from level 1 in M1 to level 3 in M3 (see Table 2) primarily due to the help of Mrs. M's scaffolding. Regarding the fact that Brian began to include the empirical data of humidity in his second model of evaporation, which he continued to do in his subsequent models, several factors from these preceding events seem to have worked together for this to happen. First, on a general level, it is likely that the absence of coherent concepts of empirical evidence and how to use it for models (O1) created an epistemological vacuum where students' various ideas of using empirical evidence such as Brian's—including empirical data in a model—for model improvement could

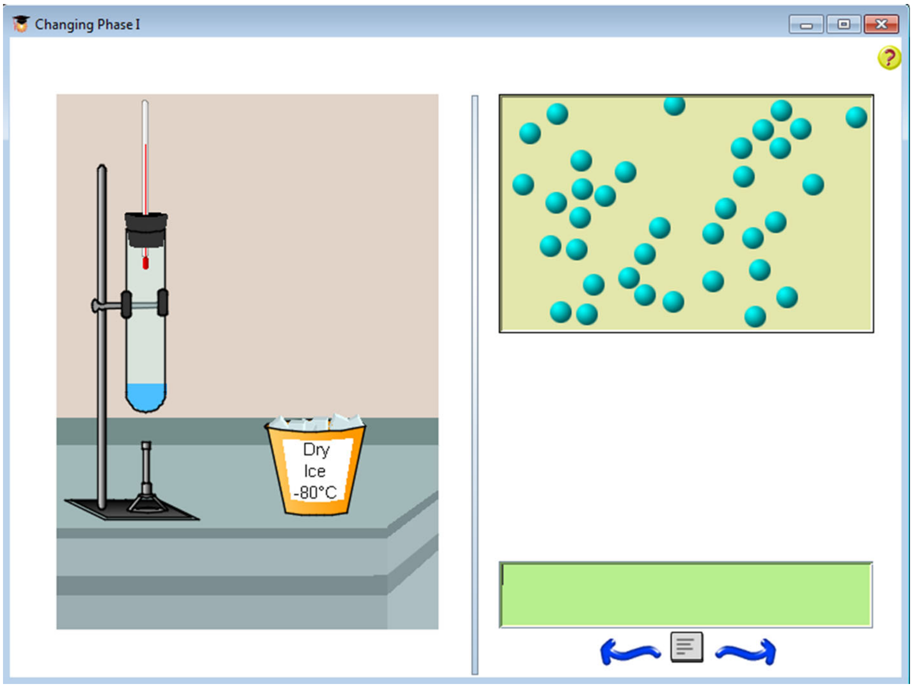

Fig. 7 Computer simulation about phase change (The Concord Consortium 2013)

emerge. More specifically, however, it appears that of the two (ADD, TEST) notions of empirical evidence that Mrs. M offered (O1), Brian picked up the first one, namely, the idea of adding empirical evidence to a model: in constructing his second model of evaporation, he added the empirical data of humidity collected in some experiments of evaporation to the model (O2).

Joon's EIM Shift Next, how did these events potentially affect Joon's EIM? First, for the shift of his EIM related to explanation from level 1 to level 2.5 (see Table 2), Mrs. M's scaffolding that helped the focus students see "humidity" and "dissolving" in terms of water particles (O3) seems to have played an important role, just as in Brian's case. However, Joon went beyond the idea of simple water particles to craft water-in-the-air particles possibly because he emphasized the role of the air in the movement of water particles and perceived the air, too, in terms of particles. Second, concerning the fact that his EIM related to empirical evidence was at level 2, multiple elements from these curricular events should be taken into consideration. First, when Mrs. M introduced empirical evidence (O1), Joon chose the ADD notion of empirical evidence over the TEST notion of it. It is transparent that he did not notice the inconsistency between his prior model and the results of some experiments about evaporation, nor did he know how to test the model with the experiment results. What, then, is the evidence that he used the ADD notion of empirical evidence? It is likely that as Joon came to translate humidity into water–air particles due to Mrs. M's scaffolding (O3), he saw the idea of water–air particles as connected to the empirical data of humidity. Given that, it can be argued that when he added water–air particles to his second model of evaporation, he employed the ADD notion of empirical evidence.

Joon's EIM Shift Between M2 and M3

To explain what potentially helped Joon's EIM related to empirical evidence shift from level 1 in his second model of evaporation (M2) to level 3 in his third model of evaporation (M3) (see Table 2),[4] we need to analyze a curricular event that occurred just before he constructed his third model of evaporation: computer simulations about state changes.

Computer Simulations About State Changes (O4) After students constructed their second models of evaporation, they evaluated one another's models.[5] Then, they saw five interactive computer simulations: three simulations about what states of matter are and two about how a state of matter changes. To illustrate what these simulations look like, an example is provided in Fig. 7.

Several notes need to be made about the simulations with respect to students' EIMs. First, it is likely that the simulations helped students improve their EIMs related to explanation by providing a sophisticated explanation. All the

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[4] Recall that his EIM related to explanation did not change at this time.

[5] Because this activity was undertaken rather briefly, we do not analyze it in this article.

simulations showed how matter behaves on both macroscopic and microscopic scales. For example, the simulation in Fig. 7 showed in parallel a macroscopic view and a microscopic view of how water in a test tube changes its states. Such juxtaposition potentially allowed students to see that scientific explanation is providing what is happening on a microscopic scale particularly by showing the behaviors of microscopic entities. Second, as they noticed dynamic synchronism between the macroscopic and microscopic views of targeted phenomena in the simulations, students were able to see how to generate macroscopic or empirical manifestation of a phenomenon and a mechanism for the phenomenon consistent and thus to improve their EIMs related to empirical evidence. As such, this event had a potentially powerful effect on students' EIMs.

Joon's EIM Shift What potential influence did this curricular event exert on Joon's EIM related to empirical evidence? Recall that whereas Joon's second model of evaporation showed that water–air particles are gone after evaporation, his third model of evaporation showed that the number of water–air particles in the air increases over the time, aligned with the result of an experiment about evaporation showing that humidity in the air increases over time as water evaporates in a hood. This shift is related to the computer simulations showing that when a substance changes its status from liquid to gas, the molecules spread out into space and do not simply disappear. It is possible or likely that Joon took notice of this feature and incorporated it in his third model of evaporation.

Joon's EIM Shift Between M3 and M4/M5

Finally, we provide our analysis of one more curricular event to explain how it potentially helped Joon's EIM develop further from M3 to M4/M5 (see Table 2).

Constructing a Group Consensus Model of Evaporation (O5) After constructing their third models of evaporation, students constructed consensus models of evaporation in groups. They invested a substantial amount of time (about 30 min) and effort into this activity. In this activity, the focus group students, including Brian and Joon, talked about what components should be in their consensus model of evaporation and then constructed it together. Two aspects of this complex process are worth highlighting.

First, the group collectively decided to adopt the water particle feature (rather than Joon's water–air particles) that the rest of the group had used in their individual models for their consensus model of evaporation. Second, although only Brian's model of evaporation included the empirical data of humidity, the focus students came to decide to appropriate the feature for their consensus model of evaporation. The following segment of conversation illustrates how this happened. Note that Adrianna was the logistical leader of the group.

Brian: We should put the humidity to show that hot water is more humid…to show that hot water evaporates fast and stuff
Adrianna: Or, maybe we could just say like "faster" and "slower," y'know, instead of humidity or=
Brian: =Yeah, but I want to put the humidity. It's just more detail, y'know?
……
Adrianna: Okay …question. First, do you want humidity like that [pointing to her own model]. See how it says, like (?) humidity. Or do you want [pointing to Brian's model] percentage? Because we don't really know the real percentage. So why don't we just do like (?)=
Brian: =We could just make up a percentage
Adrianna: No, that's=
Brian: =How about we do both? I'd say we do both
Adrianna: …We could do the humidity but still do "slower" or "faster," you know?=
Brian: =Yeah

From this conversation, one can identify at least two factors influencing this decision. One is social. Brian and Adrianna played major roles in deciding to include the data of percentage humidity in their consensus model of evaporation while Joon and the fourth student did little in this process. The other factor is cultural. Adrianna and Brian adopt both Adrianna's idea of putting "faster" and "slower" and Brian's idea of including percentage humidity. It was Brian's emphasis on "more detail"—a value frequently emphasized by elementary teachers as an important quality of work—that appealed to Adrianna and perhaps the other two students too, in the process.

Joon's EIM Shift How then did this event potentially help Joon change his EIM? First, for the shift of his EIM related to explanation from level 2.5 in M3 to level 3 in M4 (see Table 2), Joon replaced his water–air particles used in his prior model with more parsimonious water particles in his initial model of condensation. He made this replacement after noticing, in the process of constructing a group consensus model of evaporation, that all the other focus students had used more parsimonious water particles in their individual models of evaporation.

Second, regarding Joon's EIM related to empirical evidence, his inclusion of empirical data in his second model of condensation was likely influenced by the conversation presented above. More specifically, it is likely that as Joon heard the exchanges between Adrianna and Brian, he became convinced of the value and utility of including empirical data in a model.

In summary, Brian and Joon shifted their EIMs related to explanation and empirical evidence throughout the curriculum unit in different pathways due to their different appropriations of diverse curriculum components including technology, despite the similarities of their EIMs in their initial and final states.

Early in the unit, Brian came to attend to both explanation and empirical evidence in a fairly sophisticated manner. Despite the lack of a clear definition and guidelines about empirical evidence for models, as he obtained the data of percentage humidity and went through a collective process of making sense of it in which Mrs. M's scaffolding did a crucial role, he came to note that the scientific model needs to provide a mechanistic explanation, that is, an account of why or how a macroscopic event occurs by means of microscopic/theoretical entities and to be justified by empirical data. Though various curriculum components made an impact on this change, we should also acknowledge the contribution of Brian's prior knowledge ("little particles") and creative idea (including empirical data in a model) to account for such a quick shift in his EIM.

By contrast, Joon's EIM made a relatively slow and multistaged shift. With respect to explanation, Joon, like Brian, quickly attended to mechanism primarily due to Ms. M's scaffolding given to the focus students when they made sense of humidity. But, it was not until he noticed that he was the only one in his group who had water–air particles, that he converted it into parsimonious water particles. Regarding his EIM related to empirical evidence, Joon did not have a particular idea of what it involved at the beginning of the unit. He knew the importance of empirical evidence due to Mrs. M's emphasis on it, but when he made sense of humidity, he took Mrs. M's scaffolding to equate it with water–air particles. Computer simulations about state changes allowed him to better coordinate the change of humidity with the change of water–air particles. But, again in constructing a group consensus model of evaporation and more specifically when Brian made a strong case for including empirical data in a model, Joon adopted this way of using empirical evidence. In sum, diverse curriculum components made diverse contributions to Joon's gradual EIM shift.

Discussion and Conclusion

In the preceding section, we provided a detailed account of how two students' EIMs shifted over time as they engaged in a technologically enhanced, model-based unit and how various components of the learning ecology, including technological tools, the teacher's scaffolding remarks, and students' collective activities and conversations, were marshaled in the service of their shifting EIMs.

Our in-depth case study provides some contributions to the current reform efforts around engaging students in scientific practices in three interrelated aspects. First, our detailed portrait of students' work can help unpack what it looks like for individual students to engage in scientific modeling. While Brian and Joon were members of the same group, experienced virtually the same curricular events, and had similar EIMs at the outset, tracing their work throughout the unit revealed that although their EIMs ended up almost identical at the end, their patterns of engagement in scientific modeling and the shifts in their EIMs followed different pathways. Such differences may seem obvious in retrospect because student engagement in any scientific practice is a process in which students negotiate their own cognitive, epistemological, linguistic, and cultural resources with the sociocultural resources of the scientific community embedded in that scientific practice in different manners. At the same time, it is worth noting that the two students' EIMs converged after participating in multiple well-coordinated scientific activities that involved scientific tools, such as conducting empirical investigations, constructing and using models, and consensus building. This process indicates that students with diverse backgrounds can meaningfully and productively appropriate socioscientific norms and resources entrenched in scientific practices.

Second, our case study of how two students' EIMs shifted over time offers some insights for developing a learning progression of elementary students' EIMs. One of our findings indicates that although the initial and final states (levels) of Brian's and Joon's EIMs related to explanation and empirical evidence appeared similar, the pathways in which their EIMs shifted were somewhat different and impacted by the multi-pronged instructional, curricular, technological, social approach. This finding compliments the work of studies that aimed to construct a learning progression for scientific modeling using such assessment methods as questionnaires and interviews. These studies often overlook the idiosyncratic and emergent nature of individual students' learning progression in their attempts to construct a general pattern of how students make progress in modeling. Our work and other studies that show individual students' "learning trajectories" (Stevens et al. 2010) provide finer-grained and more nuanced accounts of how students move from one level to another and help the learning progression research as a whole move forward.

Finally, our work contributes to research on technology-enhanced learning (e.g., Balacheff et al. 2009) for students' engagement in scientific modeling by providing a rich picture of the complex ways in which technological tools were used and perceived in conjunction with other curriculum components of a model-based unit to help Brian and

Joon shift their EIMs. Our findings confirm some of the findings of prior work of technology for science learning and model-based learning (e.g., Blumenfeld et al. 1991; Van Joolingen and Zacharia 2009; Spitulnik et al. 1999) in that both humidity detectors and computer simulations about state changes provided Mrs. M's students great affordances in accessing information that was difficult or impossible to obtain otherwise as well as cognitive and epistemological scaffolding. However, our analyses challenge preexisting research that focus exclusively on technology in student engagement in modeling and point to the need to widen our view to see how technological tools and other curriculum components are interrelated in the service of fostering students' participation in modeling. In particular, our finding that students needed to participate in the process of making sense of data individually and collectively with Mrs. M's scaffolding in order to use empirical data from humidity detectors to improve their models indicates that students' engagement with technological tools alone do not guarantee their common and meaningful appropriation of them in achieving their learning goals. Learning technologies should be considered only one component that should enter into "orchestration," that is, "the process of productively coordinating supportive interventions across multiple learning activities occurring at multiple social levels" (Dillenbourg et al. 2009, 12) on the teacher's part. Furthermore, it should be remembered, as noted above, that even from the same orchestrated activities, individual students—such as those in our study—respond differently. In this case, Brian and Joon differed in how they made sense of data from humidity detectors and computer simulations about state changes.

We acknowledge limitations to this study. The insights of our case study are hypothetical, and more evidence is needed to confirm or refute them. For example, data about Brian and Joon's rationales would help confirm shifts in Brian's and Joon's EIMs. Additionally, one cannot conclude from our findings that Brian's and Joon's EIMs underwent permanent changes. In other words, it cannot be argued that Brian and Joon *acquired* new, scientifically more sophisticated, EIMs as a result of participating in enacting the model-based curriculum unit of evaporation and condensation. In agreement with researchers who argue for the dependency of students' epistemologies on contexts (Hammer and Elby 2002; Sandoval and Morrison 2003), we are aware that Brian's and Joon's more advanced EIMs were context-bound and may not have been stable enough to be employed across different contexts at the time they were investigated. To make a case that these students came to obtain more sophisticated EIMs that were permanent requires more evidence indicating that two students employed these EIMs over an extended period of time and across different contexts which is likely to require consistent and extended support from curricular, instructional, technological and social resources like the one provided in this unit.

In conclusion, this work illustrates the positive impact of a technologically enhanced, model-based curriculum on two students' EIMs. Although they responded to technological tools and other curriculum components differently and thus their EIMs shifted using somewhat different pathways, their EIMs both became increasingly sophisticated over time. Our work provides some promising support for a practice-based approach to science learning. Studying the nature and mechanisms of how students' modeling develops over time will continue to help us refine how to better support scientific modeling, the robust use of technology in the process, and the related curriculum and instruction. Such work will advance our understanding of how to engage all learners in scientific practices such as scientific modeling.

Acknowledgments This research was funded by the National Science Foundation under the grants DRL1020316 and ESI-0628199 to the MoDeLS and Scientific Practices projects at Northwestern University. We appreciate our colleagues, Hayat Hokayem, Li Zhan, Jing Chen, Mete Akcaoglu, and Li Ke, for their work in these projects. The opinions expressed herein are those of the authors and not necessarily those of any one or party mentioned above.

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