Presently under review at the revise and resubmit stage in the *Journal of Teacher Education*

A Comparative Longitudinal Case Study of Two Fifth-Grade Teachers' Engagement in Scientific Modeling Pedagogical Practice

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Teachers play a critical role in how new education standards, such as those from the Next Generation Science Standards (NGSS) are interpreted and enacted in the classroom. These new standards require ambitious teaching efforts and new kinds of classroom pedagogy. Ambitious pedagogy in science requires engaging learners in scientific practices to understand disciplinary core ideas, and crosscutting concepts. Despite potential difficulties, prior research has demonstrated that ambitious practice and change is attainable for teachers with appropriate conditions, support, and guidance (Lampert et al., 2013; Smith & Girod, 2003; Thompson, Windschitl, & Braaten, 2011; Windschitl, Thompson, Braaten, & Stroupe, 2012). Nonetheless, there are many questions regarding how reform-based approaches may be taken up in practice, and how teachers develop their pedagogical practice over time in the context of reform-based approaches.

This manuscript addresses some of those questions within the contexts of the recent reform efforts in science education. Those reform efforts are embodied in NGSS whose hallmark is a focus on a three-dimensional view of science learning that highlights the integration of the science and engineering practices, disciplinary core ideas and crosscutting concepts (Codere, Dansah, Bayer, & Mun, 2014). In their pedagogical practice, teachers can use disciplinary core ideas as the focus of repeatedly engaging students in scientific practices—not only scientific modeling but also other practices such as developing explanations. Moreover, A curricular focus on modeling or practices does not make content less important: Rather, it suggests a pedagogical approach—engagement in science and engineering practices—through which learning about content and cross-cutting ideas is effective and meaningful.

Among the three-dimensional aspects, the *scientific practices* dimension is likely to be new and challenging for teachers as it focuses less on the knowing of particular facts and ideas, and more on the practices or the doing of science and engineering that lead to making sense of ideas and applying ideas. The practice of scientific modeling is especially unfamiliar and demanding for teachers and students (Author, 2009a; Harrison & Treagust, 2000; Justi & Gilbert, 2002). We define modeling as a practice that entails developing, using, evaluating, and revising models over time (Author, 2009a). Further, a scientific model is a sense-making tool that enables one to predict and explain the world. Models abstract and simplify a system by focusing on key features of that system (Author, 2009b) such as components, relationships and interactions of that system that enable prediction and explanation. Models can range in form from diagrams to physical objects, to words, equations or computer programs (Harrison & Treagust, 2000). The practice of modeling is critical in scientific as well as other disciplinary work, and can play important role in students' scientific sense-making as well (Author, 2015a). Scientific modeling can help students externalize their ideas and make them visible and revisable (Author, 2009a; Author, 2009b). It can also help them better understand the nature of the scientific endeavor when models are continually evaluated and revised with respect to empirical data and scientific criteria (Author, 2009a; Author, 2009b).

Teachers are generally unfamiliar with modeling practice or use models in limited ways. Traditionally, teachers have used models to demonstrate canonical scientific systems rather than as tools for student thinking (Justi & Gilbert, 2002). Still others engage students in constructing models for the sake of constructing models rather than for using them to predict or explain phenomena in the world (Stewart, Cartier, & Passmore, 2005). Further, those that use models as theory-building and revising tools in the classroom- struggle with how to help their students evaluate and revise models over time with respect to empirical data and theoretical ideas (Windschitl, Thompson, & Braaten, 2008). Additionally, they find it challenging to bring diverse ideas back to a consensus-modeling product that is both aligned with canonical science and resonates with student ideas (Author 2015a; van Driel & Verloop, 2002; van Driel & Verloop, 2002). Because scientific modeling as a theory building and revising practice, is a critical to scientific sense-making, but unfamiliar to the traditional norms of school, and, teachers will need much support and guidance.

In order to better understand how the practice of scientific modeling might be taken up or develop over time, we present a comparative longitudinal case study of two teachers who incorporated modeling into their teaching across eight years. In particular, we ask: *How do teachers take up and use scientific modeling in their teaching as understood through their reflections on their practice and through their understanding and perceptions of modeling?* Answering this question can contribute to the ongoing discussion about helping teachers to enact modeling as a core reform-based science practice and about how to sustain teachers' efforts and buy-in to ambitious reform efforts over a long period of time. This is a critical topic to address as the vision of the new standards is enacted throughout the country.

Background

Teacher Development of Reform-based Practice

Much of the recent research on policy implementation in education has focused on teachers as active participants who think about and make sense of reform efforts (Bryk & Gomez, Grunow, & LeMahieu, 2015; Coburn, 2003; Cuban, 2013; Spillane, 1999). Viewing policy implementation from the perspective of teachers as having the ability to think about, adapt, and then implement educational reform suggests that mandating or requiring teachers to implement policy is less effective than developing policy with the ways it will be implemented already in mind, especially when professional development is designed along best practices (Desimone, 2009; Gallucci, 2008). Recent research-practice partnerships attempt to bring to scale policy in such a way (Coburn & Penuel, advance online publication).

From recent research on how teachers develop reform-based practice, we know some characteristics of teachers who are more inclined to take-up reform-based practice than others. Some specific factors that impact teachers' capacity are general across all content areas, while others are specific to science teachers, yet a recent report argues that there is significant overlap between the two (Wilson, Schweingruber, and Nielsen (2016). For example, across content areas, teachers' knowledge, beliefs, professional vision, sense of belonging, and identity are critical (e.g., Coburn, Russell, Kaufman, & Stein, 2012). Additionally, teachers' social context impacts their capacity to take up reform-based practice such as the frequency of interactions with other teachers engaged in the reform efforts, conversations focused on the reforms (rather than or at least in addition to other topics), and the presence of expert teachers in the network.

Other factors relate to the alignment between teachers' individual characteristics and capabilities and reform efforts (Spillane, 1999). Teachers' *personal resources* influence what teachers notice in terms of the influences of reform through policy documents, professional relationships, public (i.e., parents) and private (i.e., businesses) stakeholders, and even students (Spillane, 1999). Those reform efforts on their own are unlikely to change instruction; instead, the extent to which teachers' personal resources aligns with the reform "messages," from mandated testing and administrator feedback to parents' and students' voices. Teachers who enacted reform-based practice can and do so because they are able to enact the reform without changing the foundation of their instruction. Similar research indicates that teachers' beliefs about teaching and their perceived uncertainty or inconsistency on behalf of reform efforts stymied (or supported; Wood, Cobb, & Yackel, 1991) teachers' capacity to change (Rosebery and Puttick, 1998; Smith & Southerland, 2007).

An important aspect that is relevant to the goal of this study is that prior research has found that viewing science and science teaching as endeavors focused on sense-making is an important factor that can impact teachers' capacity to teach in ways aligned with reform-based practice. For example, teachers that learn to view science practice as "a human, meaning-making activity, a particularly way of inquiring into, conceptualizing, and making sense of the world" (Author, 2009, p. 651) also viewed science teaching in a similar way, with the object of teachers' inquiry what children know and what children should know in science.

Models and Modeling in Science Education

Scientific modeling is central to science (Giere, 2004; Godfrey-Smith, 2003) and student science learning (Lehrer & Schauble, 2006; Morgan & Morrison, 1999; National Research Council, 2007, 2012). There has been rich research indicating that while the practice of modeling appears complex, it builds on children's cognitive skills (Lehrer & Schauble, 2004; Lehrer & Schauble, 2006) and can be particularly productive practice for students' science and mathematics learning (Lehrer & Schauble, 2006).

Nonetheless, many preservice and inservice teachers have limited experience teaching from a model-based instruction or modeling-centered approach (Author, 2009; van Driel & Verloop, 2002; Windschitl & Thompson, 2006). Research, has demonstrated that preservice teachers can understand and begin to plan in a model-based fashion (Author, 2008; Windschitl & Thompson, 2006; Author, 2009b). Specifically, frameworks for modeling can help pre-service teachers plan modeling-centered lessons (Author, 2007). As previous stated, teacher often consider models as tools to demonstrate the canonically-corrected scientific information, rather than as tools students can develop, revise, and apply (Author, 2007; Justi & Gilbert, 2002). Other research has demonstrated which types of changes are possible and can be expected from inservice teachers. For example, Author (2015a) found that teachers emphasized some practices (e.g., constructing and using models) more than others (e.g., evaluating and revising), and that teachers considered the generality of students' models more than other considerations. Similarly, van Driel, and Verloop (2008) found that a subset of the in-service teachers they worked with developed knowledge about models, while others developed knowledge about models and how to design learning experiences for students with them.

Conceptual Framework

Teachers' alignment of their personal resources—their knowledge, beliefs, and other factors, such as their identity as teachers--with the new vision for science learning is critical to success of the reforms (Coburn, Russell, Kaufman, & Stein, 2012; Smith & Southerland, 2009). Yet the ways in which teachers have opportunities to reflect on and integrate their efforts at enacting new curricula, pedagogical approaches, and goals for science learning is also essential (Spillane, 1999). From prior research on teacher development of reform-based practice and models and modeling, we conceived of teachers' engagement in scientific modeling pedagogical practice over time first through teachers' alignment of their personal resources with our efforts to support their use of scientific modeling provided the opportunity to try out and use scientific modeling. Spillane (1999) used the notion of a *zone of enactment* to characterize the space between teachers' personal resources and the tools of reform: policy, professional expectations, public (and private) stakeholders in the reform, and learners and their expectations. In this model, teachers' efforts to enact scientific modeling occur separately but connected to their pedagogical practice—as well as other possible zones of enactment such as those related to other school, district, or state reform efforts or policies—and are influenced by contextual factors that support or limit teachers' capacity to enact scientific modeling. Because using scientific modeling in their zones of enactment does not speak to how teachers' take up and sustain their use of scientific modeling over time, teachers integrate their scientific modeling experiences with their ongoing pedagogical practice over time. In summary and in Figure 1, we considered teachers' engagement in scientific modeling practice across three factors: 1) the alignment of their personal resources with scientific modeling, b) their use of scientific modeling in their zones of enactment, and c) their integration of their experiences using scientific modeling with their pedagogical practice, as in Figure 1.

[FIGURE 1]

Method

To develop an understanding of how teachers come to engage and sustain engagement of students in modeling, we report on case studies of two teachers who engaged in scientific modeling practices within two sequential educational research projects spanning eight academic years.

Participants and Context

The participants were two science teachers, Mrs. M and Mr. H, who each had seven years of teaching experience when they began collaborating on a modeling-based research project in 2007. Both have master's degrees in science education, which they earned prior to their participation in the research project. Both teachers taught in public schools near a large Midwestern University in the United States. When they first began collaborating with the researchers, each teacher taught 5th grade in two K-5 elementary schools in the same district.

The teachers has been a part of a two-phase research project where they first worked with researchers to provide feedback and pilot a newly developed modeling unit on evaporation and condensation designed for 5th grade (Authors, 2015). They implemented the unit two years in a row. By the end of the first research project and by the start of the second research project, the district closed their elementary schools, and consolidated all 5th and 6th grades in the district into one 5-6 middle school. During the second phase of the research project, the teachers implemented the units, as well as an additional modeling unit on light. This additional unit was modified and shortened from the Investigating and Questioning our World Through Science and Technology (IQWST) curriculum. The 5-6 school in which the teachers taught together had a population of 15% of students received free and reduced-price lunch. In the district, 74% of students were Caucasian, 13% were Asian, 8% were African-American, and 5% were another race/ethnicity (District name removed to blind manuscript, 2011).

The two teachers were provided with and gave feedback on the curricular materials, including student workbooks and teacher guides. They also participated in summer and ongoing professional development in which they were introduced to modeling, provided with opportunities to observe and design modeling-related activities, and reflect on their pedagogical practice. The overall curricular sequence for the modeling units began with a driving question about phenomena. Students then constructed their first, or initial, model of the phenomena, and then conducted empirical investigations, after which they revised their initial models. Students then engaged in computer simulations and other empirical investigations, as well as discussion of theoretical ideas, after which they revised their models once more. Students (and the teacher) then developed group and then class consensus models, which they then applied back to the original problem or question. This sequence then repeated several times – to address any new, substantial questions (e.g., moving from evaporation to condensation n; Author, 2015b).

Data Sources

As part of our overall research in collaboration with the teachers, we collected various samples of data related to teacher ideas and teacher practices. We focused on two interviews we conducted with the two teachers, the first from 2008, and the second from 2014. Throughout the duration of both research projects, we provided ongoing, continuous professional development, answered questions of teachers, and participated in in-class activities while collecting other data, including videos of class sessions. Our collaboration over many years with these two teachers forms the foundation for this project. The teachers were initially asked about teaching a modeling unit; because its focus did not align exactly with the district's unit on mixtures and solutions, the research project created a substitution unit on evaporation and condensation that aligned with another unit that was being tested at middle school. Our role in the project was initially as researchers interested in understanding and supporting modeling practice – for students, and more broadly teaching scientific practices, in middle school settings. While the teachers were interested in engaging students in scientific practices, they did not bring to us a specific problem of practice. One of the authors was the principal investigator of who led the support of teachers, development of curricular materials and other resources, and research project. Another author was a former science teacher and research assistant, who conducted the interviews of the teachers with the principal investigator. A third author who was a research assistant analyzed the data with the first author. All spent multiple hours in the classrooms observing students and teachers in the modeling units.

The data sources used are presented along with a timeline of when the data were collected in Figure 2. These interviews were semi-structured and focused loosely around three questions:

1. What does scientific modeling mean to you?
2. In what ways is modeling useful for students
3. What challenges and opportunities exist when implementing modeling?

[FIGURE 2]

Coding and Data Analysis

The teacher interviews were transcribed and then entered into spreadsheets. Two of the authors identified relevant text segments that on the basis of their frequency or reoccurrence, or their implicit or stated importance. Then, the coders met to discuss each transcript individually and to begin the process of coming to agreement about the meaning of the data. They collectively grouped together relevant text segments and their codes in an inductive (Hatch, 2002) (or in-vivo; Saldana, 2015) manner. They kept the codes as representative of participants' meaning as possible when we grouped together relevant text segments and their codes. As the codes and themes developed, each coder went back to the data to clarify, deepen, and question the codes. In cases of disagreement, the process of providing examples in the forms of text segments helped us to argue for the inclusion or exclusion of a code and to see the evidence the other coder was able to use to support his or her claim. They met frequently as we analyzed each transcript to discuss the codes and their descriptions, and to identify text segments that served as examples for each code. As coding went on, they began seeing redundancy, in that fewer and fewer additions, deletions, or changes were made to the codes (and their text segments) when they met. They then grouped together codes and their relevant text segments into a codebook.

After developing the codes, we further analyzed the cases by identifying commonalities and differences between teachers and over time that seemed to lead to different ways in which modeling was integrated. We then developed these aspects that led to different integration into four different themes, and argued about their importance based on the data and especially the codes, as well as their experience working with the teachers throughout the duration of the study. When disagreements emerged, they used our different viewpoints—as principal investigator and other research assistants to add verity to the results.

Findings for Mrs. M

Over the time we worked with her, we learned Mrs. M was a creative, energetic teacher who described herself as someone for whom science came easily, but, at the same time, "didn't learn science the way everybody" did and was an outdoor educator before teaching in an elementary school, and, later, a combined fifth- and sixth-grade middle school as a fifth grade teacher. For Mrs. M, modeling was easy to try out. Even early, in terms of modeling Mrs. M reflected she thought, "let's just go with it and see what we get." When we asked in 2008 about her early becoming comfortable engaging students in something new, modeling, she said she initially felt uneasy, reporting, "I did feel at first that I was dong something wrong, but, then, it was my classroom."

A characteristic of Mrs. M—viewing science "as being fun . . . and something that I was comfortable with"—affected how she thought about science learning. As a learner, Mrs. M was drawn to the outdoors. She reflected:

> "I didn't look at our natural world as being science. I looked at it as being fun and I looked at it as being me and something that I was comfortable with. And it wasn't until I

> got into college and I was in these science classes and I was like, "Oh, I see that! I don't see it in this book at all but I see that outside."

Mrs. M continued that she was drawn to environmental science, and "the community of learners when you get outside and you're teaching and kids and you're learning yourself about just what our natural environment is."

Like how the way Mrs. M viewed science affected how she thought about her own and her students' science learning, it also affected her teaching. According to Mrs. M, when she started teaching, she visited the class of her colleague, Mr. H, "who taught a little traditional but he taught a little traditional in a way that he was using this wetland activity and a sponge and he built this really cool thing." Mrs. M reflected that seeing Mr. H teach in this way helped her see how she could apply what she liked about outdoor education in a formal setting, "which is a challenge." Translating what she liked about outdoors education—teaching and learning in a community of learners— was a challenge before and at the beginning of her participation in the first phase of the research project. While "having a friend like [Mr. H] has helped me do that," in 2008, Mrs. M reflected that she was uneasy, in particular about what should be the focus of students' model: "I was like, 'Oh, my gosh!] Am I supposed to do that?" She was especially concerned about balancing the sequence of steps in the curriculum with using other modeling-related experiences. In the lesson she planned, Mrs. M said, "I believe I was supposed to stick with *Draw your model again*," but "we just kind of jumbled everything together and said, 'Okay, based on your experience with the humidity detector . . .. How would you change your model?'". The result of "going on where my kids were going" was surprising to Mrs. M, but, it went well, and she said, "I think it was my enthusiasm . . . I was learning from them," and that "I really do feel that it enriched their own independent understanding."

Early on, an instructional approach related to group activities helped Mrs. M use modeling in a more effective way. In 2008, Mrs. M said her "turning point" with modeling was seeing Mr. H's difficulty structuring collaborative modeling practice in an effective way, and that she "didn't want to run into the same thing where the kids just pitted their ideas against one another." So, according to Mrs. M, "seriously on the fly I had to figure out what to do." She said that she spoke with a member of the research team, who encouraged Mrs. M to do what she thought would work. The result was Mrs. M's development of a technique for structuring group work, *Three Stars and a Wish,* in which students identify three aspects of peers' models they say they like and one aspect they say may improve:

> It was, "I really like how you used this, I really like that you did this." It was identifying things that were different than their own model. And then what they wished they could see. So it was actually giving them an idea of what else to add or what to take out or something like that.

When we asked about a specific example of using this, Mrs. M recalled teaching about evaporation and condensation, and her thought that after asking students responded that water in a covered cup will evaporate (if it is sealed tightly, the water will not evaporate), "I guess I just put it in the back of my mind that that's a possible teachable moment when you've got that many kids who sincerely are not following your line of questioning." She continued, "I think that to create a safe environment for them to feel like it's okay to be wrong" is important, and that *Three Stars and a Wish* helped students to be more comfortable with their ideas not being right. She continued:

> They also told me that it evaporated and then it snuck out under the window and under the door and it went out the door and up into the sky. So because it wasn't just one

> student, it was a lot, I played on that and said, "How did it know? Or is there something scientific going on here?" And they all kind of did that, "Oh, my gosh! How in the heck did I even think that that was a possibility?" So they kind of went away from that.

When students modeled the process of evaporation, Mrs. M said, "I had some kids who wanted more wishes!" She continued, "They're realizing that just because they might not have thought about it, it's certainly not a place that they can't go." As an instructional approach, Mrs. M said, *Three Stars and a Wish* served as "an extremely productive tool that I used where I continued to use throughout my whole teaching last year."

In 2014, we asked Mrs. M about what prompted her to say to the principal investigator of the project, "Oh, now I really get it!" She reflected, "I think it was actually when we started the whole *GAME* – that really clarified a lot of modeling." During the second phase, the research team shared guidelines with Mrs. M designed to support students' efforts to make sense of and build knowledge about what they are learning. When asked what she liked about *GAME*, Mrs. M said, "There was a lot more structure to it but it was a lot easier for someone like me to get my head wrapped around it." Mrs. M continued, *GAME* helped her say to students, "You're looking at the model for these reasons; this is how we are evaluating this model" and that with *GAME "*it can be broken down into the purposeful pieces." We asked Mrs. M about how she used *GAME*, she said she prompts students, "Tell me how this can be a generalized model or tell me how mechanism comes out here." Specifically, important to using *GAME,* according to Mrs. M, is "having them practice it and giving them a purpose to practice" but that for her it "took models to another level." In this case as well as earlier in terms of structuring collaborative modeling activities, Mrs. M demonstrated that she had to try scientific modeling to then take action to make modeling work more effectively in terms of her teaching and student's learning.

In addition to using *GAME,* Mrs. M reported in 2014 that over time models had become important to her teaching for multiple reasons. She said she considered modeling as being "not just best practices, but being the practice." She continued that with respecting to trying out and using modeling, "There's a lot of layers to it," and for other teachers, it is important for them to ask, "What does it offer you?" as well as "What does it offer the kids?" Thinking about her experience and considering other teachers with other curricula, Mrs. M asked, "How can you navigate through it realistically with the time that you have, how can you be creative and using groups and using the information that the kids come up with, and how can you use modeling in a program such as, let's say . . . a scripted, canned, activity?"

Because modeling was important to her, Mrs. M began to take steps to make modeling easier, both in terms of continuing to change her teaching, which had become "so much more quick and creative and clever," as well as in terms making it easier to integrate modeling into the district curriculum. Mrs. M seemed having agency to do so. She also reported in 2014 that she later began every school year with a week introducing students to modeling:

> I might choose one specific concept and spend five days on it and say, "Here's how you will be learning science in my classroom," and teach them how to make a good model and teach them what it is. So I would have to take what we did in models and break that six weeks down to five days but really give them the groundwork to say, "Here's why you're doing this, here's what I'm looking for and here's how you share it."

Finally, because of the way Mrs. M integrated aspects of scientific modeling closely into her teaching, the steps she took to make modeling easier affected not only the way she introduced students to how they will learn science differently but also her colleagues in the district. She reported that "our district absolutely supports whatever we decide" and that she worked to select a district-wide curriculum that would be suitable to engaging students in modeling practice. In addition to being supported by the district, when asked about parents' response to students' experience in her class, she said:

> Parents in particular! Oh my gosh! They come to conferences and say to me, "My kid is so excited about science. What are you doing? How are you doing it?" I've had parents ask if they can come sit in my classroom and watch me teach. I've had parents say to me, "I didn't understand this concept until my kid came home and taught it to me." That's so cool!

Taken together, for Mrs. M, modeling became an organizing principle for her instruction.

Findings for Mr. H

Mr. H was an engaging, often-funny teacher who reflected that he joked with students to his benefit, saying, "I guess I do try to use comedy and humor as much to my advantage as possible . . . It puts kids at ease and I think it's probably one of my main tools that I use." One reason why Mr. H used humor was he wanted students to feel that "the answer that they give or the experience that they share is going to be validated." Mr. H continued, he would rather be laughed at then have students not feel comfortable, "because getting laughed at is not something you want to do." He continued in 2008, "I was always kind of a misfit and oddball and I don't want students to feel that way."

Mr. H was eager to work with the research team to use scientific modeling in his teaching, reporting in 2008 that "doing it for the first time, from the students' perspective, I thought it went great." When Mr. H began using scientific modeling, he said he initially tended to use them as teaching tools. As he explained in 2008, "I just think when we're teaching something new to the kids . . . a model or diagram or some kind of picture that you can slap up on the board helps them see it in a little easier way." When asked about whether he used modeling to engage students in the practice, he replied that his initial effort in modeling "was very driven by me," so students were less likely to use models than he was, but, according to Mr. H, "I can see where that would be useful to do." *While using models as teaching tools is helpful, it may suggest that students' modeling efforts— developing, using, evaluating, and revising models—were secondary to using models to convey scientific ideas to students.*

When asked about what about modeling worked best, he replied seeing students "share their ideas" and "seeing some of the different things that they had changed in their models." During the first phase of the project, Mr. H reported he liked the organization of the curriculum:

> From my end, I liked it because it got kids actively thinking about the activities or experiments that we did. All of the activities I thought were good activities. I think that as we went through the process we kind of tweaked out what was needed to make them work better.

Something Mr. H adapted in the curriculum was focusing on the same phenomena throughout the modeling unit. He said that "trying to keep everything the same throughout was good." However, Mr. H reported that when students were studying evaporation and condensation:

> By the end I think it wore the kids down coming up with . . . I think that might have been good to bring that in and say, "Here's some other avenues. We've looked at evaporation on the can, here's condensation which is a totally new idea and here are some other ways that we could look at that." That was a tough one to do, coming up with different ideas and activities and being able to execute them well . . . Because it always came back to the can. Here we are a month into it and we're still talking about the can."

To help students model a similar process (i.e., evaporation or condensation), Mr. H said he found things that students experienced in their everyday lives and that were interesting to them. Mr. H reflected in 2008:

> For me, my biggest thing is I always want to try and find something that connects with them. We're always talking about evaporation and condensation but I would try to find things that they would have experienced in their everyday life that was close to it to help them bridge that gap to something that's totally new.

To Mr. H, the relevance of content to students' areas of interest, prior knowledge, and experience seemed to provide an entry into the scientific concepts students are learning and provide opportunities for students to apply the knowledge they learned in their lives.

Structuring modeling activities was a common topic in our interviews with Mr. H earlier and later. In particular, Mr. H reported that organizing group work and collaborative modeling practice was sometimes a challenge. Mr. H was cognizant of this, and when we asked him what are some things he would like the research team to change, he replied, "I think it's from my end," continuing:

> Constructing groups a little bit more, kind of prepping them before the project so that they see kind of how it works. I mean, we've done group things but they've been very simple. It wasn't as in depth as what you guys have done. Maybe on my end, making sure that they understand those roles within a group a little more. Because it seemed like that was the most confusing part for my classroom.

Mr. H said he was interested in "setting that up a little bit better" and also expressed a lack of confidence in understanding how groups in his class worked, reflecting "group dynamics is such a strange thing," and "sometimes it works, sometimes it doesn't." Similarly, Mr. H noted difficulty with peer evaluations of their models. Looking back, in 2014 Mr. H noted that "one of the biggest challenges was being able to evaluate and bring some of those things that were considered strengths into their own models." He continued:

> Obviously, they revised theirs but I wonder sometimes how much of that revision was self driven and how much of it was forced up them . . . I think that one part that could use more was the evaluating part. I think that comes from the struggle that I had. It might not have been that big of a deal but I thought it was a real struggle for them to constructively evaluate.

Taken together, structuring collaborative modeling practice and students' peer evaluations of one another's models were challenges for Mr. H, although these were challenges he was aware of and considered possible to address.

Later on, Mr. H was impressed by how much students were able to take ownership over their learning and to be motivated to look for answers through models, and he found that students' sharing and communication of their ideas in a constructive way was possible. In 2014, Mr. H explained that while earlier students' ideas that "Your model is different than mine so it's not that good" was common, while later "getting kids to critically look at someone's model and give feedback that we could obviously easily be negative about" was "huge." Mr. H continued:

> I think in short, the most impressive thing for me was just seeing how kids interacted with the science talking that was going on in the classroom. I mean, it wasn't just me talking; it was them kind of taking over what they were thinking about, what they understood and really looking for answers or changing what they understood or what they knew. So that part was always the most impressive to me, whether it was through the

> models or the different activities. That was one thing I thought modeling did well was it gave kids time to digest what was going on in the classroom.

While earlier Mr. H had reflected on challenges with modeling, he later expressed that despite these challenges over time his students became more capable of talking about science and sharing what they thought. Moreover, he found that he could do something to foster students' understanding by structuring activities and classroom norms: Mr. H. reflected, "They're fifth graders; they should know how to respond to each other and be able to take those relationships and interact." He continued, "They don't necessarily know how to do that." Mr. H said that as a result, "it's like a re-teaching of behavior and social interactions that I was not ready for when I first started." While structuring group work in particular was a challenge for Mr. H, he understood what that social norms around collaborative modeling practice could make modeling easier to enact.

At the same time that Mr. H considered how he could engage students in collaborative modeling practice, he said in 2014 that he did so in a more targeted way than he initially thought. One reason was the time modeling took. He said it was hard to dedicate the time to modeling that he thought he needed for it to be effective:

> This is from someone who, when you look at the two teachers that did it here in the beginning, I was the one who always pushed for, "I've gotta get through it," and now when I look back on it, that shouldn't have been a huge focus of mine. That should have been something that was like, "Okay, I understand. I'm a little bit behind but that's okay." Jay was willing to sit on things a lot longer than I was and for me, I had a schedule and a plan that I tried to push. I would give them limits, but in hindsight, that would be one

> place where I would have wanted to let go a little bit more and allow that time to let students kind of do what they need to do.

Mr. H continued, "I always felt like the time that we gave students was the best part of modeling. But it was also, for me as the educator, the hardest thing to kind of let go." In particular, Mr. H said that he felt the need "to teach this curriculum and I'm always two to three months behind because of that." He reported:

> "Because modeling took so much time and it was something that, if it was part of my curriculum, I would have had no problem with . . . I felt that pressure of taking two or three months to work on this research project and I still need to cover all this other stuff for my students. If there was a way to build it around a curriculum that was already there, that would be a way better seller."

Feeling the need to address not only the district curriculum but also that of the research project, Mr. H seemed to not perceive support for integrating modeling into his teaching in a way that worked for and was usable to him. Mr. H's suggestion to build modeling around the existing curriculum is helpful, and supports his belief that modeling was a productive but not-always-easy to use or integrate approach. He reflected that he "felt this crunch for getting through all the responsibilities I had to get through." Because of these time constraints and the pressure of covering the content, he said that at the end of the project he still used modeling, but more as an effective reform-based intervention among others instead of making modeling an organizing principle. Mr. H reported, "I still use it," and that "we try to put pieces of modeling in it . . . its like mini lessons of modeling." Mr. H continued, "It's not like the full-blown curriculum of modeling," but instead "putting little pieces her and there."

Cross-case Analysis and Discussion

This analysis of two fifth-grade science teachers who engaged in modeling pedagogy helps us understand how teachers can engage students in three-dimensional learning and especially scientific practices. To analyze the findings, we drew from prior research on teacher development of reform-based practice and models and modeling and considered how teachers' personal resources—their knowledge, beliefs, identity, and other individual characteristics—aligned with scientific modeling, the ways in which teachers used scientific modeling in their zones of enactment, and their integration of their experiences using scientific modeling with their pedagogical practice. In addition to the findings for how the teachers' practices and ideas about modeling changed over time and what were some of the ways in which they did so, we found themes that indicated some possible ways to support and advance teachers around modeling practices.

Overall, Mrs. M's pedagogical practice was amenable to fostering a community around students' sharing their ideas about phenomena. This focus on her classroom community existed earlier in her pedagogical practice but developed over time to incorporate and even become centered around scientific modeling. She increasingly used modeling over time, as she perceived support in her context, as modeling became an organizing factor for her science teaching. More importantly, Mrs. M focused students' modeling efforts around understanding and making sense of phenomena: Doing so required her to restructure activities and adapt resources from the research team, but the result—students having greater opportunity share and revise their ideas and develop the capacity to engage in scientific sense-making. Moreover, being able to adapt and integrate modeling meant that Mrs. M used techniques that blended what she knew about herself and her practice and students with the goals of curricular reform, demonstrating agency. This may strengthen not only the implementation of such curricula, or the implementation of student modeling in ways that includes their attention to epistemic considerations, but also her beliefs in herself as a teaching capable of enacting scientific modeling.

Contrarily, Mr. H's pedagogical practice was initially more amenable to instruction focused on students' engaging with relevant content and being able to use that content in specific contexts. Due to the demands he perceived from his context, he used modeling less over time and more as useful as a peripheral strategy in terms of contextual demands. Mr. H's pedagogical practice was more focused on students as individual learners, and less on how students learned within a classroom community. While Mrs. M productively established classroom norms and communities and structured group work to focus on making sense of phenomena, Mr. H struggled with these two aspects of modeling.

While over time Mrs. M's pedagogical practice came to focus on communal sense-making, Mr. H's came to focus on students' individual knowledge of relevant content. While teachers who focus on individual's knowledge may also focus on sense-making, and teachers who focus on group activities and participation in classroom communities, the way in which these two characteristics were woven into Mrs. M and Mr. H's teaching may suggest possible profiles for other teachers using scientific modeling. For those teachers who either already engage students in communal sense-making, modeling criteria—such as the GAME criteria Mrs. M adapted and used to focus students' learning on knowledge-building and epistemic goals—may be important because of the open-ended nature of modeling. Those criteria or goals can help teachers guide their students forward in their sense-making knowing more about the aims of the process and products. For those teachers who focus more on individual students' knowledge of content, support for their efforts to enact scientific modeling—in particular around collaborative modeling practice and supporting students' capacities to productively share their ideas as they develop better understanding of disciplinary core ideas—may be critical. For those teachers focused on students' learning of relevant content, support in recognizing the importance or and developing a productive community of practice may help teachers to see that students' scientific modeling can and should connect with curricular content and the standards—in particular the disciplinary core ideas and crosscutting concepts in the NGSS—associated with them.

While we examined the pedagogical practice of two teachers over a long period, there are other possible profiles and patterns for different kinds of teachers seeking to integrate modeling. For example, while Mrs. M was focused on establishing a classroom community of learners earlier and using students' already-existing ideas about phenomena as resources, other teachers may focus on communal practices but not focus so explicitly on students' efforts to make sense of phenomena but rather on other hands-on, learner-centered activities. These teachers may be supported in their enactment of scientific modeling through tools that help them to elicit and use students' ideas (e.g., Windschitl, Thompson, Braaten, & Stroupe, 2012).

Other teachers may, be focused not on communal sense-making, individual knowledge of relevant content, or hands-on activity, but on knowing scientific facts needed to perform on assessments. For these teachers, the three-dimensional vision of science learning in the NGSS—and especially engaging students in the scientific practice of modeling—may ask for substantial, challenging shifts in their pedagogical practice. Even so, these teachers may be supported in their efforts to, as Mr. H said later, "let go" and take risks. Thus, for these teachers, supporting their efforts to enact scientific modeling may be less necessary than working to align their inclinations and characteristics with the purpose and role of scientific modeling. Specifically, professional development providers and other stakeholders may consider what about modeling scientific modeling may support, such as teachers' classroom management efforts for which specific collaborative modeling approaches may need to be developed.

While both of these teachers collaborated with the research team, and therefore had opportunities to enact modeling and receive feedback and support that may not be typical of other teachers beginning to teach in a way that supports students' three-dimensional learning. At the same time, these teachers faced challenges that other teachers, especially those engaging students in modeling and other scientific practices in the future, may not, such as the need to establish an understanding among parents, administrators, and other stakeholders about the new teaching and learning approaches Mrs. M and Mr. H advanced. Moreover, despite the differences in their teaching, both teachers were interested in learning about and aligning their pedagogical practice with scientific modeling, going so far as participating in two research projects over eight years. Moreover, both were dedicated, experienced teachers concerned with improving their practice to help students learn, albeit in different ways that led to different uses of scientific modeling and ways in which they ultimately integrated scientific modeling into their teaching.

In addition to the findings from the two teachers individually, we add to the discussion the importance of collaboration. Both teachers reflected on the collaboration and reiterate the importance other researchers have found for collaboration among colleagues regarding the diffusion of ambitious teaching practices such as scientific modeling. Aligning with Mrs. M and Mr. H's beliefs, collaboration and what Desimone (2009) calls *collective participation* in professional development activities is a focus of recent research on effective professional development for in-service teachers.

Conclusion

The teaching called for to enact the *Next Generation Science Standards (NGSS)* is ambitious yet potentially within reach for teachers given thoughtful guidance, support and tools over time. Nonetheless, many questions remain regarding how teachers potentially align with and enact reform-based pedagogy as they engage students in the reform-based practices. The cases of these two teachers who were engaged with support over a considerable period of time in the practice of scientific modeling can help us better understand how teachers enact and sustain reform-based practice. Specifically, drawing from prior research on teacher development of reform-based practice and models and modeling prior research on teacher development of reform-based practice and we focused on 1) the alignment of Mrs. M and Mr. H's personal resources with scientific modeling, b) their use of scientific modeling in their zones of enactment, and c) their integration of their experiences using scientific modeling.

The cases of Mrs. M and Mr. H show how different initial alignment with modeling pedagogical practices—Mrs. M was focused on responding to students' ideas and Mr. H on science content—provided different opportunities to apply and use modeling in their pedagogical practice. While Mrs. M's efforts to try out modeling in her zone of enactment led to adapting and integrating aspects of modeling as an organizing and central principle of her teaching, Mr. H's efforts led over time to less use of modeling. Nonetheless, the key aspects that led to the different aspects of integration highlighted in the cross-case analysis included a) focus on communal versus individual learning, b) taking up and developing epistemic criteria, c) agency and perceived constraints versus curriculum coverage, and d) collaboration and fulfilling different responsibilities. These are all important towards the adoption of Next Generation Science Standards and particularly scientific practices. While these were key aspects with respect to Mrs. M and Mr. H's efforts to engage students in modeling, they may be similar to closely related science and engineering practices, such as constructing explanations and engaging in argument from evidence. Moreover, while the first two aspects are unique to science standards and the NGSS in particular (a focus on communal versus individual learning and taking up and developing epistemic criteria), the other two have played important role in other reform-based challenges (Bryk & Gomez, Grunow, & LeMahieu, 2015; Coburn, 2003).

In order to better understand and support teachers to respond and enact reforms today, longitudinal studies can help us understand not only how teachers can use scientific modeling, but in particular how they can do so in a way that leads to their sustained use over time. Moreover, future research can examine which leverage points are helpful or important for teachers in other settings: How teachers enact scientific modeling and other scientific practices in classrooms, districts, and schools with less support is an especially important imperative topic to consider. In addition to understanding how teachers use scientific modeling into their teaching, we are reminded to consider not only what teachers know and believe, but also their professional visions and identity needed to support their enactment and integration of new pedagogies (Coburn, Russell, Kaufman, & Stein, 2012). These, along with support and guidance for teachers during their efforts to enact reform-based practice can contribute to more productive and sustained experiences teaching in new, ambitious ways over time.

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Figure 1

Teachers' Engagement in Scientific Modeling Pedagogical Practice Over Time

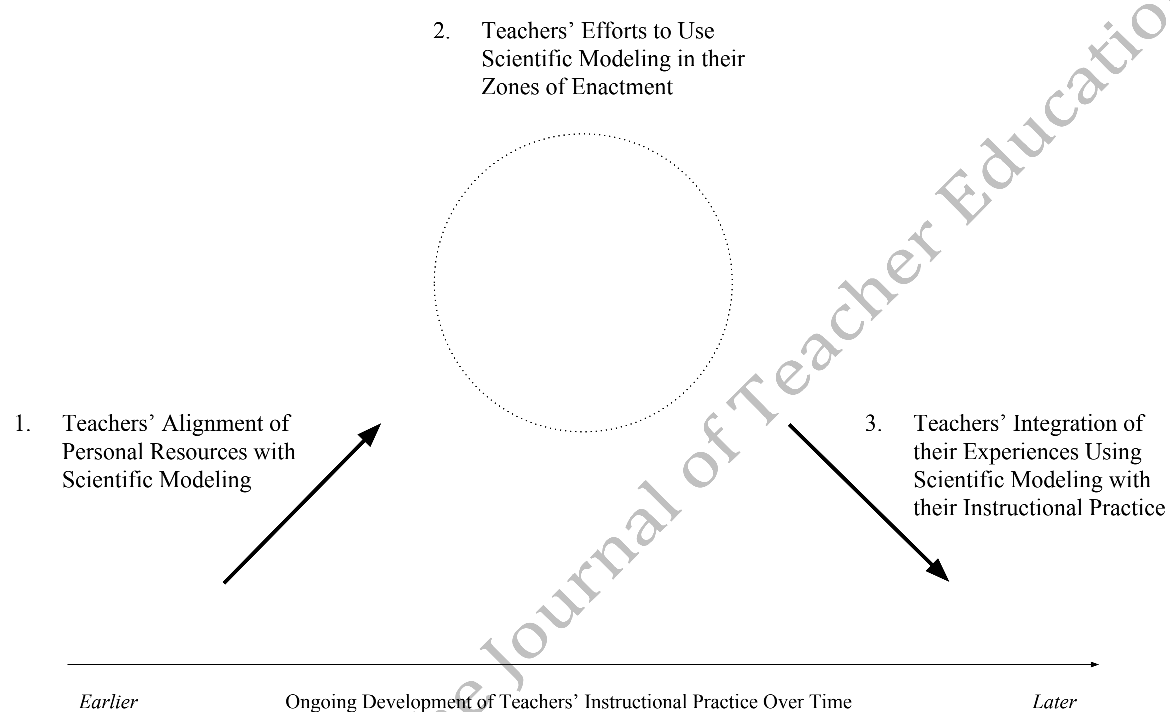

Figure 2

Timeline of collection of data sources