



Secondary science teachers' implementation of a curricular intervention when teaching with global climate models

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ABSTRACT

In the past decade, emphasis on promoting “climate literacy” in K-16 science classrooms has increased. Teachers play a critical role in cultivating these opportunities, especially in secondary science classrooms. However, most prior climate education research has focused on students and student learning; little is known about how teachers implement climate-focused curricular interventions. Here, we report findings from a concurrent mixed methods, multiple-case study of four secondary science teachers' implementation of a new, NGSS-aligned, model-centric climate curriculum module grounded in the use of a data-driven, computer-based climate modeling tool—Easy Global Climate Model (EzGCM). We employ multiple data sources, including video-recorded classroom observations, interviews, and instructional artifacts, and both qualitative and quantitative analyses, to investigate how teachers implemented the curriculum. Findings show that, overall, teachers implemented the curriculum in ways that were less model-centric than designed, placing greater emphasis on EzGCM itself rather than using the model to investigate Earth's changing climate. Additionally, we present detailed single-case studies of each participant teacher that highlight differences in teachers' implementation of the curriculum module and their reasoning for making observed instructional decisions. This research sheds light on the design of secondary science learning environments by illustrating the varied ways teachers implement a climate-focused curriculum to support students' developing climate literacy. This has important implications for the design of climate-focused curriculum and supports for teachers.

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Global climate change (GCC) is arguably the most pressing challenge of our age. The Intergovernmental Panel on Climate Change (IPCC) indicates that average global temperatures have increased by 0.85°C between 1880 and 2018, and global carbon dioxide emissions have increased by 50% since 1990 (IPCC, 2018). GCC introduces unprecedented global challenges, and increased emphasis is being placed on empowering citizens through outreach and education to prepare the next generation of scientists, policymakers, industry leaders, and citizens for a changing climate. It is therefore imperative to cultivate individuals' climate literacy (United States Global Change Research Program [USGCRP], 2009). This is particularly the case for secondary science students (Next Generation Science Standards [NGSS] Lead States, NGSS Lead States, 2013) since, for many, these experiences represent the end of their formal, compulsory education (U.S. Census Bureau, 2020).

While cultivating climate literacy in K-12 science classrooms is essential, resources for doing so are limited (Bhattacharya et al., 2021b). The use of models affords students an opportunity to overcome abstractness in climate concepts and establish understanding within their own experiences. The NGSS prioritizes model-based teaching and

learning about Earth's climate and GCC, particularly at the high school level (NGSS Lead States, 2013). However, few empirical studies have investigated the effectiveness of model-based strategies in developing students' understanding of GCC (Bhattacharya et al., 2021a; Pallant et al., 2012; Pallant & Lee, 2015; Svihla & Linn, 2012; Tasquier et al., 2016). Additionally, research has shown that science teachers use and implement purposefully designed science curriculum in widely variant ways (Fogleman et al., 2011; Forbes & Davis, 2010; Roehrig et al., 2007). There is, therefore, a need not only to make climate-focused curriculum resources available, but also to understand how and why teachers implement model-centric curricular resources in particular ways.

We conducted this mixed methods, multiple-case study to understand secondary science teachers' enactment of a curricular intervention grounded in students' use of a particular global climate model (GCM): Easy Global Climate Model (EzGCM; Bhattacharya et al., 2020, 2021a, 2021b; Forbes et al., 2020). This research aims to identify similarities and differences in teachers' curriculum enactment strategies and to further illuminate how models can be leveraged for teaching and learning about the Earth's climate and GCC.

We also provide insight into how and why teachers implement developed curricular resources. We use multiple data sources collected from classrooms of four secondary science teachers—including video-recorded classroom observations, pre-/post-interviews of teachers, and daily audio-recorded reflections during implementation of a three-week, model-based, climate education curricular intervention—to investigate the following research questions (RQs):

- How do secondary science teachers implement a GCM-based curriculum module?
 - How does secondary science teachers' implementation of the module compare to a provided curriculum?
 - How do secondary science teachers' implementations of the module compare?
- Why do teachers enact the curriculum in the ways they do?

We use mixed methods to address RQ1a and 1b and qualitative methods to address RQ2 as part of a comprehensive, multiple-case study.

Teaching with GCMs

The NGSS emphasizes teaching and learning about Earth's climate and GCC using models in secondary science classrooms (NGSS Lead States, 2013). The NGSS has provided goals for developing novel climate education interventions; however, realizing them will be challenging. Opportunities for teaching and learning about Earth's climate system and GCC are decentralized across subject areas and grades, and Earth science is increasingly de-emphasized across the K-12 science curriculum (Banilower et al., 2018). Furthermore, teachers may feel underprepared in their science content knowledge for teaching about GCC, describe instruction in this area as a low priority, and report limited resources to support teaching and learning about GCC. An underdeveloped understanding of GCC may lead both teachers and students to underestimate the impact of the Earth's changing climate, perceive uncertainty in climate data as a lack of information, and foster a general mistrust of climate science (Pallant & Lee, 2015; Plutzer et al., 2016; Pruneau et al., 2003).

Despite evidence that science teachers often do not use curriculum materials as designed (Fogleman et al., 2011; Forbes & Davis, 2010; Roehrig et al., 2007), little research has been conducted to explore teachers' implementation of climate education curriculum (Bhattacharya et al., 2021b). Climate education research has shown that in K-12 classroom settings instruction about GCC and the climate system is most frequently found within secondary science classrooms; biology, environmental science, and Earth science teachers most commonly report teaching climate-related concepts (Colston & Ivey, 2015; Herman et al., 2017; Monroe et al., 2013; Plutzer et al., 2016; Wise, 2010). Instructional time varies widely, with the subject often viewed by teachers as an extension of related science topics rather than a

primary focus. Teachers' reported instructional time on climate topics vary between no formal planned instruction to about a full week (Dawson, 2012; Feierabend et al., 2011; Herman et al., 2017; Monroe et al., 2013; Plutzer et al., 2016; Wise, 2010). Additionally, social and political ideologies can affect the time and depth of teaching about climate and GCC in classrooms (Dawson, 2012; Plutzer et al., 2016).

When climate concepts are taught in formal secondary science classrooms, instruction is often dictated by core disciplinary concepts (Herman et al., 2017; Plutzer et al., 2016; Slater et al., 2009), for example, through an emphasis on real-time problems and socioscientific issues (Dawson, 2012; Teed & Franco, 2014; Zangori et al., 2017). Many teachers feel challenged finding time to include climate concepts and GCC within subject area curricula (Colston & Ivey, 2015; Dawson, 2012; Monroe et al., 2013; Slater et al., 2009; Wise, 2010). Additionally, many teachers cite a lack of adequate standards-based curriculum materials for climate education, commonly reporting creating their own curricula by piecing together information from a multitude of resources (Colston & Ivey, 2015; Dawson, 2012; Michail et al., 2007; Slater et al., 2009).

Scientific modeling

Scientific modeling is one of eight science and engineering practices foregrounded by the *Next Generation Science Standards* for secondary-level teaching and learning about Earth's climate system and GCC (NGSS Lead States, 2013). NGSS standards necessitate that climate learning experiences in secondary science classrooms involve computer-based computational models and data visualizations, like the GCMs used by climate scientists. While such tools have been employed to varying levels in grade 6–12 classrooms (e.g., Pallant & Lee, 2015; Svihla & Linn, 2012; Tasquier et al., 2016), including the one here (Bhattacharya et al., 2021a), there still exist challenges to incorporating these resources. Students and teachers require access to well-developed, coherent curriculum to use these tools effectively and to begin to develop the skills that define the work of climate scientists. However, research has shown that the availability of coherent, purposefully developed curriculum to accompany such tools is limited (Bhattacharya et al., 2021b).

For modeling experiences to be meaningful for students, teachers must integrate models fully within classroom activities; however, teachers often have limited experience using scientific models in their classrooms (Justi & Gilbert, 2003; Oh & Oh, 2011). Moreover, modeling is either rarely incorporated into educational experiences or used for the limited purposes of illustration (Khan, 2011; Windschitl et al., 2008). Teachers may engage in model-based instruction in varied ways based on their experience and knowledge (Justi & Gilbert, 2003). Teachers often use models as tools of exploration inquiry rather than focusing on the practice of modeling (Carpenter et al., 2019). It is therefore important that teachers firmly understand the disciplinary and epistemic dimensions of models, as both components are critical to model-based teaching (Berland et al., 2016).

This understanding can be supported through professional development and teacher-educative curriculum resources.

Theoretical framework

While perspectives on modeling in science education may vary in their emphasis on students' learning about models (e.g., Halloun, 2007; Krell et al., 2015) as compared to engaging in modeling practices (e.g., Berland et al., 2016; Schwarz et al., 2009), they share a common focus on core features: a) disciplinary concepts, b) epistemic features, and c) modeling practices for developing students' reasoning about scientific phenomena (Gilbert & Justi, 2016). This shared perspective has served as a foundation for our research and development work (Baumfalk et al., 2019; Bhattacharya et al., 2021a; Forbes et al., 2015; Vo et al., 2019, 2015; Zangori et al., 2017). Here, we apply this framework, specifically modeling practices for developing students' reasoning, to the investigation of model-based teaching about the Earth's climate and GCC in secondary science. We focus on a subset of its elements—the practices of model construction and use (Table 1)—to operationalize the ways teachers afford students opportunities to engage in the construction and use of a GCM for investigating and reasoning about increasing average global surface temperatures through implementation of the project-developed curriculum. As illustrated in Table 1, both modeling practices—construction and use—require students to learn about the nature and purpose of models, two critical epistemic dimensions of scientific modeling. In the present study, the construction

of models requires students to learn how EzGCM is built and the underlying principles of the climate system that allow for model-based projections. Students then use the model to study natural phenomena in ways reflecting these epistemic dimensions.

Methods

The concurrent mixed methods, multiple-case study approach used here allows for the integration of rigorous quantitative and qualitative methods. We use multiple data sources—analyzed both qualitatively and quantitatively—to cross-validate study findings, thus overcoming limitations of using these methods alone and allowing for a more robust accounting of phenomena under study (Morgan, 2013; Plano Clark & Ivankova, 2019). Additionally, this method allows for deep exploration of cases by answering “how” and “why,” especially when the manipulation of participant behavior is not possible, contextual conditions need to be accounted for, and context likely influences the phenomenon (Yin, 2009). In this study, the contextual conditions (traditional secondary science classrooms) are a critical component of the teachers' choices and strategies; it would be impossible to understand teachers' curriculum enactment without considering this setting. The cases in this study investigate the decisions and strategies of secondary science teachers while teaching a model-based climate curriculum unit. To ensure that this research remains within a reasonable scope, this case is bounded by time (3-week curriculum module) and place (secondary science classroom) (Baxter & Jack, 2008; Creswell & Poth, 2018).

Table 1. Framework for model-based teaching and learning focusing on the practice of model construction and use.

		Modeling Practices	
		Construct	Use
Epistemic Considerations	Nature of Models (A model is...)		
	Evidence-based	Learner conceptualizes construction of model that incorporates evidence about a phenomena	Learner uses a model to incorporate new evidence about a phenomena
	Appropriately detailed/complex	Learner conceptualizes construction of model that is appropriately detailed/complex to represent a phenomena	Learner uses a model that is appropriately detailed/complex to describe a phenomena
	Generalizable	Learner conceptualizes construction of model that is generalizable to/from a phenomena	Learner uses a model to make a generalization about a specific phenomenon
	Purpose of Models (A model is for...)		
	Predict/hypothesize	Learner conceptualizes construction of model that aids in making predictions or hypothesizing about a phenomena	Learner uses a model to predict and hypothesize about a phenomena
	Explain (whole/part)	Learner conceptualizes construction of model that aids in explaining some of phenomena	Learner uses a model to explain some of a phenomena
	Organize	Learner conceptualizes construction of model to organize their ideas about a phenomena	Learner uses a model to organize their ideas about a phenomena
	Generate	Learner conceptualizes construction of model to generate new information/ideas about phenomena	Learner uses a model to generate new information/ideas about a phenomena

Research context and sample selection

This study is part of a collaborative project involving two research universities, a Midwestern public school district, and NASA (Forbes et al., 2020). The overarching project, *High School Students' Climate Literacy through Epistemology of Scientific Modeling* (CliMES), is a four-year, NSF-funded collaborative project aimed at increasing high-school students' climate literacy and model-based reasoning. Through the project, a three-week model-based climate curriculum has been designed, implemented, and evaluated for effectiveness (Bhattacharya et al., 2020, 2021a). In this study, we investigate four secondary science teachers' enactment of the model-based climate curriculum during the second year of the project.

Study context

The present study occurred in a mid-sized school district in a conservative Midwestern state's second-largest metropolitan area. The district enrolled 42,020 students and employed 3,119 teachers across 60 different schools and specialty programs during this study. Forty-six percent of students qualify for free or reduced lunch programs. Teachers and students in this study were located in three of six secondary schools in the partner district: Meadowlark High School, Goldenrod High School, and Cottonwood High School (Table 2). Pseudonyms were

selected to protect identities of all involved. At the time of this study, the district had just adopted and begun implementing state science standards that closely aligned with NGSS, including its climate-related standards at the secondary level. As part of this effort, the district was in the process of revising the semester-long geoscience course.

Teacher participants

Access to the participating teachers was obtained through the school district's K-12 Science Curriculum Specialist. The four teachers—Julie, Monica, David, and Michael— chose to participate. As part of the project, they helped develop the curriculum and received additional training on teaching with climate models. Additionally, teachers were offered funding to complete a six-week online climate change course, which two participant teachers—Julie and Monica— completed. Participating teachers were split evenly by gender and represented a wide range of teaching experience (Table 3). Teachers were not provided with specific instructions regarding how or when to implement the curriculum materials, but were presented with the curriculum module and encouraged to adapt lessons in light of students' needs and schedule constraints. Julie and Monica began implementation in late September, while David and Michael began implementation in late October.

Table 2. District and participating high school demographic data.

		District Wide	Meadowlark High School	Goldenrod High School	Cottonwood High School
Teachers Employed		3648	178	159	155
Teacher Racial Identity (%)	White	94.4	90.0	93.0	94.0
	American Indian or Alaska Native	0.1	**	**	**
	Black or African American	1.1	2.9	0.9	0.9
	Asian	0.9	1.2	0.9	0.9
	Hispanic/Latino	2.4	3.8	2.8	5.7
	Native Hawaiian or Pacific Islander	0.1	**	**	**
	Two or More Races	1.1	2.4	1.4	**
Teacher Gender Identity (%) *	Male	32.1	45.6	46.6	47.1
	Female	67.9	54.4	53.4	52.9
Teachers with Master's Degrees or higher (%)		45.0	56.0	57.0	49.0
Total Student Enrollment		42,020	2304	2202	2218
Student Racial Identity (%)	White	66.5	46.0	57.3	82.0
	American Indian or Alaska Native	0.6	1.5	0.8	0.4
	Black or African American	6.3	11.4	7.9	2.3
	Asian	4.6	10.2	6.5	3.5
	Hispanic/Latino	13.7	21.4	20.8	7.4
	Native Hawaiian or Pacific Islander	0.1	0.1	0.1	0
	Two or More Races	8.2	9.4	6.6	4.5
Student Gender Identity (%) *	Male	51.2	48.8	51.7	51.9
	Female	48.8	51.2	48.3	48.1
English Language Learners (%)		7.4	**	**	**
Students Qualified for Free or reduced Lunch (%)		46.3%	60.1	55.5	21.9
Students in need of special education services (%)		16.1%	**	**	**
Students Identified as gifted (%)		12.7	17.4	9.1	21.8
Yearly average student attendance rate (%)		94.1	88.9	89.9	92.6

*District collected data employs a binary gender system.

**This data was not collected by the district.

Table 3. Demographic characteristics of the four participate teachers.

	Teacher	Gender	Age Range	Race	Education Level	Certification	Teacher Certificate	Years Teaching
Meadowlark High School	Michael	Male	30-39	White	Bachelor's	Science Education	Traditional	10-20
Goldenrod High School	David	Male	30-39	White	Master's	Science Education and Meteorology	Alternative	3-9
Cottonwood High School	Monica	Female	50-59	White	Master's	Science Education	Traditional	Over 20
	Julie	Female	20-29	White	Bachelor's	Science Education	Traditional	3-9

**Figure 1.** Student view of the EzGCM interface at the three major phases of the model interaction, simulations, post-processing, and visualization.

Curricular context

The partner district was selected, in part, due to a district-wide requirement of a one-semester geoscience course at the ninth-grade level. In the year prior to the beginning of this project, the state was undergoing a process of adopting new science standards. The revised state standards went into effect in the first year of the project. For the first time, state science education standards emphasized teaching and learning about Earth's climate system, including GCC. These were incorporated into the partner district's geoscience course.

The climate model

The project-developed curriculum is designed around EzGCM (Figure 1; Bhattacharya et al., 2020), a data-driven, computer-based climate modeling tool developed by NASA. EzGCM allows users to access and interact with large data sets over long timescales, and was developed for engaging non-scientists, educators, and students in exploring global climate data. Through EzGCM and the curriculum, students interact with three major climate model simulations. Students use the models to explore multiple climate variables and their impacts on and relationships to carbon dioxide and surface air temperature, and to create time-series plots and climate visualizations. These allow them to make and test their own predictions, observe interactions of climate-related variables, and ultimately assess carbon's impact on the global climate.

The CiMES curriculum module

The curriculum module, designed around EzGCM, addresses NGSS performance expectations and district-level science standards (Table 4) surrounding two key objectives: a) engaging students in scientific modeling, and b) supporting students to develop in-depth understanding of Earth's climate and GCC. The curriculum provided opportunities to explore increasing average global surface temperatures, determined to be the anchoring phenomenon, through a) analyzing temperature anomalies from 1850–2017, b) comprehending the rate of change of global average surface temperatures, c) analyzing the data set for carbon dioxide concentrations in the atmosphere, and d) formulating the causes of increasing global average surface temperatures.

This curriculum was developed through the Construct-Centered Design (CCD) process in which it was iteratively developed, implemented, tested, and refined (Shin et al., 2010). The four teachers in the present study were directly involved in the development of the curriculum (Forbes et al., 2020). During the year prior to starting this project, teachers met with the research team on multiple occasions to generate ideas, concepts, and pedagogy for the curriculum. Drafts of curriculum lessons were then sent to the teachers for edits and revision, additional workshop meetings were held, and a preliminary curriculum developed.

Two of the teachers (Julie and Monica) then piloted the curriculum in their classrooms during year one (Y1) of the research project. Both prior to and following implementation, these teachers met with the research team for

Table 4. NGSS performance expectations and district-level science standards addressed in the CliMES curriculum module.

Organization	Standards	
NGSS	HS-ESS3-5.	Analyze geoscience data and the results from global climate models to make an evidence-based forecast of the current rate of global or regional climate change and associated future impacts to Earth systems.
State Standards	SC.HS.12.2.C	Analyze geoscience data and the results from global climate models to make an evidence-based forecast of the current rate and scale of global or regional climate changes.
State Standards	SC.HS.12.2. D	Evaluate the validity and reliability of past and present models of Earth conditions to make projections of future climate trends and their impacts.

Table 5. CliMES curriculum lesson plans outline.

Lesson	Main Objective	Estimate Class Periods to Complete
Lesson 1: What are models? What are GCMs? Why do we use GCMs?	Students engage in conceptually understanding the complexity of climate models through this non-data, non-model based lesson.	1
Lesson 2: Guided Practice Lesson- Exploring Simulation using EzGCM	Students explore the anchoring phenomenon – increasing global average temperatures – through their use of a global climate modeling (GCM) tool.	1
Lesson 3: General concepts- tools needed to understand EzGCM output	Students learn the general concepts, vocabulary, and methods needed to understand the use of models in Global Climate Science.	1
Lesson 4: What is climate data? How is climate data obtained?	Students gain an understanding of the different types of climate data; proxy data, instrument-based data, and model-based data, while exploring the concept of how much data is needed to create strong evidence.	1
Lesson 5: What do we know about the change in average global surface temperatures?	Students will use scientific data to assess and interpret the unit's anchoring phenomenon – “increase in Earth's average global temperatures” using climate data for investigating the rate of increase in average global temperatures.	3
Lesson 6: How do we explore the Earth's global average temperature increase using a global climate model (GCM)?	Students will use the model to complete two climate simulations producing a time series graph of surface air temperature for each simulation.	3
Lesson 7: Fingerprinting the causes of global warming- Why are the global average temperatures increasing?	Students investigated long-term records of carbon dioxide levels and use the model to examine the difference between two different carbon dioxide scenarios.	3
Lesson 8: Mapping Data, Creating Visualization, and Using Visualizations to Make Predictions	Students will gain an understanding of the management (averaging and extraction) of the large amounts of digital data produced by Global Climate Models by extracting “Big Data” and creating visualizations with post-processing. Students will then compare Global Climate Model Data from two Visualization to Predict Temperature Trends. Students will explore the results of their global climate model simulations in more detail by creating a visualization that represents anomaly data for global surface air temperature maps.	3
Lesson 9: Application: Use a model to reason and explain	Student makes the decision about what data do they need and demonstrate the process to obtain it using the model.	2

Note: The average class period was 50 minutes in length. Additionally, an extra class period at the beginning and end of the curriculum module was included for pre-/post-assessment student tasks, totaling 20 class periods.

professional development. Following Y1 implementation, teachers provided the team with feedback on classroom implementation and assisted in revising the curriculum used in the present study (Y2). In the summer prior to Y2, the teachers participated in formal professional development designed to prepare them for using the curriculum, and the GCM, in their classrooms. By Y2 the curriculum included nine lessons and was designed to last approximately four school weeks (20 days) of 50-minute class periods (Table 5),

with an additional day for students to complete a post-evaluation (21 total days).

Data collection

The curriculum was implemented during the fall semester in 14 classes divided among the four teachers. Data collection occurred in all classes during the period of curriculum implementation. The present study used multiple data

Table 6. Data collected and analyzed by individual teacher.

	Classes Taught	Classroom observations	Pre-/post- interview	Daily reflections
Monica	3	37	1/1	15
Julie	3	42	1/1	15
Michael	3	31	1/1	11
David	5	60	1/1	13
Total	14	170	8	54

sources—classroom observations, pre- and post-interviews, daily reflections, and instructional artifacts, including the lesson plans for the curriculum (Table 6).

Classroom observations

Implementation of the designed curriculum was documented through classroom observations, conducted in-person and video-recorded by the authors, in all class periods for all teachers for the duration of the curriculum implementation period. The authors took field notes on teachers' enactment of the curriculum with a focus on documenting instances when teachers diverged from the materials. Video-recorded observations were analyzed using the modeling protocol (described below), while field notes were used to cross-validate research analysis.

Teacher interviews

Teachers participated in two, 30–45-minute open-ended, semi-structured interviews: one before the implementation of the curriculum, one after (Merriam, 2009; Merriam & Tisdell, 2016; Appendix A). The pre-implementation interview was designed to elicit teachers' understanding of the curriculum and scientific practices being used and assess how they anticipated implementing the curriculum. The post-interview reviewed these same concepts, with the addition of reflection on the curriculum. Interviews were digitally recorded and transcribed for analysis.

Daily reflections

At the conclusion of each day of curriculum implementation, teachers participated in a short reflection lasting approximately 5–10 minutes. Teachers were prompted with a single question, "How do you feel about today's lesson?" (Appendix A). These post-lesson reflections were conducted by coauthors and typically occurred at the conclusion of teachers' last class period of the day. The reflections were digitally recorded and transcribed for analysis.

CLIMES lesson plans and curriculum resources

Each lesson included six major sub-sections: lesson objectives, summary of needed background information, important vocabulary, stepwise lesson procedures, discussion, and teacher resources. The discussion section provided teachers with a conclusion to the main lesson content as well as questions that could be used to initiate classroom discussion. Many of the individual lessons also included materials for student use, like figures and datasets. The written curriculum was analyzed using the same model-based protocol as the recorded observations (described below).

Data analysis and verification

Data were analyzed using both quantitative and qualitative methods. This provided an in-depth, overarching description of secondary science teachers' decisions and strategies. This mixed methods, multiple-case study approach to data analysis allows for the identification and articulation of complexities occurring within and across the cases. Through these analyses, we illustrate the teachers' differing approaches to teaching a single curriculum unit as well as trends across the four teachers.

Quantitative data analyses

Using a validated observation protocol (Baumfalk et al., 2019—see supplemental material included for review), both the written curriculum (lesson plans) and teachers' observations were quantitatively scored by three research team members. This protocol consisted of 34 indicator statements designed to measure four practices of scientific modeling: construct, use, evaluate, and revise. Each statement was assigned a numerical value from zero to three. A zero indicated the practice was nonexistent during the recorded class time. A score of one indicated it was present but without depth, meaning the practice was addressed but lacked discussion. A score of two signaled average use of the practice and represented the teacher discussing or demonstrating the practice. Finally, a score of three was assigned when the use was exemplary, including in-depth discussion involving both teacher and students and student participation in modeling practice. The practices of construction and use of models remained the focus of this inquiry, as the curriculum at the time of implementation was not designed to elicit evaluation or revising modeling practices.

Each rater independently scored 20 classroom observations. Fleiss's multi-rater kappa ($\kappa=0.447$) was calculated to estimate the level of agreement among the three raters. This value suggests that the three raters were in moderate agreement, an acceptable agreement level (Landis & Koch, 1977). Raters reconciled differences, reached a consensus, and scored the remainder of the data for evidence of model-based teaching and learning.

Qualitative data analyses

Voice-recorded data was transcribed and consolidated into a single database, allowing for comparison across data types and among individual teachers. First, readings of transcribed documentation were completed and notes were made for each teacher for each question. Themes were identified from points of divergence and justifications for changes to the

curriculum. These themes were compared to initial notes. Video-recorded classroom observations were then reviewed and documented with researcher interpretations of the teachers' intentions, goals, and classroom activities within each class period, and compared to initial field notes. This inquiry was furthered by reviewing data sources through a lens of the theoretical framework's four practices of scientific modeling—construct, use, evaluate, and revise—serving as a priori codes; this processes is described as deductive coding practice or provisional coding (Saldaña, 2016). While all four of the described modeling practices served as a priori codes, we focused on teachers' affordance of model construction and use. An inter-rater agreement of 90% was reached and followed by reconciling differences after discussion and consultation of the raw data. The coded data were then triangulated to identify overlapping codes and refined into categories to identify themes. Finally, both data strands—quantitative and qualitative—were compared to create a holistic view.

Results

Research question 1

In RQ1 we asked, *how do secondary science teachers implement a GCM-based curriculum module?* Scores from the modeling protocol for the overall curriculum, as well as subscores for modeling practices construction and use, were analyzed for each teacher and the written curriculum. Results of one-way ANOVA tests show a significant effect of curriculum condition (designed curriculum and individual teachers) on the overall model scores, $F(4, 403) = 9.84$, $p < 0.0001$, model construction subscore, $F(4, 410) = 11.12$, $p < 0.0001$, and model use subscore, $F(2, 234) = 13.02$, $p < 0.0001$. These primary results show that teachers' enacted curriculum varied in its emphasis on overall modeling, as well as construction and use. Here, we present a comparison of the four teachers' enacted curricula to the designed curriculum (RQ1a), followed by a comparison of the teachers to one another (RQ1b).

Comparison of teachers and curriculum (RQ1a)

In RQ1a we asked, *how does secondary science teachers' implementation of a GCM-based curriculum module compare to a provided curriculum?* Overall, teachers' enacted instruction averaged slightly lower in overall modeling practices compared to the curriculum, though this difference was not statistically significant, $t(54) = -2.14$, $p = .076$, $d = 0.59$ (see Table 7, Appendix B, and Appendix C). As Table 7 shows,

this trend was consistent for all four teachers. Results of post-hoc t-tests comparing each curriculum condition show that statistically significant differences between the designed curriculum and teachers' individual implementation scores were observed only for Julie's mean curriculum enactment scores (see Appendix B). Overall, teachers implemented the curriculum in ways that were less model-centric than the curriculum design; but, in all cases other than Julie, they were comparable to the design.

When the modeling practices of construction and use are examined independently, however, overall results show that teachers' curriculum enactment was characterized by less model use and higher levels of model construction than the designed curriculum. As shown in Table 7, observed differences between mean scores for model construction in teachers' enacted curriculum and the designed curriculum were statistically significant, $t(54) = 3.95$, $p = .007$, $d = 0.11$. Observed scores of model construction for all four teachers were higher than those for the designed curriculum, although results of post-hoc tests from the ANOVA show that differences from the design were statistically significant in model construction scores only for Monica and David (Appendix B).

Observed differences between mean scores for model use in teachers' enacted curriculum and the designed curriculum were also statistically significant, $t(54) = -16.91$, $p < .001$, $d = 0.47$. Scores of model use for all four teachers were lower than those for the designed curriculum, and were statistically significant for Monica and David (Appendix B). While Julie's and Michael's model use scores were also lower than the designed curriculum, they are excluded from the analyses because both teachers had confidence intervals which included zero and therefore were not statistically meaningful.

Overall, the teachers emphasized model construction at a higher level than the curriculum while de-emphasizing model use. This increased emphasis on construction had a significant influence on in-class activities. All four teachers used additional resources that were not part of the provided curriculum. These additional materials, and additional classroom time, focused on how climate models are constructed, not the use of models to make climate projections. As a result, the students' time using the model provided with the curriculum was limited across all classrooms.

The teachers also omitted some of the more student-directed modeling activities. For example, in Lesson 2, students were instructed to explore EzGCM with an accompanying guiding document to introduce them to the model. Michael instructed his students to watch him demonstrate using the model follow his steps exactly, forgoing

Table 7. Comparison of mean scores for overall curriculum unit and modeling practices construct and use.

	Overall		Construct		Use	
	M	SD	M	SD	M	SD
Monica	9.07	0.93	6.61	0.44	1.60	0.66
Julie	4.96	0.90	4.16	0.41	–	–
Michael	6.22	1.05	4.95	0.55	–	–
David	8.43	0.92	7.07	0.42	1.38	0.67
Curriculum	9.22	1.51	2.99	0.98	5.34	0.92
Teacher Average	7.17	1.91	5.70	1.37	1.07	0.50

instruction to openly explore other variables and simulations. In Monica's implementation, very little of the original curriculum was enacted. She elected to skip Lesson 3 in its entirety and much of Lesson 4. David followed the curriculum to a higher degree but still reduced student use of the model compared to the curriculum, largely due to running out of class time.

Comparison of teachers' implementation (RQ1b)

In RQ1b we asked, *how do secondary science teachers' implementations of a GCM-based curriculum module compare?* Again, scores from the modeling observation protocol for overall modeling practices, as well as subscores for construction and use, were analyzed for the four participating teachers. Results of post-hoc *t*-tests indicated statistically significant differences in pairings involving Julie's and Michael's mean curriculum enactment scores (see Table 7, Appendix C). When comparing mean overall modeling practice scores, Julie's modeling score ($M=4.96$, $SD=0.90$) was the lowest among participating teachers, and Monica's ($M=9.07$, $SD=0.93$) the highest. Differences between Julie's modeling practice scores and those of both Monica— $t(54) = -5.29$, $p < .0001$, $d=0.48$ —and David— $t(54) = 4.63$, $p < .0001$, $d=0.38$ —were found to be statistically significant, though not in comparison to Michael's enactment scores— $t(54) = -1.41$, $p=0.16$, $d=0.47$ (Appendix C). Differences between mean modeling scores for Monica and David were not statistically significant. Additionally, Michael's modeling practices scores were significantly lower than both David's— $t(54) = -2.54$, $p=0.0114$, $d=0.23$ —and Monica's— $t(54) = 3.00$, $p=0.003$, $d=0.28$. This indicates that mean modeling scores for, on the one hand, Monica and David, and, on the other, Julie and Michael, were statistically significantly different from one another. There was not a statistically significant difference between the pairs of teachers within each group (Appendix C).

Examining the modeling practice of construction independently, Julie's construction score ($M=4.16$, $SD=0.41$) was the lowest among the participating teachers, with David's ($M=7.07$, $SD=0.42$) as the highest (Table 7). Similarly, significance was observed compared to the overall modeling practices scores within multiple pairwise *t*-tests of construction scores. Julie's modeling construction scores were statistically significantly different from both Monica's— $t(54) = -4.41$, $p < .0001$, $d=0.48$ —and David's— $t(54) = 5.40$, $p < .0001$, $d=0.45$, though not Michael's— $t(54) = -1.23$, $p=0.221$, $d=0.46$ (Appendix C). Differences between mean construction scores for Monica and David, $t(54) = 0.81$, $p=0.418$, $d=0.23$, were not statistically significant. Additionally, Michael's construction scores were significantly lower than both David's, $t(54) = 3.31$, $p=0.001$, $d=0.24$, and Monica's, $t(54) = 2.48$, $p=0.013$, $d=0.32$. Finally, only Monica and David's modeling use scores were included as Julie and Michael received scores that were not statistically meaningful. Monica's use scores were only slightly higher than David's; there were no significant differences— $t(54) = -0.50$, $p=0.619$, $d=0.59$ (Appendix C).

Although the curriculum was designed to last twenty days, all four teachers completed the curriculum module in three weeks (15 days) by not enacting certain curriculum elements. Exclusion of curriculum material that foregrounded model use was seen across all teachers' enactments of the curriculum. Findings from RQ1b indicate that the teachers could be divided into two groups: teachers scoring higher on modeling practices, Monica and David, and teachers scoring lower on modeling practices, Julie and Michael.

Julie and Michael deemphasized model use during their implementation of the curriculum. For example, Lessons 6–8 (model use-focused lessons) were combined in Michael's classrooms, and Lesson 9 removed in its entirety. During Michael's teaching of Lessons 6–8, he asked students to watch as he used the model, at times having students follow him, rather than using the provided student instructions or tasks. During Michael's teaching of lesson six through eight, he elected to have his students watch as he used the model, at times having the student do parts of these lessons following him not through the provided student instructions or student tasks. Lesson seven provided a student task document aimed to guide student through using the model, instead of using this document in his classroom, Michael recreated the guide in a teacher-controlled software familiar to his students. This limited students' ability to explore the climate model as intended. Similarly, Julie had students watch as she ran the model simulations and used EzGCM. Though she did ask students to repeat the guided steps on their own personal computers, this still largely removed students' authentic engagement with the model. Julie's students also completed Lesson 9 without her first demonstrating the steps. This allowed students some, limited, engagement in the use of the model. Conversely, while David and Monica demonstrated the use of the model early in the curriculum model (Lesson 2), they both allowed students to work in small groups during the model use-based lessons, only providing additional assistance when needed. Although David and Monica condensed Lessons 6–8, it was not to the extent seen in Julie and Michael's classrooms.

Research question 2

In RQ2 we asked, *why do teachers enact the curriculum in the ways they do?* While results presented for RQ1 illustrate how teachers implemented the curriculum, findings for RQ2 emphasize why they implemented the curriculum in these ways. Below we present four case summaries providing qualitative descriptions of how teachers engaged students in the modeling practices of construction and use, and their reasoning for implementing the curriculum in the ways they did.

Julie

Julie scored the lowest in modeling practices overall, as well as in construction and use. Julie noted that her students lacked conceptual understanding of climate terms used both in the climate model and student assessments.

Students' lack of background knowledge led Julie to provide students additional "time to process," with much of a class period often spent reviewing previous topics. Julie's overall low protocol scores resulted from a focus on teaching skills outside of climate content, including note-taking or proper behavior. This focus on "soft skills" limited the amount of time students spent with the provided model and modeling practices.

Julie scored lower in model use than model construction. Her relatively higher model construction scores likely reflect her focus on students understanding the "background of climate models." Julie continually engaged students with videos from scientific organizations that focused on how GCMs are created, what inputs are needed, and the projection creation process. Having students understand the practice of model construction was, for Julie, critical for allowing students to independently find answers to their questions. Using a majority of classroom time to focus on the background of climate models (construction) was viewed as a necessary step in furthering students' understanding of how a model would be used. Julie's enactment of the curriculum was largely guided by her expressed concerns that students should know "how to create models" and that students did not have a firm understanding of what a climate model was or represented.

Michael

Michael scored the second lowest both overall and in use and construction. Michael tended to use sensationalized videos to provide material to students. He felt that the tradeoff of "less-scientific" was worth students' engagement. In addition, Michael's focus was often not on lesson material but on behavior management. Using videos allowed Michael to manage his students independent of his teaching, rather than in tandem. For Michael, being able to manage students' behavior is a "top priority above content knowledge." These factors led Michael to diverge heavily from the provided curriculum and to circumvent modeling practices. Michael believed his students lacked both conceptual knowledge about climate and the technological ability to effectively interact with the model. Many of Michael's students entered his classroom without adequate background knowledge, which he viewed as a "failing of the educational system and current culture." Michael often remarked that many of his students would benefit from special educational support or adult aids, but these were unavailable.

Additionally, Michael stated that he had previously used other simulations and models in his geoscience classes (outside of the CliMES curriculum) and found that his students would "shutdown when they became frustrated." Consequently, Michael preferred to create a pattern with his students and maintain that structure throughout the semester. For example, in the CliMES curriculum students were asked to complete tasks using Google Forms. However, because Michael's students had no experience with Forms, Michael elected to forgo these tasks or recreate them using a familiar platform. Additionally, when using EzGCM in his classroom, Michael would convert students' solo work into

full class discussions, through which he led students step-by-step using the model.

Michael's construction scores were higher than the model use scores. He rarely asked students to engage with the climate model, stating that the "model was not age appropriate." In the rare instance that Michael had students engage in model use, it was done in a rigid fashion. Students were unable to interact freely with the model as suggested by the curriculum but rather reproduced what Michael modeled for them. When Michael taught from the provided curriculum he modified the lesson, forgoing most of the suggested procedures. For example, lesson two of the curriculum introduced students to the GCM; instead of allowing students to work through the lesson's accompanying google form that instructed them to explore and investigate the model, Michael chose to have students observe him working through the process of using the model. In doing this, his students were unable to engage in the model themselves, resulting in the lower model use scores.

Michael pointed out that, in his belief, in the "real-world," "climate is not about using scientific models, but rather the economic and social structures." He felt his students needed to have a stronger background in model construction to gain any "meaningful experience" from using scientific modeling.

David

David had the highest of the construct modeling practice scores and the second highest in both use and overall protocol. David found that many of his students lacked abilities, such as math skills, outside the direct content of the class. He often planned to implement the curriculum in his classes as written and expressed frustration that he was unable to finish his lesson plans during the time allotted. For example, David planned to teach the concept of temperature anomalies using temperature data, followed by students using the model to create an anomaly visualization. However, the students struggled to grasp the concept of subtracting the control value from an experimental value. So, he abandoned his plan and instead used multiple class periods to describe the concept of anomaly and how it fit into the construction of the model. David had planned to evenly divide the class time between these two modeling practices but instead focused solely on model construction.

Additionally, at multiple points during the implementation David elected to provide supplementary lessons to cover reading graphs and calculating slopes. He believed his students could not effectively engage with the GCM without this understanding. David struggled to find the true objective of the curriculum, often asking if the goal was "for the students to understand what we're doing [content] or have them use the software [the practice of climate modeling]." David felt he needed to focus on the climate content knowledge so that when his student did engage with the model they were able to interpret the outputs, but found he often needed to "move slower." Students largely experienced climate content knowledge, not the practice of using modeling. David felt students should know "the information that we

need to build a climate model” and be able to “explain what a climate model is.”

Monica

Finally, Monica scored highest overall and in model use. Interestingly, Monica relied not on the provided curriculum but on outside curriculum modules to achieve her relatively high model use score. These “extension lessons” were used to support her students with the background she felt they needed. For example, Monica used a class period to show students a slideshow presentation from a conference she had visited explaining how GCMs were constructed and used for the IPCC documents. She then had students watch the IPCC meeting opening, aiming to show students the global scale of climate phenomena. Monica’s use of “extension lessons” was not limited to external curricula resources; she also used the model provided, EzGCM, to create one such lesson. While Monica had students use the model to create data visualizations, the intent of the lesson was to understand what variables needed to be input into the model to create the final output and then to examine these outputs over time. The practice of model use was central during the duration of this lesson. While students were engaged in authentic modeling use, it was not an application endorsed by the ClMES curriculum. One explanation for Monica’s willingness to diverge from the provided curriculum is her experience. With over 20 years of teaching experience, Monica has acquired a large collection of teaching resources by participating in professional development opportunities. Monica valued students’ understanding of why the climate model works and is a reliable tool; she aimed to have students understand both the construction and use of models. Students needed to know “what would be necessary for a climate modeler to put into their model” before fully understanding how to use a model.

Discussion

Teachers face many challenges in supporting their students’ learning about Earth’s climate system and GCC. It is therefore critical that Earth science teaching and learning not only be prioritized, but supported through intentionally designed, empirically based, innovative curricular resources made widely available to teachers. However, little research has investigated how teachers use climate-focused curricular resources to cultivate model-centric science learning environments (Bhattacharya et al., 2021b). As novel science curriculum resources are designed and implemented, we must understand how teachers use these resources and, ultimately, how they cultivate effective environments to support learning about Earth’s climate and GCC. We undertook this project to understand secondary science teachers’ enactment of a GCM-based curricular intervention (Bhattacharya et al., 2020; 2021a; Forbes et al., 2020), aiming to identify similarities and differences in teachers’ chosen curriculum enactment strategies and provide insight into how and why teachers implement developed curricular resources. Results presented here build upon and contribute to research on

model-based teaching and learning in science (Baumfalk et al., 2019; Forbes et al., 2015; Krell et al., 2015; Schwarz et al., 2009; Vo et al., 2015, 2019), climate education (Colston & Ivey, 2015; Herman et al., 2017; Monroe et al., 2013; Pallant et al., 2012; Pallant & Lee, 2015; Plutzer et al., 2016; Svihla & Linn, 2012; Tasquier et al., 2016; Wise, 2010), and teachers’ use of science curriculum materials (Fogleman et al., 2011; Forbes & Davis, 2010; Roehrig et al., 2007).

Our findings illustrate how a purposely developed, standards-aligned curriculum module was implemented by secondary science teachers. Overall, the teachers’ enacted curriculum was less model-centric than the designed curriculum, despite being part of the curriculum design process. The teachers emphasized model construction and de-emphasized model use compared to the curriculum, reinforcing findings from previous research (Carpenter et al., 2019; Khan, 2011; Vo et al., 2019, 2015; Windschitl et al., 2008). Additionally, these trends varied widely across the teachers’ observed curriculum implementation; this reinforces findings showing that teachers rarely enact curricula precisely as intended by developers (Fogleman et al., 2011; Forbes & Davis, 2010; Roehrig et al., 2007). Each teacher employed unique instructional strategies to engage with students in the epistemic and practice-based dimensions of modeling, supporting findings from previous teacher-focused climate education research (Dawson, 2012; Teed & Franco, 2014; Zangori et al., 2017). Though prior research has shown that the geosciences are largely underemphasized in the K-12 curriculum by high school (Banilower et al., 2018) and that the broader curricular context can influence the nature of climate-focused teaching and learning (Colston & Ivey, 2015; Dawson, 2012; Feierabend et al., 2011; Herman et al., 2017; Monroe et al., 2013; Plutzer et al., 2016; Wise, 2010), results presented here indicate that even when these elements are in relative alignment variation is still likely in how the planned curriculum is implemented.

The varied approaches the teachers took in enacting the curriculum resulted from a complex combination of factors, including the learning outcomes and teaching strategies prioritized; each teacher’s background with Earth’s climate, climate education, and scientific modeling; and perceptions of affordances and constraints of their classroom contexts, including perceived student needs. These factors likely explain the generally higher scores within David and Monica’s classrooms compared to Julie and Michael’s. Monica had the most classroom teaching experience, including experience using models, while David, as an alternative route teacher (Table 3), held a previous career in a highly model-based scientific field—thus, both had increased exposure to scientific modeling. This again corroborates prior research documenting the many reasons teachers implement the same curriculum in various ways (Fogleman et al., 2011; Forbes & Davis, 2010; Roehrig et al., 2007).

In foregrounding model construction, teachers emphasized the need for students to understand the inherent nature and purpose of EzGCM’s design before they could use it meaningfully. A shared emphasis among the teachers was that students needed “the information that we need to build a climate model,” or the abstract pieces of the GCM.

This observation is an example of long-standing discussion in the literature about the degree to which models should be presented as “black boxes” to students (e.g., Halloun, 2007). Findings presented here contribute to this body of work by showing why high school teachers emphasize these epistemic dimensions of GCMs and engage in climate-related instruction based heavily in perceived student learning needs (Herman et al., 2017; Plutzer et al., 2016; Slater et al., 2009).

Though study results may help identify why teachers prioritized model construction, they also highlight why these efforts were met with varying degrees of success. Efforts to strongly foreground the design of EzGCM, and GCMs more generally, resulted in emergent challenges in some cases. Not only did students struggle at times to understand these epistemic dimensions of GCMs, the teachers may have as well. Only partially developed conceptions about Earth's climate and GCC have been documented in prior climate education research for both students (Michail et al., 2007; Pallant & Lee, 2015; Pruneau et al., 2003) and teachers (Dawson, 2012; Michail et al., 2007; Plutzer et al., 2016). This research thus reinforces the need for teachers' firm understanding of the epistemic and practice-based dimensions of models, scientific modeling, and model-based teaching and learning (Justi & Gilbert, 2003; Oh & Oh, 2011; Vo et al., 2015, 2019). Together, these results illustrate how teachers' knowledge and priorities for model-based teaching and learning and understanding of core climate concepts may work in tandem to influence how they use climate-focused, model-based curricular resources.

Limitations

Study findings help explain how and why teachers implement climate-focused, model-based curriculum resources, and begin to address a gap in the literature. However, the study is limited in three ways. First, it occurred in a rare and unique curricular context: the partnering school district had a required high school geoscience course. In most formal high school settings, compulsory Earth science courses are rare (Banilower et al., 2018). Teachers also had access to a fully-developed set of curriculum resources, which research has shown to be relatively rare for climate education (Colston & Ivey, 2015; Dawson, 2012; Michail et al., 2007; Slater et al., 2009). Second, this study is limited by the small number of teachers involved. These four teachers were highly motivated to teach climate concepts and are likely not comparable to the average secondary science teacher. Finally, it was not within the scope of this study to compare student outcomes for the individual teachers, and therefore it does not address knowledge differences among students related to teaching practices. While a primary objective of the curriculum is to help students learn about Earth's climate and GCC, the present study does not provide this evidence. This additional data would be crucial not only to objectively assess the potential impact of curriculum implementation, but also to give teachers more concrete diagnostic information around which to design instruction, particularly given their emphasis on students' conceptual understanding

illustrated in the study findings. Future research, including measures of student outcomes, would provide a valuable contribution to the climate education literature.

Implications

Despite limitations, the study provides insight regarding several potential implications. Our findings show that teachers may not always have a complete understanding of students' background knowledge or may question students' understanding of climate content and modeling practices. As new curricular resources are developed, formative assessment tools must be included to serve as diagnostic tools for teachers to identify areas in which students need additional support. For this climate curriculum, which foregrounds both conceptual (Earth's climate and GCC) and epistemic (modeling) elements, formative assessment tools could help teachers gauge students' grasp of both.

Additionally, findings highlight the need for effective teacher professional development related teaching climate concepts and modeling practices. This need is well documented in the literature (Bhattacharya et al., 2021b; Colston & Ivey, 2015; Dawson, 2012; Michail et al., 2007; Slater et al., 2009). Moreover, teachers need professional learning opportunities that highlight how to effectively support students' model-based reasoning about Earth's climate and GCC. Study findings highlight that teachers may prioritize some modeling practices over others when utilizing model-based teaching in their classrooms. Teachers, like students, need to be presented with authentic modeling experiences. Additionally, professional development needs to embrace the three core elements of scientific modeling—a) disciplinary concepts, b) epistemic features, and c) modeling practices—for developing students' reasoning about scientific phenomena (Gilbert & Justi, 2016). As noted, the practices emphasized in this study—construction and use—require understanding of the nature and purpose of models, both critical epistemic dimensions of scientific modeling. Teachers need a firm understating of these dimensions.

Finally, while not a focus of our study, tentative evidence suggests that some, if not all, curriculum-related teaching and learning within the study were affected by contextual factors of the schools, students, and classroom contexts, including factors such as students' socioeconomic status, race, ethnicity, systemically racist classroom practices, ableism, sexual orientation, and gender identity. Students, especially those who have intersectional marginalized identities, likely experience additional challenges outside of the data this study collected. These factors could have shaped how and why the curriculum was implemented in the above-described ways. In a recent review of climate education literature (Bhattacharya et al., 2021b), only a small number of the included studies accounted for contextual factors and their influence on student outcome or teacher enactment (Dawson, 2012; Plutzer et al., 2016). Future climate education research needs to examine the intersectionality of contextual factors to ensure that climate-focused

curriculum and instruction provides equitable learning opportunities.

Conclusion

Earth science teaching and learning must be supported through intentionally designed, empirically based, innovative curricular resources. Teachers play a critical role in cultivating authentic modeling experiences for students, and meaningful modeling opportunities require teachers to integrate models fully within classroom activities. This study illustrates the ways secondary science teachers implemented a GCM-based curriculum, as well as how and why they enacted the curriculum the ways they did. It thus advances the literature on model-based teaching (Carpenter et al., 2019; Khan, 2011; Vo et al., 2019, 2015; Windschitl et al., 2008) and climate education (Herman et al., 2017; Plutzer et al., 2016; Slater et al., 2009).

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References

- Banilower, E. R., Smith, P. S., Malzahn, K. A., Plumley, C. L., Gordon, E. M., & Hayes, M. L. (2018). *Report of the 2018 NSSME+*. Horizon Research, Inc.
- Baumfalk, B., Bhattacharya, D., Vo, T., Forbes, C. T., Zangori, L., & Schwarz, C. (2019). Impact of model-based curriculum and instruction on 3rd-grade students' scientific explanations for the hydrosphere. *Journal of Research in Science Teaching*, 56(5), 570–597. <https://doi.org/10.1002/tea.21514>
- Baxter, P., & Jack, S. (2008). Qualitative case study methodology: Study design and implementation for novice researchers. *The Qualitative Report*, 13(4), 544–559.
- Berland, L. K., Schwarz, C. V., Krist, C., Kenyon, L., Lo, A. S., & Reiser, B. J. (2016). Epistemologies in practice: Making scientific practices meaningful for students. *Journal of Research in Science Teaching*, 53(7), 1082–1112. <https://doi.org/10.1002/tea.21257>
- Bhattacharya, D., Carroll Steward, K., Chandler, M., & Forbes, C. T. (2020). Using climate models to learn about global climate change. *The Science Teacher*, 88(1), 58–66.
- Bhattacharya, D., Carroll Steward, K., & Forbes, C. T. (2021a). Climate education in secondary science: Comparison of model-based and non-model-based investigations of Earth's climate. *International Journal of Science Education*, 43(12), 1–24. <https://doi.org/10.1080/09500693.2021.1958022>
- Bhattacharya, D., Carroll Steward, K., & Forbes, C. T. (2021b). Empirical research on K-16 climate education: A systematic review of the literature. *Journal of Geoscience Education*, 69(3), 223–247. <https://doi.org/10.1080/10899995.2020.1838848>
- Carpenter, S., Iveland, A., Moon, S., Hansen, A., Harlow, D., & Bianchini, J. (2019). Models are a “metaphor in your brain”: How potential and preservice teachers understand the science and engineering practice of modeling. *School Science and Mathematics*, 119(5), 275–286. <https://doi.org/10.1111/ssm.12340>
- Colston, N. M., & Ivey, T. A. (2015). (un)Doing the next generation science standards: Climate change education actor-networks in Oklahoma. *Journal of Education Policy*, 30(6), 773–795. <https://doi.org/10.1080/02680939.2015.1011711>
- Creswell, J. W., & Poth, C. N. (2018). *Qualitative inquiry and research design choosing among five approaches* (4th ed.). SAGE Publications, Inc.
- Dawson, V. (2012). Science teachers' perspectives about climate change. *Teaching Science: The Journal of the Australian Science Teachers Association*, 58(3), 8–13.
- Feierabend, T., Jokmin, S., & Eilks, I. (2011). Chemistry teachers' views on teaching 'climate change'-an interview case study from research-oriented learning in teacher education. *Chemistry Education Research and Practice*, 12(1), 85–91. <https://doi.org/10.1039/C1RP90011K>
- Fogleman, J., McNeill, K. L., & Krajcik, J. (2011). Examining the effect of teachers' adaptations of a middle school science inquiry-oriented curriculum unit on student learning. *Journal of Research in Science Teaching*, 48(2), 149–169. <https://doi.org/10.1002/tea.20399>
- Forbes, C. T., Chandler, M., Blake, J., Bhattacharya, D., Carroll-Steward, K., Johnson, V., DeGrand, T., Mason, W., & Morrow, B. (2020). Fostering climate literacy with global climate models in secondary science classrooms: Insights from a collaborative partnership. In J. Henderson & A. Drewes (Eds.), *Teaching climate change in the United States* (pp. 29–43). Routledge.
- Forbes, C. T., & Davis, E. A. (2010). Curriculum design for inquiry: Preservice elementary teachers' mobilization and adaptation of science curriculum materials. *Journal of Research in Science Teaching*, 47(7), 820–837. <https://doi.org/10.1002/tea.20379>
- Forbes, C. T., Zangori, L., & Schwarz, C. V. (2015). Empirical validation of integrated learning performances for hydrologic phenomena: 3rd-grade students' model-driven explanation-construction. *Journal of Research in Science Teaching*, 52(7), 895–921. <https://doi.org/10.1002/tea.21226>
- Gilbert, J. K., & Justi, R. (2016). *Modelling-based teaching in science education*. Springer International Publishing.
- Halloun, I. A. (2007). Mediated modeling in science education. *Science & Education*, 16(7–8), 653–697. <https://doi.org/10.1007/s11191-006-9004-3>
- Herman, B. C., Feldman, A., & Vernaza-Hernandez, V. (2017). Florida and Puerto Rico secondary science teachers' knowledge and teaching of climate change science. *International Journal of Science and Mathematics Education*, 15(3), 451–471. <https://doi.org/10.1007/s10763-015-9706-6>
- IPCC, 2018: Climate Change. (2013). The physical science basis. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, & P.M. Midgley (Eds.), *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, 1535 pp.

- Justi, R. S., & Gilbert, J. K. (2003). Teachers' views on the nature of models. *International Journal of Science Education*, 25(11), 1369–1386. <https://doi.org/10.1080/0950069032000070324>
- Khan, S. (2011). What's missing in model-based teaching. *Journal of Science Teacher Education*, 22(6), 535–560. <https://doi.org/10.1007/s10972-011-9248-x>
- Krell, M., Reinisch, B., & Krüger, D. (2015). Analyzing students' understanding of models and modeling referring to the disciplines biology, chemistry, and physics. *Research in Science Education*, 45(3), 367–393. <https://doi.org/10.1007/s11165-014-9427-9>
- Landis, J., & Koch, G. (1977). The measurement of observer agreement for categorical data. *Biometrics*, 33(1), 159–174. <https://doi.org/10.2307/2529310>
- Merriam, S. B. (2009). *Qualitative research: A guide to design and implementation*. Jossey-Bass.
- Merriam, S. B., & Tisdell, E. J. (2016). *Qualitative research: A guide to design and implementation* (4th ed.). Jossey-Bass.
- Michail, S., Stamou, A. G., & Stamou, G. P. (2007). Greek primary school teachers' understanding of current environmental issues: An exploration of their environmental knowledge and images of nature. *Science Education*, 91(2), 244–259. <https://doi.org/10.1002/sce.20185>
- Monroe, M. C., Oxarart, A., & Plate, R. R. (2013). A role for environmental education in climate change for secondary science educators. *Applied Environmental Education & Communication*, 12(1), 4–18. <https://doi.org/10.1080/1533015X.2013.795827>
- Morgan, D. L. (2013). *Integrating qualitative and quantitative methods: A pragmatic approach*. SAGE Publications.
- NGSS Lead States. (2013). *Next Generation Science Standards: For states, by states*. National Academies Press.
- Oh, P. S., & Oh, S. J. (2011). What teachers of science need to know about models. *International Journal of Science Education*, 33(8), 1109–1130. <https://doi.org/10.1080/09500693.2010.502191>
- Pallant, A., & Lee, H. S. (2015). Constructing scientific arguments using evidence from dynamic computational climate models. *Journal of Science Education and Technology*, 24(2–3), 378–395. <https://doi.org/10.1007/s10956-014-9499-3>
- Pallant, A., Lee, H. S., & Pryputniewicz, S. (2012). Modeling earth's climate. *The Science Teacher*, 79(7), 38.
- Plano Clark, V. L., & Ivankova, N. V. (2019). *Mixed methods research: A guide to the field*. SAGE Publications.
- Plutzer, E., McCaffrey, M., Hannah, A. L., Rosenau, J., Berbeco, M., & Reid, A. H. (2016). Climate confusion among US teachers. *Science*, 351(6274), 664–665. <https://doi.org/10.1126/science.aab3907>
- Pruneau, D., Gravel, H., Bourque, W., & Langis, J. (2003). Experimentation with a socio-constructivist process for climate change education. *Environmental Education Research*, 9(4), 429–446. <https://doi.org/10.1080/1350462032000126096>
- Roehrig, G. H., Kruse, R. A., & Kern, A. (2007). Teacher and school characteristics and their influence on curriculum implementation. *Journal of Research in Science Teaching*, 44(7), 883–907. <https://doi.org/10.1002/tea.20180>
- Saldaña, J. (2016). *The coding manual for qualitative researchers*. SAGE Publications.
- Schwarz, C. V., Reiser, B. J., Davis, E. A., Kenyon, L., Achér, A., Fortus, D., Shwartz, Y., Hug, B., & Krajcik, J. (2009). Developing a learning progression for scientific modeling: Making scientific modeling accessible and meaningful for learners. *Journal of Research in Science Teaching*, 46(6), 632–654. <https://doi.org/10.1002/tea.20311>
- Shin, N., Stevens, S. Y., & Krajcik, J. (2010). Tracking student learning over time using construct-centered design. In S. Rodrigues (Ed.), *Using analytical frameworks for classroom research: Collecting data and analyzing narrative* (pp. 38–58). Taylor & Francis.
- Slater, S. J., Slater, T. F., & Olsen, J. K. (2009). Survey of K–12 science teachers' educational product needs from planetary scientists. *Astronomy Education Review*, 8(1), 1–20. <https://doi.org/10.3847/AER2009005>
- Svihla, V., & Linn, M. C. (2012). A design-based approach to fostering understanding of global climate change. *International Journal of Science Education*, 34(5), 651–676. <https://doi.org/10.1080/09500693.2011.597453>
- Tasquier, G., Levrini, O., & Dillon, J. (2016). Exploring students' epistemological knowledge of models and modelling in science: Results from a teaching/learning experience on climate change. *International Journal of Science Education*, 38(4), 539–563. <https://doi.org/10.1080/09500693.2016.1148828>
- Teed, R., & Franco, S. (2014). Increasing teachers' confidence and pedagogical content knowledge through a workshop and follow-up program on climate change. *Journal of Geoscience Education*, 62(4), 587–597. <https://doi.org/10.5408/13-039.1>
- U.S. Census Bureau. (2020). *Educational attainment in the United States: 2019*. The United States Census Bureau. Retrieved October 1, 2020, from <https://www.census.gov/data/tables/2019/demo/educational-attainment/cps-detailed-tables.html>
- U.S. Global Change Research Program. (2009). *Climate change impacts in the United States: U.S. national climate assessment*.
- Vo, T., Forbes, C. T., Zangori, L., & Schwarz, C. (2015). Fostering 3rd-grade students' use of scientific models with the water cycle: Elementary teachers' conceptions and practices. *International Journal of Science Education*, 37(15), 2411–2432. <https://doi.org/10.1080/09500693.2015.1080880>
- Vo, T., Forbes, C. T., Zangori, L., & Schwarz, C. (2019). A longitudinal investigation of primary inservice teachers' modeling the hydrological phenomena. *International Journal of Science Education*, 41(18), 2788–2807. <https://doi.org/10.1080/09500693.2019.1698786>
- Windschitl, M., Thompson, J., & Braaten, M. (2008). Beyond the scientific method: Model-based inquiry as a new paradigm of preference for school science investigations. *Science Education*, 92(5), 941–967. <https://doi.org/10.1002/sce.20259>
- Wise, S. B. (2010). Climate change in the classroom: Patterns, motivations, and barriers to instruction among Colorado science teachers. *Journal of Geoscience Education*, 58(5), 297–309. <https://doi.org/10.5408/1.3559695>
- Yin, R. K. (2009). *Case study research: Design and methods* (3rd ed.). Sage.
- Zangori, L., Vo, T., Forbes, C., & Schwarz, C. (2017). Supporting 3rd-grade students' model-based explanations about groundwater: A quasi-experimental study of a curricular intervention. *International Journal of Science Education*, 39(11), 1421–1442. <https://doi.org/10.1080/09500693.2017.1336683>

Appendix a

Year two teacher interview protocol

Thanks for talking with me today. We want to learn about your knowledge of Earth's climate and the use of global climate models to understand it. Please refer to your experience of teaching with EzGCM in the last few weeks for answering these questions. Do I have permission to record?

These questions are focused on eliciting teachers' own understanding of content (Changing climate, increasing global surface temperatures)

1. As a learner, could you describe the phenomenon of increase in average surface temperatures? What evidence supports your understanding of this phenomenon?
2. Discuss other physical characteristics of the climate system that you would expect to change in addition to surface air temperature?
3. Does increasing average global temperature give us the best measure of global climate change?

These questions are focused on eliciting the understanding of content (Changing climate, increasing global surface temperatures) through the use of EzGCM

4. What do you know about global climate models? How can we use GCMs to predict change in temperature?
5. In the EzGCM interface, we compared the control run to a simulation where climate is changing (IPCC_A1FI_CO2). How did this process help you in analyzing the phenomenon of increase in Earth's global surface temperature?

These questions are focused on eliciting the understanding of models and model-based instruction

6. What are models?
7. How are models used in science?
8. How do you think models should be used in the classroom for science? Why?
9. How do you think students should use models to... (these are probes)
 - a. Represent natural phenomena
 - b. Communicate
 - c. Account for evidence/observations
 - d. Explain natural phenomena
10. What do you think of the new unit? How effectively does this unit help students to (these are probes)
 - a. Represent natural phenomena
 - b. Communicate
 - c. Account for evidence/observations
 - d. Explain natural phenomena
11. How can you support students' model-based reasoning about climate? What are important instructional strategies?

These questions are focused on teacher's views and experience about the CliMES curriculum

What are you most excited about/looking forward to with teaching this new curriculum module?

Year two teacher daily reflection prompt question

How do you feel about today's lesson?

Appendix B

Table B1. Pairwise comparisons between teachers and provided curriculum, including all modeling practices.

		Estimate	Standard Error	t Value	Pr > t
Curriculum	Monica	0.1477	1.4383	0.10	0.9182
Curriculum	Julie	4.2540	1.4256	2.98	0.0030*
Curriculum	Michael	2.9936	1.5383	1.95	0.0523
Curriculum	David	0.7823	1.4578	0.54	0.5918

*Significant at $\alpha = 0.05$.

Table B2. Pairwise comparisons between teachers and provided curriculum, modeling practice of construction of model.

		Estimate	Standard Error	t Value	Pr > t
Curriculum	Monica	-3.62	1.05	-3.46	0.0006*
Curriculum	Julie	-1.17	1.05	-1.12	0.2619
Curriculum	Michael	-1.96	1.11	-1.77	0.0769
Curriculum	David	-4.08	1.05	-3.90	0.0001*

*Significant at $\alpha = 0.05$.

Table B3. Pairwise comparisons between teachers and provided curriculum, modeling practice of use of model.

		Estimate	Standard Error	t Value	Pr > t
Curriculum	Monica	3.95	0.80	4.87	<.0001*
Curriculum	Julie	--	--	--	--
Curriculum	Michael	--	--	--	--
Curriculum	David	3.95	0.80	234	<.0001*

*Significant at $\alpha = 0.05$.

Appendix C

Table C1. Pairwise comparisons between teachers, including total scores of all modeling practices.

		Estimate	Standard Error	t Value	Pr > t
David	Julie	3.4717	0.7496	4.63	<.0001*
David	Monica	−0.6345	0.8127	−0.78	0.4354
David	Michael	2.2113	0.8697	2.54	0.0114*
Julie	Monica	−4.1062	0.7758	−5.29	<.0001*
Julie	Michael	−1.2604	0.8960	−1.41	0.1603
Monica	Michael	2.8458	0.9495	3.00	0.0029*

*Significant at $\alpha=0.05$.

Table C2. Pairwise comparisons between teachers, modeling practice of construction of model.

		Estimate	Standard Error	t Value	Pr > t
David	Julie	2.9114	0.5387	5.40	<.0001*
David	Monica	0.4562	0.5624	0.81	0.4178
David	Michael	2.1167	0.6396	3.31	0.0010*
Julie	Monica	−2.4552	0.5573	−4.41	<.0001*
Julie	Michael	−0.7947	0.6485	−1.23	0.2211
Monica	Michael	1.6605	0.6684	2.48	0.0134*

*Significant at $\alpha=0.05$.

Table C3. Pairwise comparisons between teachers, modeling practice of use of model.

		Estimate	Standard Error	t Value	Pr > t
David	Julie	--	--	--	--
David	Monica	−0.2195	0.4413	−0.50	0.6193
David	Michael	--	--	--	--
Julie	Monica	--	--	--	--
Julie	Michael	--	--	--	--
Monica	Michael	--	--	--	--

*Significant at $\alpha=0.05$.