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Enhancing Teachers' Capacities for Technology-Rich Climate Education: Studying the Impact of a Virtual Professional Development Program for Secondary Science Teachers

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Climate education at the high school level involves teaching about Earth's climate system and global climate change (GCC; Next Generation Science Standards Lead States, 2013). Integrating data-rich technologies is crucial for educators and scientists alike. Teacher professional development programs (PDPs) offer teachers access to these resources, helping them integrate them into their classrooms to support students' learning about climate and GCC. The shift to remote and hybrid learning, accelerated by the COVID-19 pandemic, emphasized the importance of hybrid and virtual PDPs, providing teachers meaningful professional learning experiences that benefit students. In 2022, the authors conducted a 1-week virtual PDP for secondary science teachers, introducing them to technology-rich climate curricula. They aimed to assess: (a) the conceptual gains teachers made about climate change, (b) the ways workshop participation enhanced their self-efficacy in teaching about climate change, (c) their overall experience with the PDP, and (d) differences across participants. They collected pre- and postassessments and surveys from $N = 55$ and interviewed $n = 7$ participants. Using mixed methods, they found significant improvements in participants' understanding and teaching self-efficacy regarding climate change post-PDP. Teachers valued the PDP for improving climate-based teaching, instructional strategies, collaborative learning, and access to teaching materials.

Global climate change (GCC) is a phenomenon where the greenhouse effect is intensified by the emissions of infrared absorbing gases, producing anomalies in global temperature that bring about changes in other Earth systems. The social, economic, and political impacts of these changes are variable, as they depend on the resiliency and capability to implement climate-related adaptation and mitigation strategies among systems (IPCC, 2021).

To help mitigate and adapt to these impacts, individuals should develop climate literacy, which enables citizens' understanding and decision-making about GCC. Formal education can provide opportunities to support climate literacy. The *Next Generation Science Standards* (NGSS Lead States, 2013) emphasize the importance of climate education in high school science classrooms. While the implementation of the standards varies across states, teachers' knowledge, self-efficacy in teaching about Earth's climate and GCC, and understanding of scientific processes are vital for enhancing students' climate literacy (e.g., Beach, 2023; Bhattacharya et al., 2021a; Buhr Sullivan et al., 2014; Drewes et al., 2020; Plutzer et al., 2016).

The use of data-rich technologies such as modeling and visualization tools provide meaningful support to students learning, as they allow students to engage with authentic climate data across diverse educational settings (e.g., Dupigny-Giroux et al., 2012; Gold et al., 2015; Hestness et al., 2014; Monroe et al., 2017). Professional development programs (PDPs) can provide teachers with access to these resources and opportunities to utilize them effectively to support students' learning about Earth's climate and GCC. Additionally, the shift to remote and hybrid learning, accelerated by the COVID-19 pandemic, has illustrated the potential of virtual formats and associated technologies in teacher professional development. Thus, it is essential to expand supportive avenues for teachers' learning about Earth's climate, GCC, and pedagogical approaches, with further research needed on the effectiveness of these experiences (Beach, 2023; Bhattacharya et al., 2021a; Buhr Sullivan et al., 2014; Hestness et al., 2014).

In response to these needs, we implemented a 1-week online PDP for secondary teachers across the United States. This program focused on Earth's climate and GCC using data-rich, technology-based, NGSS-aligned high school-level curricula. The study aimed to address the following questions:

1. What conceptual gains about climate change did teachers obtain because of the PDP?

2. How did workshop participation enhance teachers' self-efficacy in teaching about climate change?

3. What was the teachers' overall experience with the PDP?

4. Were there any differences across participants' types?

Results of the study can inform about the design and potential benefits of online PDPs using computer-based models for teaching climate change.

Literature Review

Climate Literacy and Teaching Self-Efficacy Among High School Teachers

Teachers' understanding of Earth's climate system and GCC, along with their teaching self-efficacy, are crucial to support student learning. However, many teachers feel inadequately prepared to teach about GCC and Earth's climate (e.g., Beach, 2023; Bhattacharya et al., 2021a; Liu & Roehrig, 2019; Zummo & Dozier, 2022). Prior research highlights the need to support teachers' increasing understanding of Earth's climate and GCC, including atmospheric composition, energy transfer, the role of greenhouse gases, the greenhouse effect, the carbon cycle (Bhattacharya et al., 2021a; Buhr Sullivan et al., 2014; Clary & Wandersee, 2012; Hestness et al., 2014), climate projections and impacts, modeling, and adaptation and mitigation strategies (Hestness et al., 2014), among others.

Also, while many teachers believe and express concern about GCC, their perspectives on its causes — whether natural or anthropogenic — vary (e.g., Bhattacharya et al., 2021a; Buhr Sullivan et al., 2014; Clary & Wandersee, 2012), which can lead to inconsistent messaging to students (e.g., Beach, 2023; Liu & Roehrig, 2019; Plutzer et al., 2016; Zummo & Dozier, 2022). Teachers often have limited knowledge about climate models compared to other fields (Plutzer et al., 2016), and they face challenges in learning to use technological tools, particularly if their discipline rarely incorporates them (Gold et al., 2015; Hestness et al., 2014).

Integrating tools like an Excel spreadsheet into instructional resources allows students to utilize its data analysis and visualization capabilities. Instructors may encounter difficulties using these tools without guidance (Gold et al., 2015). These factors influence teachers' decisions to include Earth's climate and GCC in their courses, the teaching methods they utilize, and the overall quality of instruction.

Climate-Focused Professional Development for Secondary Teachers

Innovative approaches to teacher preparation and professional development, particularly for educators without a background in Earth sciences, can significantly enhance their content knowledge, increase confidence and positive attitudes toward teaching these topics, and ultimately, improve student learning outcomes (e.g., Clary & Wandersee, 2012, 2014; Drewes et al., 2020; Plutzer et al., 2016). PDPs focused on Earth's climate and GCC frequently incorporate a range of data-rich technological tools. These initiatives offer teachers hands-on experiences with authentic climate-related data through modeling tools, computational visualizations, Google Earth, geospatial technologies, satellite imagery, aerial views of the globe, and sensor-equipped balloon launches. Teachers may also develop their own climate models.

Such activities simulate scientific inquiry and deepen understanding of climate science concepts (e.g., Dupigny-Giroux et al., 2012; Ellins et al.,

2014; Gold et al., 2015; Hestness et al., 2014; Li et al., 2021; Liu & Roehrig, 2019; Teed & Franco, 2014). By engaging in these practices, educators build practical skills for evaluating and interpreting scientific data, strengthening both their instructional effectiveness and their grasp of the nature of science. These strategies help teachers create authentic, inquiry- and problem-based learning environments, clarify complex concepts, confidently respond to student questions, and provide real-world examples that enrich student learning (e.g., Beach, 2023; Bhattacharya et al., 2021a; Brey et al., 2015; Buhr Sullivan et al., 2014; Zummo & Dozier, 2022).

Use of Virtual Technologies for Climate-Focused Teacher Professional Development

Climate-focused PDPs often utilize hybrid formats with virtual components to enhance learning and collaboration among teachers. These programs leverage online platforms to extend the benefits of face-to-face sessions, facilitating ongoing communication, resource availability and sharing, and support, reflection, and collaboration among peers (e.g., Brey et al., 2015; Clary & Wandersee, 2012, 2014; Gold et al., 2015; Teed & Franco, 2014; Zummo & Dozier, 2022). This approach has broadened the reach of climate-focused PDPs across multiple states, fostering collaborative communities among educators, supporting them in understanding and effectively teaching GCC, and facilitating the sharing of instructional practices across diverse disciplines.

For example, virtual programs enable participation of teachers from more geographically diverse areas, providing opportunities for teachers to design place-based learning experiences that can support interest in identifying actionable solutions for GCC (Drewes et al., 2020; Dupigny-Giroux et al., 2012). Virtual program formats also leverage the inherent nature of technological tools increasingly at the core of climate education. For example, as part of climate-focused PDPs, teachers have also taught their peers on using these tools, expanding the opportunities for accessing these resources (Drewes et al., 2020; Ellins et al., 2014; Li et al., 2021). Expanding access to these virtual professional learning opportunities for teachers can improve the overall effectiveness of climate education.

Theoretical Framework

Technological pedagogical content knowledge (TPCK, or technology, pedagogy, and content knowledge [TPACK]) (Mishra & Koehler, 2006) provides a framework for the integration of technology into teaching in ways that enhance learning. It combines three primary forms of knowledge. Content knowledge (CK) refers to knowledge about the subject matter that is to be taught or learned. Pedagogical knowledge (PK) refers to knowledge about the processes and practices or methods of teaching and learning. Technological knowledge (TK) refers to knowledge about the various technologies that can be integrated into teaching and learning. This includes understanding how to use digital tools, software, and other technological resources. Intersections between these forms of knowledge include pedagogical content knowledge (PCK), Technological content knowledge (TCK), and technological pedagogical knowledge (TPK). The intersection and integration of all is TPCK.

The TPACK framework emphasizes that the effective integration of technology in education requires a deep understanding of how content, pedagogy, and technology interact with each other. In the study, the PDP aimed to foster the integration of the three knowledge domains by allowing teachers to develop a holistic understanding of ways to use a modeling tool to teach specific Earth's climate and GCC-related content effectively, experiencing appropriate pedagogical strategies and utilizing pedagogical resources. This approach aimed to support their teaching self-efficacy and content knowledge, making them more confident in using the resources and the model.

Methods

Study Design and Context

This study was part of a collaboration between three R1 universities and the Livermore Lab Foundation (LLF) to disseminate secondary NGSS-based curricula focused on GCC. The curricula covered various aspects of Earth's climate and GCC. The resources can be found at LLF's Carbon Cleanup Initiative and EzGCM's website. Central to the curricula was EzGCM, a modeling tool that facilitated exploration of climatic variables, such as global temperatures and temperature anomalies. The EzGCM curriculum development was part of a 5-year project funded by the National Science Foundation in the United States.

Throughout the project's duration, its impact on students' learning outcomes and teachers' instructional practices was systematically evaluated (Bhattacharya et al., 2020, 2021a; Carroll Steward et al., 2022, 2023, 2024; Forbes et al., 2020; Mostacedo-Marasovic et al., 2024, 2025; Olsen et al., 2023). After the development of the curricula, a PDP was designed to introduce secondary teachers from the United States to the curricula, providing active learning experiences, and exploring potential applications in their classrooms (see appendix).

PDP Characteristics

The PDP was conducted as a 1-week online synchronous workshop in the summer of 2022 for secondary teachers across multiple US states. The workshop included curricula-derived presentations and activities, personal and group discussions, and reflections about the resources from the curriculum. It included presentations from guest speakers about the use of EzGCM and applications of models in real world contexts. Teachers had opportunities to plan adaptations and implementation of the curricula for their classrooms. The PDP design alignrf with recommended practices for enhancing teacher self-efficacy in technology integration, such as modeled instruction, scaffolded practice, and opportunities for reflection and feedback (Williams et al., 2023). Parallel research was conducted to evaluate teachers' interest in adopting the resources (Mostacedo-Marasovic et al., 2025).

Participants

Prior to the PDP, participants were asked to review a consent form approved by the University of Texas at Arlington's Institutional Review Board to participate in the research. Data were collected from 55 teachers who participated in the workshop. Teachers were recruited through existing teacher networks of the institutions involved and were all voluntary participants. Of the participants, 85% taught about Earth's climate and climate change. Table 1 provides participants' demographic information. Participants who completed all workshop activities received opportunities for graduate course credit, continuing education credits, or a stipend. Interviewees received an additional $25 USD compensation for their participation.

Table 1
Participants' Demographic Information

Categories	**Responses**				
Place of Residence	Texas 39 (71%)	California 6 (11%)	Nebraska 6 (11%)	Other locations[a] 4 (7%)	
Gender	Female 38 (69%)	Male 16 (29%)	Preferred not to respond 1 (2%)		
Age group (years)	20 to 29 12 (22%)	30 to 39 14 (25%)	40 to 49 14 (25%)	50 to 59 11 (20%)	60 to 69 5 (9%)
Education	Bachelors 27 (49%)	Masters 24 (44%)	Doctorate 3 (6%)	Education specialist or professional diploma 1 (1%)	
Political affiliation	Democrat 18 (33%)	Republican 5 (9%)	Independent 14 (25%)	Preferred not to answer 18 (33%)	
Race or ethnicity	White-Caucasian 31 (56%)	Person of color 16 (29%)	Bi/Multi Racial 8 (15%)		
Teaching experience (years)	0 to 5 22 (40%)	6 to 10 7 (13%)	11 to 15 10 (18%)	16 to 20 8 (14.5%)	More than 21 8 (14.5%)

[a] Other locations include Indiana, Minnesota, South Carolina, and Nigeria. (2) Other races or ethnicities include Asian (4%), Black or African American and Latino or Hispanic (2%), White-Caucasian and Asian (2%), White-Caucasian, Black or African American and Native American (2%), White-Caucasian and Native American (2%), White-Caucasian, Native American and Latino or Hispanic (2%), White-Caucasian, and Native Hawaiian or Pacific Islander (2%), Other (2%), and preferred not to answer (2%).

Data Sources

Pre- and Postassessments

The pre- and postassessments consisted of 63 questions about climate-related concepts. The assessments were built based on existing instruments (Bodzin et al., 2014; Dowd et al., 2014; Jarrett & Takacs, 2019; Libarkin et al., 2018; Wallquist et al., 2010; You et al., 2017) and items selected to align with PDP topics and content. The assessments involved true-false and multiple-choice questions. They were scored from 0 = *incorrect* to 1 = *correct*. Intermediate scores reflected partially correct answers in some cases. We used the pre- and postassessments to evaluate teachers' gains in their knowledge about climate change.

Pre- and Postsurveys

The presurvey consisted of 35 questions, while the postsurvey had 43 questions. Both surveys included 12 common items scored on a Likert-type scale ranging from 1 (*novice*) to 5 (*expert*), assessing participants' perceptions of their teaching abilities related to Earth's climate and GCC. Additionally, the presurvey included seven demographic questions and 16 queries related to teaching experience. The postsurvey included 17 Likert-scale questions focusing on the curricula and activities, along with nine Likert-scale and five open-ended questions providing feedback on the workshop. Responses were scored on a scale from 1 (*Strongly disagree*) to 6 (*Strongly agree*).

To address any missing data, participant responses were averaged by dividing the sum of their responses by the number of completed questions. This normalization allowed for comparison across different survey lengths and ensured that scores reflected the participants' overall responses relative to the total number of questions answered.

Interviews

We conducted 30-minute interviews with $n = 7$ participants between March and April 2023. We used a semistructured interview protocol to learn more about participants' experience with the workshop and how it supported their future teaching activities. The interviews were recorded, and the transcripts were obtained using Microsoft Teams. All personally identifiable information was removed for the analysis.

Data Analysis

To address Research Questions 1 and 2, we used match-paired-samples *t*-tests to evaluate mean differences between the pre- and postassessment percentages and pre- and postsurvey percentages to evaluate changes in conceptual knowledge and self-efficacy scores. Effect sizes were measured using Cohen's *d*, where 0.20 were considered small, 0.50 moderate, and 0.80 large effects (Cohen, 1992). We also performed an Analysis of Variance (ANOVA) to evaluate differences between each question for changes in the self-efficacy questions.

To address the Research Question 3, we used descriptive statistics to characterize teachers' responses and ANOVAs to evaluate differences between each question for changes in the workshop evaluation questions. We complemented the results from the statistical analysis with the results from the open-ended questions from the postsurveys and the interviews. The qualitative analysis was informed by methods described by Merriam and Tisdell (2016).

We used MaxQDA (a qualitative analysis software) to code the survey responses first, and the interviews second. We coded the survey responses into two broad categories: (a) aspects of the workshop that were most effective (effective aspects) and (b) aspects of the workshop that could be improved (areas to improve). We used open coding to characterize the topics covered within each category.

After reorganization of the codes, the main subcategories within the effective aspects category were as follows:

1. Workshop organization,
2. Organization of materials,
3. Benefits for teacher's learning, and
4. Benefits for students' learning.

The main subcategories within the areas to improve category were (a) additional support, (b) improvements related to the materials, (c) improvements related to the workshop, and (d) characteristics of EzGCM. These categories, subcategories, and their corresponding codes were used to evaluate the interviews. We summarized the results first for the postsurveys, followed by the interviews using the identified categories and subcategories. We used the analysis to further evaluate differences in teaching self-efficacy between groups and the overall workshop experience.

To address the Research Question 4, we conducted two multiple regression analyses. For the first analysis, the outcome variable was the difference between the pre- and postassessments (i.e., posttest percentage minus the preassessments percentage). Percentages were used instead of raw scores, because some individuals were missing data.

The second analysis had the workshop score as the outcome variable. In our models, we also included other teacher variables of interest, including the state teacher resided in (Texas or another state), gender (male or female), age (20-29, 30-39, 40-49, 50-59, or 60-69 years old), race/ethnicity (White; person of color, that is, Black or African American, Latino or Hispanic, or Asian; or bi/multi-racial), political affiliation (Republican, Democrat, Independent, or preferred not to answer), degree type (bachelors or higher than a bachelor's degree), certification type (regular or probationary/alternative), years teaching (10 years or less or greater than 10 years), and whether they taught about Earth's climate and climate change (yes or no).

We performed Fisher's exact tests, a type of nonparametric test, to determine if demographic variables such as gender, age, and others differed significantly in the case where the regression model identified statistically significant differences (i.e., in teachers' state residence). The results from Fisher's exact tests served as a form of control for demographic confounding variables. By establishing that demographic factors were not significantly different, the study could more confidently attribute differences in posttest scores to the variable of interest (residence in or outside Texas) rather than to underlying demographic differences.

Results

Teachers' Conceptual Learning About Climate Change and Differences Across Participants' Types

Results from the matched-paired samples *t*-test on the content knowledge instrument (pre- and postassessment) showed a statistically significant difference, $t(54) = -11.34$, $p < .001$, with a large effect size, $d = 1.69$. Teachers scored higher on the postassessment ($M = 0.82$, $SD = 0.12$) compared to the pre-assessment ($M = 0.61$, $SD = 0.13$). For the regression analysis, statistically significant differences were found in the content knowledge assessment scores. Teachers residing outside of Texas scored lower on the post-assessment compared to those residing in Texas ($B = -0.11$, $p < .05$). Fisher's exact tests showed no statistically significant difference between any of the demographic variables and whether individuals resided in Texas or not. This suggests that the demographic characteristics between these two groups do not significantly vary. This means that any differences observed in the regression analysis (such as the lower content knowledge assessment scores for non-Texas residents) are less likely to be due to demographic variations and more likely to be attributed to other factors, such as the educational program or context.

Teachers' Self-Efficacy to Teach About Climate Change and Differences Across Participants' Types

Results from the matched-paired samples *t*-test for the self-efficacy instrument (pre- and postsurveys) showed a statistically significant difference, $t(54) = -7.17$, $p < .001$, with a large effect size, $d = 1.22$. Teachers scored higher on the postsurvey ($M = 0.74$, $SD = 0.10$) compared to the presurvey ($M = 0.59$, $SD = 0.14$). For the regression analysis, no statistically significant differences were found between any of the demographic groups on the self-efficacy instrument. For the ANOVAs, there were no differences between any of the questions regarding changes in self-efficacy.

Overall Evaluation of the PDP and Differences Across Participants' Types

The scores for the workshop experience were high ($M = 84\%$, $SD = 9\%$, $Min = 52\%$, $Max = 100\%$), left-skewed (*Skewness* = -0.66), and light-tailed (*Kurtosis* = 1.55) compared to the normal distribution. For the regression

analysis, there were no differences between any of the demographic groups on the workshop score ($p > .05$).

The descriptive statistics of each workshop-related question are in Table 2. The means of the responses ranged from 4.40 to 5.46 out of 6 points (73% to 91%). Results from the ANOVAs showed statistically significant differences between the workshop-related questions ($F(8,484) = 8.301$, $p < .000$). Table 3 shows the differences found between statements based on the posthoc tests. The statements related to collaboration and networking (Statement 3), and the length (Statement 6) and structure (Statement 7) of the workshop had the lowest mean values, whereas those that reflect teachers' understanding of climate-based teaching and learning (Statement 1), and the effectiveness of instructors (Statement 8) had the highest mean values. Following, mean values for Statements 3 and 6 also had lower mean values than the statement related to gaining interest in climate-based teaching and learning (Statement 4). Finally, when compared to Statement 3, the statements related to the supports to shape the course (Statement 2), and the fulfillment of the workshop goals (Statement 9) also had higher mean scores. No other differences were observed.

Table 2
Descriptive Statistics of Workshop-Related Questions

Statement Number and Statement		Mean	Standard Deviation
1	The workshop aided in my understanding of climate-based teaching and learning	5.46	0.72
2	The workshop aided me in shaping the course I intend to develop/revise	5.16	0.81
3	The workshop allowed me to meet colleagues with whom I intend to continue collaborating	4.40	1.30
4	The workshop increased my interest in climate-based teaching and learning	5.29	0.69
5	The workshop increased my interest in doing research about climate-based teaching and learning	5.04	0.98
6	The length of the workshop was effective	4.63	1.05
7	The structure of the workshop was effective	4.84	0.94
8	The instructors for the workshop were effective	5.34	0.67
9	My goals for this workshop were met	5.20	0.80

Table 3
Post-Hoc Results Workshop-Related Questions

Statement With Lower Mean Score	Statement With Higher Mean Score	Adjusted *p*-Value
Statement 3	Statement 1	< .0000
	Statement 2	.0135
	Statement 4	.0008
	Statement 8	.0003
	Statement 9	.0071
Statement 6	Statement 1	.0002
	Statement 4	.0071
	Statement 8	.0021
Statement 7	Statement 1	.0066
	Statement 8	.0360

Note: The table shows only pairwise comparisons that were statistically significant.

Affordances and Areas of Improvement of the Professional Development Program

Teachers shared how the PDP enriched their understanding and ability to teach about Earth's climate and GCC. These benefits included the use of data-rich technologies, which enhanced teachers' conceptual understanding, teaching self-efficacy, and the understanding and use of models. Additionally, engagement in a virtual environment supported teachers' accessibility to high-quality materials, hands-on activities, virtual field trips, peer collaboration, and adaptability to teachers' recommendations and individual characteristics. Within some of these areas, teachers also offered recommendations for improvement.

Regarding the use of data-rich technologies, the teachers in the study appreciated learning about GCC and the different data models from experts in the field. Participants found these tools to be valuable resources for teaching about climate change. The focus on student-driven learning and the incorporation of real-life data into lessons were seen as effective strategies for engaging students and enhancing their understanding of complex concepts. This increased their confidence to teach the material in the classroom. A teacher said, "I feel much more confident in teaching about climate change in a way that will engage students and encourage them to take charge in their learning" [H240]. This also included the use of data-rich technologies, like EzGCM. One teacher commented, "After that week… I was really excited that I will be comfortable using the global

climate modeler and my students will have access to this and can see this" [A61].

Teachers' engagement in a virtual environment provided them access to resources that they evaluated as good quality, well-organized, and available to facilitate their teaching practice and benefit their students' learning through the learning management system, Canvas. Some indicated they would share the resources with other teachers too. An instructor said,

> I really appreciated that there were lessons that were already organized, as I am constantly looking for new ways to increase student driven learning in my classroom. This provided me with a template that I can use as it currently exists and/or allows me to use certain aspects that are more relevant to my course objectives while adjusting them to meet my individual needs. [H14]

The availability of materials and recordings allowed participants to review, revisit, and catch up on content at their own pace, which was particularly helpful for those facing technical issues or time constraints. A teacher commented,

> I appreciated that everything was kept up from pre-recordings so that I could go back and review. It also gives me more confidence that when I go to teach these concepts, I can always review and refresh my knowledge before jumping in. [H107]

Some teachers recommended having the teaching resources sooner to be able to review them and print them if necessary. An instructor suggested "having materials up a day early so I could look over things beforehand and spend some time thinking about them" [H157]. A structured list of instructions and the ability to print slides for notetaking were suggested to help manage switching between video sessions and documents.

The curricula-based activities allowed teachers to explore the materials and understand what students may experience when using the resources. They appreciated the opportunity to see activities demonstrated and then work on them individually. A teacher said, "I think what was most effective for me in the workshop was actually doing the tasks that will be asked of students as the lesson progresses" [H57]. Teachers valued the hosts' delivery of the background and use of the curricular resources, including explanations about their own teaching experiences. An instructor said: "Suggestions were constantly being thrown around about different ways you might use different things. I appreciate that because every class works a little different and students need different ways to connect to material" [H49].

Teachers valued having time for individual and group work to discuss the curricula and plan how it could be used. A teacher said, "I found the independent work time and time to reflect and plan effective. This made it so there was a relevant and useful 'take-away' from the workshop" [H93].

Having virtual field trips and guest speakers demonstrating applications of the models was considered engaging and informative. These elements

provided real-world context and expertise that enhanced the learning experience. One instructor commented, "The panelists were sharing with us their expertise. Just to hear their background, what they are working in, what they are innovating about was very meaningful" [A49]. Some teachers suggested that the virtual field trips would be better scheduled at the beginning of the PDP. An instructor said, "The virtual field trips to see the different agencies. Those were both awesome. The second one may have been more effective earlier in the week" [H10].

Participants valued the opportunity to engage and collaborate with other teachers and instructors from different regions and domains, which enhanced their understanding and application of the content. They appreciated the collaborative environment and the opportunity to discuss and share ideas. One teacher said, "To be able to collaborate with other teachers from different parts of the country is an invaluable experience. This helped to put concepts in perspective by analyzing other people's point of view" [H41].

Some would have preferred to be able to exchange even longer with groups from common domains and have a guide that would help them stay focused while working in groups. An instructor said, "Maybe have a document for all to access when in breakout rooms to contribute and make sure discussions are being done in an appropriate manner" [H216].

Participants appreciated the responsiveness to feedback. This adaptability made the PDP more effective and relevant to their needs. For example,

> I feel like [the facilitators] were very good at making adjustments on the fly and were very flexible about what the group needed at different times. Thank you for taking the time each morning to discuss the Glows and Grows from the day before. It showed how much you deeply cared about making the workshop relevant for everyone. [H169]

The synchronous mode of the workshop was beneficial for participants to help them balance their time with their own personal and professional commitments. One teacher said, "The virtual workshop allowed me to attend this, which was lovely. I feel like being at home, it was easy to take time out of my day to be here" [H72].

Regarding other modes, some participants were interested in an in-person option, while others were interested in an asynchronous format. Some teachers considered the time distribution and format of the workshop as an area for improvement. Having more time for breaks than was provided or extending the workshop over 2 weeks would have been beneficial for deeper understanding and less fatigue. Also, the length of some sessions was seen as excessive, with suggestions for more efficient use of time and better balancing between different activities. A teacher said: "I would like to have shorter days over a longer period. I believe that some down time in-between presentations would be helpful and allow for deeper understanding in the long run" [H172].

Others would have preferred an asynchronous format to the online PDP to accommodate different learning paces, locations, and time zones. One instructor said, "I think that allowing asynchronous viewing of the

meetings would be better for many of us in rural areas that struggle with internet issues and time" [H140].

Discussion

Climate literacy is a key learning goal for secondary students (NGSS Lead States, 2013). To support this, various strategies increasingly incorporate data-rich technologies (e.g., Bhattacharya et al., 2021a; Dupigny-Giroux et al., 2012; Li et al., 2021; Liu & Roehrig, 2019; Monroe et al., 2017). Teaching about Earth's climate and GCC effectively requires teachers not only to understand the content but also use engaging, technology-enhanced instructional methods (e.g., Beach, 2023; Buhr Sullivan et al., 2014; Plutzer et al., 2016).

PDPs have been designed to strengthen teachers' content knowledge, pedagogical skills, and use of data-driven tools (e.g., Brey et al., 2015; Drewes et al., 2020; Gold et al., 2015; Hestness et al., 2014; Teed & Franco, 2014; Zummo & Dozier, 2022). Many of these programs also include virtual environments, which have become especially relevant since the COVID-19 pandemic (Clary & Wandersee, 2014, 2012; Ellins et al., 2014). This study examined the impact of a 1-week virtual PDP that introduced high school teachers to climate-focused curricula (Mostacedo-Marasovic et al., 2025). We explored how the program supported teachers' knowledge, boosted their self-efficacy, and identified workshop elements that contributed to these outcomes. This research was part of ongoing efforts related to the development of GCC curricula and teachers' evaluation of EzGCM (Bhattacharya et al., 2020, 2021b; Carroll Steward et al., 2022, 2023, 2024; Forbes et al., 2020; Mostacedo-Marasovic et al., 2024; Olsen et al., 2023).

Use of Technology to Support Teachers' Conceptual Understanding of Earth's Climate and GCC

The study provided multiple data points to demonstrate the impact of the PDP on teachers' conceptual understanding of Earth's climate and GCC. Several characteristics of the workshop may have contributed to these outcomes. Teachers indicated that active engagement with the curricula-based tasks and learning from peers, instructors, and guest speakers, all of which occurred in a virtual environment, allowed a deeper conceptual understanding of Earth's climate and GCC. Teachers highlighted the role that engaging with the resources, using EzGCM, and conducting their own analysis supported their learning about Earths' climate, GCC, and the use of data-rich technologies (e.g., Beach et al., 2023; Bhattacharya et al., 2021a; Dupigny-Giroux et al., 2012; Gold et al., 2015; Teed & Franco, 2014; Zummo & Dozier, 2022).

This understanding may provide support to teachers for addressing alternate conceptions they may have about Earth's climate and GCC (Buhr Sullivan et al., 2014; Carroll Steward et al., 2023). This may also support students' thinking of the climate system (Plutzer et al., 2016), which is an outcome teachers seek to achieve using the resources (Mostacedo-Marasovic et al., 2025). Prior research has shown that the implementation of the curricula in the classroom supported students' reasoning about

climate variables and GCC and understanding of what models entail (e.g., Bhattacharya et al., 2021b, 2020; Carroll Steward et al., 2022; Mostacedo-Marasovic et al., 2024). It also supported teachers to engage students in meaningful learning opportunities focused on big data, data analysis, representation, and validity of data (e.g., Forbes et al., 2020). These skills are valuable across science, technology, engineering, and mathematics disciplines, which highlights the potential for using the resources across disciplines (e.g., Dupigny-Giroux et al., 2012; Ellins et al., 2014; Liu & Roehrig, 2019), where guidance to utilize the resources is essential (Hestness et al., 2014).

The study results also support the benefits of providing teachers an online space for communication among peers benefiting their content knowledge (Clary & Wandersee, 2014, 2012; Drewes et al., 2020). Having guest speakers was valuable to provide teachers with perspectives from scientists working on various projects related to the applications of this knowledge and practices across different contexts (Drewes et al., 2020; Ellins et al., 2014; Gold et al., 2015).

Use of Technology to Support Teachers' Teaching Self-Efficacy to Teach About Climate and GCC

Similarly, the study provides evidence of the impact on how the PDP supported teachers' self-efficacy to teach about Earth's climate and GCC. Teachers were able to observe and experience teaching methods using data-rich technologies and working in a virtual environment. They gained access to and experience with purposefully developed curricular materials aligned with the NGSS, insights from instructors and peers, and time to plan their own instruction using these resources.

Prior research on EzGCM found that instructors' utilization of the model and assessment of the use of the resources are influenced by teachers' prior experience, age, and teaching experience (Carroll Steward et al., 2022; Mostacedo-Marasovic et al., 2025). Research by Li et al. (2021) also observed that participation in a PDP supported teachers' self-efficacy, and their teaching was more efficient among all participants, but these gains were higher for participants who had prior experience teaching about GCC. In the study, participation in the PDP improved teacher's self-efficacy regardless of demographic factors and prior experiences. This indicates that the PDP was effective in supporting teachers' confidence and practice in using these and similar resources.

The increase in teacher self-efficacy scores is particularly promising given that self-efficacy in technology integration is associated with greater use of technology in instruction and enhanced student engagement (Williams et al., 2023). Furthermore, findings from Carroll Steward et al. (2023) regarding the instructional use of EzGCM showed that a group of 240 students, regardless of their instructor, improved their knowledge of Earth's climate and GCC. This also underscores the importance of providing ongoing opportunities for teachers to improve their familiarity and practice with data-rich technologies (Hestness et al., 2014).

In the study, having a virtual environment allowed instructors from multiple states, including those without local access to this opportunity, to

learn about NGSS-aligned curricular resources, regardless of their geographical location, where they indicated their interest to share the resources with their peers. Having access to purposefully developed materials with comprehensive guidance on how to utilize them contributes to teachers' feeling more comfortable to use them in their classrooms (Drewes et al., 2020; Ellins et al., 2014; Hestness et al., 2014; Li et al., 2021). It also supports the use of active approaches that contribute to teachers' interest to redesign the resources to their own needs and insights into the resources needed to use EzGCM and the curricula effectively in their classrooms (Dupigny-Giroux et al., 2012; Mostacedo-Marasovic et al., 2025).

The PDP allowed teachers to communicate, collaborate, and share reflections about their experiences and plans for using the resources virtually (e.g., Drewes et al., 2020; Ellins et al., 2014; Gold et al., 2015; Hestness et al., 2014; Teed & Franco, 2014). Lesson planning sessions, a key component of the PDP, allowed participants to identify the most beneficial ways to incorporate the resources into their courses (Beach et al., 2023; Brey et al., 2015; Drewes et al., 2020; Dupigny-Giroux et al., 2012; Liu & Roehrig, 2019). While other PDPs have provided instructors across multiple locations with onsite activities followed by opportunities for online collaboration, supporting the development of teacher networks (Brey et al., 2015; Li et al., 2021; Drewes et al., 2020; Ellins et al., 2014; Hestness et al., 2014) focused on teachers' interactions during the workshop.

Limitations and Research Opportunities

The study had some limitations. We focused on the evaluation of the PDP and its impacts on teachers' content knowledge and teaching self-efficacy regarding GCC and Earth's climate, their use of data-rich technologies, and their engagement in a virtual environment. While we aimed to investigate the ways in which a synchronous environment can facilitate teachers' learning, many of the affordances discussed in the study were also present in PDPs that were held in-person and/or integrated hybrid programs.

There are aspects of climate education that were not addressed in this study, including ways to incorporate sociopolitical, socioemotional, and socioeconomic aspects that may play a role in teachers and students' understanding and their perspectives of GCC (Beach, 2023; Bhattacharya et al., 2021a; Forbes et al., 2020; Hestness et al., 2014; Plutzer et al., 2016). Furthermore, the study by Mostacedo-Marasovic et al. (2025) focused on teachers' interest in adopting the resources in their classroom after their participation in the PDP, where ways in which teachers could implement place-based learning and actionable solutions (Drewes et al., 2020) and enhance learning for students with English as second language are also introduced (Dupigny-Giroux et al., 2012). Methodologically, the self-efficacy questionnaire could introduce a question that specifically addresses changes in teachers' perceptions about the use of technology in their classrooms because of their participation in the program. This was studied in the open-ended questions of the survey and the interviews. Also, while participants received some incentives to participate in the workshop, it is possible to consider that they were intrinsically motivated to be part

of the PDP. This inclination to pursue additional professional learning opportunities to support their own teaching practice could have influenced their overall outcomes.

Conclusions

Climate education aims to provide students with knowledge and tools to inform about GCC and Earth's climate and to evaluate potential mitigation and adaptation strategies. Secondary teachers play a significant role in these efforts, where their content knowledge and teaching self-efficacy are key. PDPs, including those that involve the use of teaching technologies and rely on technology for implementation, provide opportunities to support these outcomes. We evaluated a 1-week virtual PDP that introduced teachers to climate-related curricula involving learning about Earth's climate and GCC, mitigation and adaptation strategies, climate models, active engagement, peer learning, and presentations from guest scientists about applications. Outcomes and outputs from the program reinforce and extend the results of past climate PDPs, inform about the affordances of the program that have supported teachers' outcomes, provide areas of improvement, and can serve as a reference for future climate change professional development programs that are conducted exclusively online.

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Appendix
Workshop Activities

Day	Workshop Activities
Day 1	Ocean acidification due to climate change: Participants were introduced to ocean acidification due to climate change. Global implications of excess carbon: Participants were introduced to global implications of excess CO2.
Day 2	Temperature Anomalies: Participants were introduced to the EzGCM, Earth's climate, and temperature anomalies. Exploring Earth's global average temperature: Participants were introduced to global average temperatures.
Day 3	This session introduced participants to fingerprinting the causes of global warming. Running Simulations: This session introduced participants to using scientific visualization to calculate the surface air temperature anomaly.
Day 4	This session introduced participants to modeling carbon capture and storage in the delta of Kern Region, and carbon neutrality, capture and storage public service announcement.
Day 5	Wrap up: This session summarizes the activities related to the curriculum. Unit Planning: During this session participants develop their Unit Plans where they explain how they will integrate the education resources and tools they learned about throughout the week.