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Professional development design considerations in climate change education: teacher enactment and student learning

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ABSTRACT

Climate change is one of the most pressing challenges facing society, and climate change educational models are emerging in response. This study investigates the implementation and enactment of a climate change professional development (PD) model for science educators and its impact on student learning. Using an intrinsic case study methodology, we focused analytic attention on how one teacher made particular pedagogical and content decisions, and the implications for student's conceptual learning. Using anthropological theories of conceptual travel, we traced salient ideas through instructional delivery and into student reasoning. Analysis showed that students gained an increased understanding of the enhanced greenhouse effect and the implications of human activity on this enhanced effect at statistically significant levels and with moderate effect sizes. However, students demonstrated a limited, though non-significant gain on the likely effects of climate change. Student reasoning on the tangible actions to deal with these problems also remained underdeveloped, reflecting omissions in both PD and teacher enactment. We discuss implications for the emerging field of climate change education.

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Climate change; conceptual travel; professional development; learning outcomes

Introduction

Anthropogenic climate change is one of the most important and urgent of issues facing humanity (Intergovernmental Panel on Climate Change, 2013; Pope Francis, 2015). Climate change is considered a 'super wicked problem' of human creation, with time to fashion solutions and mitigate damage dwindling (Levin, Cashore, Bernstein, & Auld, 2012). Solving such difficult problems involves changing future selves via collective policy levers capable of incrementally shifting established norms (Levin et al., 2012). Many nations are beginning to address climate change across a number of sectors despite considerable pushback from status quo forces (Farrell, 2016). The educational sector has an important role in addressing this issue, because educational institutions are crucial spaces for alternative norm development, and thus the creation of alternative future selves (Long, 2011; O'Connor & Allen, 2010). The research presented here focuses empirical attention on the development of climate change education, an

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emerging area of educational inquiry and practice (Henderson, Long, Berger, Russell, & Drewes, 2017).

The educational response to climate change is highly uneven given its nascent nature, with recent research showing a patchwork of responses leading to differing levels of enactment and uptake (Colston & Ivey, 2015; Lee, Markowitz, Howe, Ko, & Leiserowitz, 2015; Plutzer et al., 2016). Nevertheless, new educational models are beginning to emerge as educators work to engage climate change by shifting norms and practices (Bangay & Blum, 2010; Holthius, Lotan, Saltzman, Mastandrea, & Wild, 2014; Shea, Mouza, & Drewes, 2016). The research presented here reports on the design, pedagogical enactment and subsequent effects on student learning of a climate change professional development (PD) model in the United States. We focus attention on how one teacher made specific curricular and pedagogical decisions in light of her participation in climate change PD. In particular, we trace salient climate change concepts from PD through instructional delivery and into evidence of student reasoning by addressing the following related research questions:

(1) How did a middle-school teacher integrate climate change concepts into her science curriculum following PD participation?
(2) How did climate change instruction influence student understanding of key climate change constructs?

Climate change education in the United States

Climate change education models and practice are beginning to emerge globally, with a proliferation of literature describing the contours of this developing global field (e.g. Chang & Pascua, 2017; Henderson et al., 2017; Öhman & Öhman, 2013). Recent comparative research showed that formal education proved the biggest individual predictor of climate change awareness, and this was more common in countries with developed educational systems (Lee et al., 2015). Climate change education patterns are emerging but remain variegated both globally (Lee et al., 2015), and within smaller geographic units (Colston & Ivey, 2015; Plutzer et al., 2016; Wise, 2010). In this article, we focus empirical attention on climate change education within the United States' educational system as one example of an emerging form.

The United States administers educational policy using a federalist model, whereby individual states retain their own constitutional authority to enact educational policy. This system produces geographic and cultural variability in educational programming broadly and works to differentially shape how climate change education emerges (or not). While some states such as New York and Maryland, for example, have included climate change principles in standards and curriculum for some time, others have omitted them entirely, often for political reasons (Plutzer et al., 2016). The recent development of the *Next Generation Science Standards* (NGSS Lead States, 2013), however, represents a national attempt to standardise science curricular topics and pedagogical approaches across state boundaries toward shared common educational goals in science education. NGSS writers, working from current scientific evidence, included mention of climate change for the first time in the national science standards for the United States. However, the topic of climate change only explicitly appears in one middle school and four high-school standards within the domain of Earth and Space Sciences. More proximally related climate change concepts, such as energy transfer from the sun and the cycling of carbon, are found throughout all grade bands (Hestness, McDonald, Breslyn, McGinnis, & Mouza, 2014; NGSS Lead States, 2013).

Importantly, climate change is absent in other subject area reforms and science education is currently the dominant vehicle for climate change education in the United States (Plutzer et al., 2016). Although formal adoption of NGSS by individual states has been sluggish, a recent large-scale and geographic survey of American science teachers found that the majority of the participants were addressing climate change in some capacity (Plutzer et al., 2016). Teachers' practices, however, were highly variable in their enactment, even within states that had formally adopted NGSS (Colston & Ivey, 2015; Henderson, Trauth-Nare, & Drewes, 2017; Monroe, Oxarart, & Plate, 2013; Sullivan, Ledley, Lynds, & Gold, 2014; Wise, 2010).

The variable implementation of climate science instruction could be partly attributed to the varying depth of teacher disciplinary knowledge and preparation (Arslan, Cigdemoglu, & Moseley, 2012; Hestness et al., 2014; Holthius et al., 2014). Prior education research has shown that teachers are often not privy to climate science in their own educational backgrounds, and that this lack of familiarity presents challenges to instruction (Porter, Weaver, & Raptis, 2012; Pruneau, Gravel, Bourque, & Langis, 2003). Science teachers in the United States, for instance, are typically credentialed as discipline specialists, with biology as the most common focus (NRC, 2012). Earth science, a more natural home for climate change, remains a relatively minor area of disciplinary focus even for states with formal earth science programmes (McNeal, 2010).

In addition to disciplinary constraints, teachers also face a challenging emotional and political context given the charged discourse that accompanies conversations about future conditions (Hung, 2014; Lombardi & Sinatra, 2013; O'Neill & Nicholson-Cole, 2009). As a result, addressing climate change means that teachers must make contextual decisions to integrate this relatively complex body of scientific knowledge into their school curricula. Two-thirds of a nationally representative sample of geoscience educators across the United States expressed interest in PD opportunities 'entirely focused on climate change' (Plutzer et al., 2016, p. 665). To help promote scientifically sound instruction and decision-making, continuous, effective PD on climate change is essential.

Teacher PD on climate change

Teacher PD is the best route to helping teachers improve their professional knowledge and alter their classroom practice to promote higher student achievement (Ball & Cohen, 1999; Wilson, 2013). Despite the wide availability of PD opportunities for science teachers, there remains a shortage of programmes that exhibit key elements of effective PD and focus explicitly on climate change phenomena. Specifically, research indicates that high-quality teacher PD is characterised by focus on content knowledge, proximity to practice, and a consideration of the context and policies surrounding teacher work (Luft & Hewson, 2014; Penuel, Fishman, Yamaguchi, & Gallagher, 2007).

According to Luft and Hewson (2014), science PD has unique requirements in terms of content. In particular, PD with a focus on the knowledge that a teacher needs to teach a specific science topic or the knowledge students should learn has the potential to enhance teacher content knowledge. Teachers who are more comfortable with the content are more likely to allow for student questioning and discussion, which are key components of high-quality science instruction (Penuel et al., 2007). Regarding climate change, several studies have found that teachers have an insufficient grasp of the content, which in turn hinders effective teaching (Plutzer et al., 2016; Shea et al., 2016; Teed & Franco, 2014). Specifically, many teachers are not aware of the scientific consensus around anthropogenic climate change, and as a result they may focus on scientifically unsupported claims. Plutzer et al. (2016) emphasise the need to improve teachers' knowledge of climate science to help them distinguish well-supported evidence from scientifically uncertain evidence. To help teachers provide more scientifically sound instruction, teacher knowledge development should also focus on common student misconceptions articulated in the literature, such as the confusion between climate and weather and the belief that climate change is caused directly by the ozone hole (Arslan et al., 2012; Choi, Niyogi, Shepardson, & Charusombat, 2010; Lambert, Lindgren, & Bleicher, 2012).

In addition to building content knowledge, PD designed with proximity to practice in mind is more likely to translate into changes in classroom practice and subsequent desired student outcomes (Penuel et al., 2007). Teachers engage in PD in ways that cohere with their own experience, the norms and expectations of their school, and in conversation with curricular concepts (Allen & Penuel, 2015). Articulating lessons learned from their PD efforts, Johnson et al. (2008) found that teachers have a critical need for credible climate science content and age-appropriate hands-on activities that focus on local perspectives and not just global averages.

When considering how climate change relates to their own practice, teachers should also recognise the emotional responses to the issue that they hold personally and that are held by their students (Lombardi & Sinatra, 2013; Ojala, 2012). When teachers avoid discussing these affective components in an effort to minimise controversy, they may miss out on meaningful connections, deeper personal engagement, and improved emotional perspectives on the issue (Hufnagel, 2015). In fact, teachers report a desire to incorporate science lessons that integrate personal and social connections to introduce actions individuals can take which may have positive impact on their communities (Griffith & Brem, 2004; Lester, Ma, Lee, & Lambert, 2006; Rooney-Varga, Brisk, Adams, Shuldman, & Rath, 2014). Employing climate change instruction with a local framing of the issue and a consideration of the learners' emotions can encourage feelings of agency which in turn may promote action as opposed to despair (Busch, 2016). To foster changes in classroom practice, PD programmes should then attend to those identified pedagogical and emotional needs as they specifically relate to climate change.

Finally, effective PD should consider the overall context and policies surrounding teacher practice. For instance, teachers' background knowledge and frames for making sense of policies as well as other practical constraints (e.g. schools schedules, resources, time for planning) are likely to influence classroom practice (Penuel et al., 2007). Further, the social context of schools also influences teachers' decisions on whether to enact or resist particular innovations (Rivet, 2006). If teachers consider PD to be aligned with their district's goals and the overall social context of their school, they will be more likely to transfer their new learning into practice (Penuel et al., 2007).

While existing literature has extrapolated key principles of effective PD, empirical research examining the interactions among evidence-based PD, changes in teacher knowledge and practice, and subsequent student outcomes is still scarce and inconclusive (e.g. Garet, Heppen, Walters, Smith, & Yang, 2016). As a result, more research is needed to identify the characteristics of climate change focused PD that prepares teachers to understand and explain the science accurately to their students. Such research should also make connections to classroom enactment and subsequent student outcomes. In this work, we address this gap via an intrinsic case study analysis (Stake, 1995) of one teacher's decisions as she navigates climate change PD, designs, and then enacts a unique form of climate change education in her science class. By sharing this process and its effects on student learning in rich descriptive depth, we intend to help both researchers and practitioners leverage important insights that facilitate the design of effective climate education instructional models.

Theoretical framework: conceptual mobility

Climate change facts are always socialised within cultural and material contexts (Callison, 2014). Climate change concepts are salient (or not) depending on the sociocultural norms of particular communities. The contextualisation of climate change concepts is especially complex given the local and global scalar issues at work. Climate change theory is a global scientific idea that is caused by and manifests in the daily actions of individuals working together as a collective (Edwards, 2010). We can say that someone learns climate change when the idea is appropriately scaled to their specific educational context. Nespor (2004) refers to such learning processes as 'educational scaling' whereby students come into relationship with larger and more distant (both spatially and temporally) social and material phenomenon. While students are coming into relationship with concepts, people, and objects in educational space and time, they are also navigating the movement of ideas within and between contexts. This movement of ideas has been referred to as *conceptual mobility* (Anderson & Libarkin, 2016; Scollon, 2013).

Educational contexts are imbued with logics that shape social interaction by determining what is or is not allowed to occur according to the dominant contextual norms (Bourdieu, 1977; Foucault, 1977). These spaces are not socially neutral and some actors – especially those in positions of institutional authority like teachers and administrators – have more power than others to shape what happens (Ball, 2012). Teachers occupy a social role as cultural authority in traditional classroom contexts and are therefore differentially powerful actors in educational spaces (Gore, 1995). Teachers' pedagogical and curricular decisions shape how learning occurs and are part of the larger educational ecosystem within which learners contextualise knowledge (Leander, Phillips, & Taylor, 2010). What 'comes to matter' in a classroom setting is influenced, in part, by how teachers enact their own knowledge, thereby moving ideas from one context to another via their pedagogical practice (Ball, Maguire, & Braun, 2012; Ingold, 2016).

Nespor's classic ethnographic study of differences between undergraduate physics and management educational programmes (1994) traced how students and concepts became enrolled in particular trajectories based on the structured decisions of educators shaping educational programmes over time and space. The physics programme, for example, placed cultural value on mathematical texts and mathematical epistemology, thereby disciplining students into a particularly narrow math-centric physics education. Alternatively, educators running the management programme prioritised sociability in their pedagogies and expected students to extend their learning outward into the larger corporate community beyond the institution. In both cases the educational experiences were structured to promote particular ways of knowing and being. Researchers working in engineering (e.g. Stevens, O'Connor, Garrison, Jocuns, & Amos, 2008) and science education (Chaffee, 2016) have also shown examples of how concepts become mobilised by both teachers and students in highly contextualised ways based on cultural and institutional norms.

In this case, climate change concepts are 'mobilized' across space and time, and how this occurs depends on several contextual variables shaping the educational experience (Callison, 2014; Lemke, 2000). As part of this work, we are interested in examining how this process occurs, including which climate change concepts are contextualised, how and why certain concepts are rendered more or less salient, and how they in turn translate into student learning. By tracing this process from PD to pedagogical enactment to student learning outcomes, we hope to describe and further theorise conceptual travel and uptake in an emerging educational space.

Research context

The year-long Climate Academy is a prominent component of a larger federally-funded research effort focused on the implementation of comprehensive climate change education in the Mid-Atlantic region of the United States. The Climate Academy included three primary components: (a) an intensive residential week-long summer institute (46 h); (b) four virtual follow-up sessions on challenging climate change concepts; and (c) two face-to-face follow-up sessions focusing on pedagogical methods for teaching about climate change. Each virtual session was 1.5 h and was conducted using web-conferencing software. Each face-to-face session was 4 h and took place in a convenient geographic location. Thus, the Climate Academy provided a total of 64 h of PD.

The design of the Climate Academy was a collaborative effort among climate scientists, learning scientists, teacher educators, practitioners, and policy stakeholders. This cross-disciplinary design team sought to create a PD experience that deepened participating teachers' understanding of climate change content while providing pedagogical support and resources necessary to implement climate education within each teacher's unique setting. Given this overarching goal, the Climate Academy was designed around three core elements supported by the literature: science content, proximity to practice, and a consideration of the context and policies of the participants' states and local environment.

Science content of the Climate Academy

The Climate Academy explicitly addressed content that has been found challenging for teachers and students. This content was organised in four strands: causal human activities, greenhouse effect mechanisms, consequences (effects), and mitigation and adaptation strategies. The focus on causal human activities and greenhouse effect was intended to help participants understand the evidence of anthropogenic climate change. The literature indicates that both teachers and students hold a number of misconceptions around these topics and thus addressing them explicitly was critical for effective instruction (Plutzer et al., 2016; Shepardson & Niyogi, 2012). The focus on effects and consequences was important for helping participants understand both local (e.g. sea level rise) and global (e.g. melting of the glaciers and changing ocean currents) impacts. Finally, the introduction of various approaches to mitigation and adaptation was intended to help participants engage with solution oriented strategies, including engineering solutions, such as novel applications of alternative energy sources or carbon recapture technology that could help mitigate the impacts of climate change.

While there was some overlap in focus, looking across all components of the Climate Academy the amount of time dedicated to each of these four constructs was calculated. The causal human activity and greenhouse effect mechanism constructs governed large proportions of the PD (35.4% and 26.6%, respectively). These topics were covered extensively both during the residential week-long institute and the virtual follow-up sessions. Effects of climate change was covered during 23.0% of the time, while mitigation and adaptation strategies was only emphasised in 15.0% of the PD hours and mostly in the follow-up face-to-face sessions.

Proximity to practice

All PD activities were designed with proximity to practice in mind. Specially, the PD modelled standards-based pedagogical activities that teachers expected to implement with their own students. Many activities included hands-on investigations where participants directly engaged with data, conducted experiments, and worked on inquiry-based outdoor activities demonstrating the effects of climate on one's local context. For example, each morning of the summer residential institute, an interactive demonstration was set up to engage teachers in developing an understanding of topics such as the thermal expansion of water. These 'morning challenges' over breakfast were used to initiate in-depth conversations of content knowledge development and instructional practice using an evidence-based approach throughout the rest of the day. During other morning and afternoon sessions, teachers participated in activities such as an outdoor field trip to explore local microclimates and hands-on modelling of the impact of climate change on ocean currents.

To facilitate stronger connections between learning and practice, participating teachers worked alone or in small teams to design an implementation plan that was specific to their grade level, science curriculum, and individual classroom needs. Throughout the Climate Academy, participants were provided with ample time and opportunities to create and reflect on their designs and share those instructional ideas with peers. On the last day of the residential summer institute teachers participated in a gallery walk of their drafted implementation plans to gather peer feedback. Additionally, at each of the six follow-up PD sessions, a collective sharing called 'Tales from the Field' was incorporated to promote a supportive professional learning environment that focused on teacher practice.

Contextual considerations

The Climate Academy was designed to specifically address context both in terms of participants' local environment but also considering standards and state policies. For instance, the participants' states are among the early adopters of NGSS, thus providing a fruitful context for the implementation of climate change education. During the Climate Academy, participants became familiar with the content and pedagogical demands of the new standards. They also had opportunities to hear from state stakeholders regarding rollout plans of NGSS in the participants' states and efforts to create curricula aligned with the new standards. The PD facilitators (which included members of the research team) developed sessions that specifically sought to incorporate information about how NGSS adoption and local connections to climate change issues would impact future instruction.

Methodology

Our study leverages a mixed-methods instrumental case study design (Stake, 1995). We use Stake's instrumental case study because we are interested in examining the conceptual mobility phenomenon in depth. This single case study sought to explore which climate change concepts became salient to a teacher and her students following participation in the Climate Academy and how they travelled from PD to student learning. We sought out detailed and varied data from diverse sources rich in context from all three stages of the experience (Creswell, 2007): the teacher's learning during PD, her teaching back in her classroom, and the students' learning as it was influenced by that instruction. By examining one case in depth we aim to explicate broader considerations for the general phenomenon of climate change education.

Participant

Our work focuses on Emma,[1] a sixth-grade teacher who was a participant in the Climate Academy. From a total of 27 teachers attending the Climate Academy, we selected Emma as a focal case for three reasons. First, as often typical of middle-school teachers, she exhibited little prior knowledge of climate change prior to her participation in the Climate Academy as measured by a content knowledge assessment given to all teacher participants. Yet, Emma demonstrated increased engagement with the PD sessions and materials throughout the Climate Academy. Second, she taught in a public charter school located close to an urban area, which served a racially and socio-economically diverse population of students. More than half of Emma's students identify as Hispanic, while about 25% are White and about 15% are African American. Finally, Emma's school was located in proximity to our research team, which allowed for in-depth and sustained data collection.

Data collection

Data were collected from multiple sources at each of the three phases of our study, including the Climate Academy, teacher instructional experience, and student learning.

Climate Academy artefacts

During the Climate Academy, we engaged as active participant observers, both taking field notes and interacting with participating teachers as they engaged in PD activities. For several of the PD activities, we acted as the primary facilitator based on our educational expertise (e.g. integration of technology-based climate activities or approaches to classroom formative assessment). In addition, we collected daily reflections where all participants reflected on what was learned, articulated remaining questions, and noted additional supports needed. Finally, we collected the implementation plans developed by all participants during the residential summer institute. For the purposes of this work, we only utilised data collected from our case study participant, including her daily reflections and plans for instructional implementation. In an effort to minimise observer bias, we sought to triangulate our data sources (i.e. implementation plans, reflections) and acted as observers when not facilitating sessions.

Teacher instructional experience

In addition to artefacts collected during the Climate Academy, the lead author conducted classroom observations for a period of two weeks, documenting Emma's integration of climate change into her existing instruction on Earth's history and geologic time scale through field notes and the collection of relevant student work products. To gain a better understanding of Emma's decision-making related to her instruction, we also conducted interviews with her both pre- and post-instruction. Interview questions focused on the following topics: (a) goals and objectives of Emma's instructional unit designed during the Climate Academy; (b) resources needed to implement the instructional unit; (c) alignment between Emma's instructional unit and NGSS practices; (d) expectations for student learning outcomes; and (e) challenges expected and encountered. To improve the authenticity of the observations and our own interpretations, during the post-instruction interview the lead author engaged in member check to better understand Emma's pedagogical decisions.

Student learning outcomes

To document student outcomes, we developed a content knowledge assessment around the four key constructs of climate change addressed in the Academy: greenhouse effect mechanism, impacts of human activity, local and global effects, and mitigation and adaptation efforts (Drewes et al., 2017). Example items for each of the four key constructs can be found in the Appendix. The assessment was developed in collaboration with climate research specialists and learning scientists through an iterative process, which included expert review of the content and face validity, followed by the appropriate revisions requested. Moreover, middle- and high-school teachers from the prior year's Climate Academy cohort reviewed the assessment for clarity of language. Again, revisions in vocabulary and content were made to reflect teachers' input. The final assessment instrument utilised in this work included 18 multiple-choice items, representing different levels of achievement. These multiple-choice items were also accompanied by a prompt that asked students to explain their choice in order to gain in-depth insight into student thinking. It was administered to students ($N = 42$) both before and after the implementation of Emma's instruction unit.

Both the pre- and post-instruction content knowledge assessment included short answer written response prompts so students could demonstrate their reasoning beyond the basic multiple-choice selection. Specifically, students were asked to provide a qualitative justification for 'why your choice is the best answer.' We collected both pre- and post-instruction justifications to examine potential changes that could be attributed to Emma's instructional unit. For the purposes of this work, we examine student qualitative responses to two questions that focused on the primary cause and effect mechanism involved in climate change science: the role of human activity. These questions read:

> There is strong evidence that there is more CO_2 (carbon dioxide) in the atmosphere now than in the past several hundred years. What is most likely cause of the current increase in carbon dioxide?
>
> a. There's more toxic chemicals in the oceans and rivers.
>
> b. Plants are releasing more CO_2 (carbon dioxide).
>
> c. Volcanoes are producing more ash and gases.
>
> d. *Humans are using more fossil fuels.*
>
> If humans continue to release carbon dioxide (CO_2) into the atmosphere at the current rate, ecosystems may be damaged or destroyed. Which of the following actions can reduce the amount of CO_2 released by humans?
>
> a. Produce less nuclear power
>
> b. *Drive cars less often*
>
> c. Use fossil fuel more
>
> d. Decrease littering

In addition to the reliability and validity efforts instituted during the assessment design, we also sought to validate the content assessment through classical test theory approaches. Employing both split-half analysis and Cronbach's coefficient alpha, the assessment was deemed to be satisfactorily internally consistent. The coefficient alpha value for all 18 multiple-choice items was .803 which exceeds the .70 recommended value but remains below the .90 value which would indicate an overly homogeneous assessment instrument (Allen & Yen, 2002). Additionally, the mean difficulty index and the mean discrimination index of the entire instrument were calculated (.70 and .52, respectively) and were within the appropriate interpretation guidelines put forth by statistics and measurement texts (e.g. Allen & Yen, 2002; Ebel, 1954). These guidelines demonstrate that the assessment was well designed to function as intended to reasonably demonstrate and discriminate between varying levels of student knowledge on the four key climate concepts (Drewes et al., 2017).

Analysis

Climate Academy artefacts and teacher instructional experience

An abductive analytic approach was implemented to examine qualitative documents collected from the Climate Academy and Emma's instructional delivery (Tavory & Timmermans, 2014). Specifically, we first used an etic coding scheme built around the four key climate change conceptual constructs that served as the focus of the Climate Academy to conduct content analysis (Miles & Huberman, 1994). This allowed us to determine the relative frequency and salience given to each of the four content codes of: (1) mechanism, (2) human activity, (3) climate change effects, and (4) mitigation/adaptation (Drewes et al., 2017). The first author coded the artefact corpus according to the four pre-established conceptual domains. Following advice from Anfara, Brown, and Mangione (2002), subsequent team members then checked, corroborated, challenged, and/or clarified the original coding to lend dependability to the analysis. Initial findings from this stage of the analysis were triangulated against additional data sources (e.g. Academy agenda and presentations, informal discussion with PD facilitators, Emma's lesson plan, observation notes from Emma's instruction) to lend further credibility to the overall findings.

Student learning outcomes

Multiple-choice content assessment items were analysed quantitatively to compare student performance gains resulting from Emma's instructional unit. In addition to examining student understanding of the four constructs, we have also analysed the assessment as a whole. Student scores were matched prior to post-instruction, therefore dependent samples t-tests were employed. Holm's sequential Bonferroni procedure was employed to correct for the familywise error due to the testing of multiple hypotheses (i.e. the multiple dependent samples t-tests). Holm's sequential Bonferroni procedure is much preferred to the widely employed, though overly conservative Bonferroni procedure due to a 'non-negligible increase of power' (Holm, 1979) while maintaining the simplicity of its calculation (Aickin & Gensler, 1996; McLaughlin & Sainani, 2014). Effect sizes were calculated utilising the Lipsey–Wilson calculator for paired samples (Lipsey & Wilson, 1993) and interpreted via Cohen's d guidelines for instructional effect (Cohen, 1992).

Student open response justification items were analysed qualitatively to determine potential changes following targeted instruction. To analyse these data, we collaboratively categorised student open-ended responses for each question to identify pre- and post-patterns and to uncover emergent themes within the pre-existing four conceptual domains (Miles & Huberman, 1994). Similar to the aforementioned qualitative analysis of teacher and PD artefacts, research team members corroborated and challenged initial coding to lend dependability (Anfara et al., 2002). Findings from this stage were also triangulated against additional data sources for credibility purposes. Finally, we have identified specific student excerpts that exemplify those emergent themes.

Findings

In this section, we present the findings of the study. First, we examine Emma's learning and enactment of climate change education in her sixth-grade classroom during her participation in the Climate Academy. In particular, we highlight how content and pedagogical practices introduced in the PD travelled to Emma's classroom. Finally, we investigate student outcomes based on Emma's instructional practice.

Emma's learning during the Climate Academy

Emma was a novice middle-school science teacher who joined the Climate Academy to improve her knowledge of climate change. When asked to explain why she chose to attend the Climate Academy, she noted:

> I wanted to further my learning/knowledge of climate change. I am the lead science teacher at my school so I hope to bring what I experience from this Academy back to my school to help teachers implement climate science education.

Emma also indicated that her students were interested in the topic but lacked awareness of the importance or scale of the issue as well as access to resources for learning more about the topic. Further, Emma acknowledged that although the topic was not prominent in the existing science curriculum she expected it to become more salient with the implementation of NGSS in her state.

In her daily reflections, Emma acknowledged that she improved her knowledge of the carbon cycle while gaining understanding of how scientists track CO_2 levels in Earth's past, using proxy data from ice cores and tree rings. Specifically, she felt more comfortable with how to analyse climate science data, graphing CO_2 data over very broad time scales, and the role that significant historical events, like evolution of land plants or ice ages, had on CO_2 levels as methods to provide scientific evidence for climate change. These activities were modelled during the residential summer institute, where teachers moved from station to station to engage as science learners.

In addition, Emma acknowledged gaining a better understanding of ice melt and thermal expansion through a series of daily morning challenges introduced in the residential summer institute. Emma remarked about the value of interactive lab demonstrations on how changing ocean currents are influenced by temperature and density on her understanding of thermal expansion. As Emma noted, through simple labs, these abstract or geographically distant concepts were made clearer for her. Finally, Emma indicated that she learned about potential responses to climate change, including mitigation strategies such as examining how small personal impacts could lead to bigger changes through a cascading flow when employed across a larger scale to reduce greenhouse gas emissions.

From a pedagogical standpoint, Emma indicated that she gained a deeper appreciation of the role of outdoor activities for experiencing climate change first hand. She also gained a deeper understanding of NGSS, the role of climate change in the new standards, and potential resources for implementation in middle-school classrooms. Finally, she recognised the importance of empowering students to act to set a positive tone when discussing climate change.

Emma's instructional enactment

Prior to joining the Climate Academy, Emma reported that she has attempted to infuse climate change into two science units, one on watersheds and the other on Earth's geological history. Both units were core components of the state curriculum that Emma expected to cover in her class albeit the infusion of climate change was not a requirement. During her participation in the residential summer institute, Emma focused her efforts on the design of an instructional unit that infused climate change into Earth's History. Specifically, Emma's overarching goal focused on having students understand how we can use

Earth's geological scale to understand and track carbon dioxide through Earth's history. She wanted to focus primarily on investigating and comparing changes in carbon dioxide levels over vast periods of times (10,000 years or more) and more recently since the Industrial Revolution. This focus was similar to an activity that Emma experienced in the summer institute where participants engaged with data demonstrating Earth's carbon dioxide through time, including an understanding of how scientists gather evidence of carbon dioxide levels in the atmosphere from Mauna Loa, from fossil records, and from ice core samples. Explaining the reason behind her decision during her first interview, Emma noted:

> Honestly it was a struggle trying to infuse climate change in my curriculum in the first place because Earth's History is so focused on rocks and just the past and not so much about going into the future. And there is obviously no mention at all about climate change in this unit. So, that's why I think the focus on the rising atmospheric CO_2 levels and its pervasive effects on Earth's system stood out to me. A big piece of the Earth's History unit is mapping time, measuring time and seeing how things have changed and the sequence of that. So, that was to be the best fit and then to kind of incorporate the climate change within that.

As part of the unit, Emma began with lessons on the difference between weather and climate and the carbon cycle. Explaining her decision Emma noted:

> We will start with what is climate because some students may not even know what weather is compared to climate. So, then we'll go into what climate is and will piece those together, and then the whole graphs over time. The last piece would be: *okay, now having that information about carbon how will this affect us?* That will lead to the discussion of climate change and the influences and impacts it is going to have on our Earth today and in the future and maybe some problem-solving aspects.

This instructional sequence described by Emma was similar to the activities she experienced in the residential summer institute of the Climate Academy where climate scientists helped participants understand these concepts through brief lectures, analysis of data, and hands-on investigations.

Emma's assessment of her students' prior knowledge served her well. Reflecting on the implementation of her unit in the post interview she noted:

> The biggest challenge overall is my students' prior knowledge of climate change. For example, some students did not know the difference between weather and climate. Others thought the global warming simply meant the Earth is only heating up. Others thought that climate change was caused by the ozone hole. Diving into these ideas and building a base knowledge was how I overcame this challenge. This is why I engaged in the KWL activity (What do you *know* – What would you *want* to learn – What did you *learn*). I wanted to explore what students know and also rate their understanding. I actually got this activity from the Climate Academy and it was really helpful because I was able to see that a lot of them [students] were coming in with ideas that they had probably heard on the news or home.

Following instruction on the difference between weather and climate and the carbon cycle, Emma introduced ice melt and thermal expansion to make a connection with the melting of the glaciers and sea level rise because of warmer temperatures. She concluded the unit with an argumentative activity using concept cartoons, where groups of students chose different perspectives, conducted their own research, and discussed the strengths and weaknesses of that position. The concept cartoon was modelled during a hands-on investigation at the residential summer institute, but Emma modified it to connect more broadly to the causes of climate change and to address the naïve understandings held initially by her students. Explaining her decision Emma noted:

> With the argumentation activity, I really wanted to make connections to NGSS, because in other science units there is almost no opportunity for arguing. These skills are important and are aligned with what our students are learning in social studies right now. I just felt that you know sometimes with science you just have to judge things and you have to know what to believe or what not to believe and how to use evidence to do that.

Finally, based on her students' interests, instruction also incorporated some discussion on the effects of climate change both locally and globally, but this discussion was limited in scope. As Emma noted, due to time constraints little instructional time was devoted to developing strong connections between the climate change effects and approaches to mitigation and adaptation to decrease the influence of these effects. During that time, Emma introduced personal changes, like driving less and planting trees, that her students could take to influence their own carbon footprint. Yet, broader connections to large-scale efforts were not observed.

Student learning outcomes

Multiple-choice items

As shown on Tables 1 and 2, results from the multiple-choice items indicated that students improved their overall understanding of climate change constructs. Out of 18 possible points, on average students scored 8.6 points on the pre-assessment compared to 10.2 points on the post-assessment ($t = 4.138$, $df = 41$, $p = .001$). The effect size is moderate (Cohen, 1992, $d = 0.49$) and represents a moderate difference between the two time periods. Specifically, students showed statistically significant improvements in their understanding of the greenhouse effect mechanisms and the role of human activity even after the *post hoc* correction for familywise errors using the Holm's sequential Bonferroni procedure. The changes in these two key constructs also reflected a moderate effect size. Results, however, indicated a non-statistically significant change in the climate change construct of local and global effects and a positive, though not statistically significant improvement on the construct of mitigation and adaptation strategies.

Open response assessment items

Results from the analysis of student open-ended responses revealed a small but marked shift toward a more accurate and complex understanding of the human mechanisms causing climate change and what might be done to mitigate the effect of those causes.

Table 1. Means and SD for student multiple-choice items.

Test section	Points possible	Pre-test Mean	Pre-test SD	Post-test Mean	Post-test SD
Overall	18	8.60	2.84	10.17	3.36
Causal human activity impacts	6	2.93	1.33	3.64	1.26
Greenhouse effect mechanism	4	1.52	1.04	2.14	1.10
Mitigation and adaptation strategies	4	1.67	0.90	2.02	1.22
Climate change effects	4	2.48	1.04	2.36	1.12

Note: $N = 42$; SD: standard deviation.

Table 2. Dependent samples *t*-test results.

	Average point gain	*t* value	Unadjusted *p*	Holm threshold	Statistical significance?	Paired *r* value	Cohen's *d*
Test overall	1.57	4.138	.001	.010	Significant	.701	.49
Causal human activity impacts	.71	3.941	.001	.0125	Significant	.592	.55
Greenhouse effect mechanism	.62	2.623	.012	.017	Significant	−.024	.58
Mitigation and adaptation strategies	.36	1.858	.070	.025	Not significant	.340	n/a
Climate change effects	−.12	−.616	.542	.050	Not significant	.342	n/a

Note: $N = 42$; Holm Threshold is the sequentially calculated alpha significance value.

For example, one student, Andrew, initially believed that nuclear power was 'going into the atmosphere and damaging the ozone layer' but later came to understand that cars were a main cause of CO_2 in the atmosphere because 'when fossil fuels are burned, they turn into CO_2.' In general students updated incorrect or partial conceptualizations of how humans were impacting the atmosphere and were then able to translate that understanding into tangible suggestions. Another student, Marguerite, could link climate change to the 'huge increase in CO_2 levels [that] began when the Industrial Revolution started, which means that humans are releasing many fossil fuels which is causing the [temperature] increase.'

We observed multiple mentions of human fossil fuel activity and the period of Industrialisation in post responses reflecting Emma's decision to frame climate change within the scope of human evolution and Earth's history. By situating climate change across time in this fashion, students were able to examine how humans both today and in the past were contributing to climate change. Although the question narrowly deals with climate change via automobile emissions, a few students were able to make broader connections to other human activities. For example, Ricardo linked auto emissions and the need to make different decisions to reduce impact:

> Most of the CO_2 in the earth's atmosphere is from the CO_2 from human activities. And one of the main reasons is gasses are produced from transportation mechanisms like cars. Driving cars or any vehicles less often and promoting public transportation as well as using bikes or walking to nearby areas will help reduce CO_2 production.

This amount of detail in a response was atypical. Most students recognised that driving a vehicle was a source of carbon dioxide in the atmosphere, but could not move beyond cars as example. A few, like Ricardo, could, but they were outliers. Again, we see the result of both Emma's and the Climate Academy's decisions to frame climate change in a particular way. While causes and mechanisms were foregrounded, what to actually *do* to change these human activities remained in the background and out of focus.

In summary, results from student content assessment indicated that students improved their understanding of the greenhouse effect and how this mechanism led to global temperature changes. These developments correspond to the instructional emphasis of Earth's history and changing atmospheric CO_2 levels. Results, however, indicated small differences in the climate change constructs on effects and mitigation and adaptation strategies. These outcomes correspond to the lack of instructional emphasis on these constructs by the teacher. Yet, students did substantially move away from the common misconception of connecting ozone depletion to anthropogenically-enhanced greenhouse effect, a topic that was introduced in passing but then was covered explicitly as a response to specific initial student thinking as demonstrated on the pre-assessment.

Discussion

Climate change science is complex and multifaceted, spanning a disciplinary terrain that includes at least palaeontology, geology, chemistry, physics, oceanography, and ecology. Climate change concepts are beginning to emerge in both teacher PD (e.g. Holthius et al., 2014; Shea et al., 2016) and in pedagogical practice (e.g. Busch, 2016; Plutzer et al., 2016), but examples of how teachers formulate and implement particular concepts into curricular decisions and the effect on student learning are sparse. Our project involves a deep dive into the specific details of one case in order to understand which climate change topics were culturally salient and travelled from PD to classroom enactment and then onward to student learning. By explicating these details, we hope that other researchers will continue broader work to consider the nuance involved in establishing the field of climate change education. In this section, we discuss the importance of our main findings and interpret their importance for future professional action.

Our data supports three primary findings. First, both during and after the Climate Academy PD, Emma integrated new climate change science information into her pre-existing knowledge and understanding. Emma originally exhibited limited content knowledge as a result of climate change not being incorporated during her teacher preparation, which is the case for many science teachers (Holthius et al., 2014; Shea et al., 2016). Participation in PD helped Emma make connections between new climate change knowledge and her existing Earth's History curriculum and to utilise instructional activities modelled during the Climate Academy. The development of her implementation plan reflected her specific school context and student curricular needs – a specific goal of the Climate Academy as a tenet of high-quality PD (Luft & Hewson, 2014; Penuel et al., 2007). The Climate Academy's design allowed space for teacher variation within their specific context, thereby giving Emma the professional agency to develop a 'locally adaptive' climate change curriculum for her students (Barab & Luehmann, 2003).

Second, the design of the PD foregrounded the causes, mechanisms and likely effects of anthropogenic climate change at the expense of mitigation and adaptation strategies, and this differentially shaped Emma's knowledge, what came to matter to her, and how she enacted climate change instruction. The design of the PD also emphasised a proximity to practice, which helped Emma translate the climate change knowledge and activities to effective classroom pedagogy. We see evidence of this conceptual salience in Emma's lesson plan, in her classroom implementation, and in subsequent student assessment data. While we were able to track the conceptual travel of certain topics, they remained limited to the causal domains of climate change and left students with few avenues for future action to actually deal with the issue.

Third and overall, we found that, at least in this case, climate change science education – from PD to implementation to student learning – preferences the scientific 'is' over an imagined future 'ought' (Hume, 1739/2003). The structure of the PD coupled with Emma's own intellectual trajectory produced a form of climate change science education that foregrounded the causal mechanisms and their environmental effects. What to actually *do* about the issue remained in the background by everyone across the educational experience. This differential treatment of scientific concepts could be attributed to the culturally and politically polarised nature of climate change (Kahan et al., 2012). Moving away from a strict focus on the science of climate change would require a shift into the realm of values, emotions, culture, morals and politics for the purposes of social change (Busch, 2016; Sharma, 2012; Sinatra, Kardash, Taasoobshirazi, & Lombardi, 2012). This remains a challenging terrain in science classrooms (Colston & Vadjunec, 2015; Long, 2011). Yet, it could leave students with only a partial understanding of the mechanistic causes of issue and miss an opportunity to leverage a more agentive form of science education (Sharma, 2012). Luckily, the NGSS aims to attend to this disconnect via design and engineering principles. The incorporation of engineering allows for learning 'to solve problems for a purpose' (Moore, Tank, Glancy, & Kersten, 2015, p. 298). As such, they could encourage student engagement with climate change mitigation and adaptation strategies.

Conclusion and implications

Our study contributes to a burgeoning literature in climate change education. Using a detailed case study approach, we showed how one teacher, Emma, integrated climate change concepts into her existing pedagogical experiences and curriculum. This mirrors recent findings that show teachers find places to knit climate change into their existing practice regardless, and sometimes in spite, of formal policy directives (Colston & Ivey, 2015; Plutzer et al., 2016; Wise, 2010). We observed a flexible approach to the design of the Climate Academy that afforded Emma space and agency so that she could translate specific climate concepts into her local practice. She was therefore able to make sense of new content knowledge as it related to both her own lived experience and her curricular requirements.

We also observed conceptual travel from the PD to artefacts of student learning that reflected the instructional priorities of the PD designers to preference the causes and likely effects of climate change. Such an approach was a limited operationalisation of climate change science education, as mitigation and adaptation strategies remained in the background across both PD and classroom practice and therefore also in student reasoning. We suggest that our study shows evidence of a larger issue in science education: teaching scientific fundamentals while shying away from advocating particular responses to the implications of these scientific realities. This phenomenon has begun to be explored through the recognition that learning about controversial issues like climate change must move beyond mere acquisition of knowledge (Griffith & Brem, 2004; Svihla & Linn, 2012; Tasquier, Levrini, & Dillon, 2016). Instead, it necessitates a local, personal, and often emotional connection on a pathway to social activism (Herman, 2015; Lester et al., 2006; Pruneau et al., 2003; Rooney-Varga et al., 2014; Sinatra et al., 2012). Yet, this is an issue that the science education community needs to address more widely and an area for future conceptual and empirical investigation: *how to prepare teachers to move toward scientifically-informed social action in science education classrooms?*

Our work is of interest to the education community in its efforts to address a complex science topic included for the first time in nationwide science standards here in the United States. Detailed studies tracing PD to student learning through teacher implementation are needed to provide descriptive detail to identify not only potential frictions but also areas of growth and opportunity in educational settings. Similar to Tasquier et al. (2016) and

Holthius et al. (2014), our results indicate that students remained unclear following instruction about what to actually do about climate change given their newfound scientific knowledge. We believe that this uncertainty was an artefact of how climate change was presented in both the Climate Academy PD and subsequent teacher implementation. We echo the call of other climate change educational researchers (e.g. Herman, 2015; Lester et al., 2006; Sinatra et al., 2012) that science educators need strategies for moving beyond teaching the state of knowledge toward an action-oriented stance that provides students with the tools for mitigating and adapting to the problem. A climate change education that merely presents causes and effects of climate change will remain of limited import and unable to address the nature of the problem in its totality.

Note

1. Names of all research participants are pseudonyms.

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Appendix

Example items for the four key climate change constructs

Construct	Assessment item
Greenhouse effect mechanism	17. Which of the following activities will lead to future intense storms? a. Ozone layer depletion b. Changes in the tilt of Earth's axis c. Variations in the energy put out by the Sun d. *Heat trapped by increased greenhouse gases*
Causal human activity impacts	5. There is strong evidence that there is more CO_2 (carbon dioxide) in the atmosphere now than in the past several hundred years. What is most likely cause of the current increase in carbon dioxide? a. There's more toxic chemicals in the oceans and rivers. b. Plants are releasing more CO_2 (carbon dioxide). c. Volcanoes are producing more ash and gases. d. *Humans are using more fossil fuels*.
Climate change effects	6. Likely outcomes of climate change are: a. Ice sheets will grow larger in the Arctic areas. b. The temperature will rise equally around the world. c. *Ocean levels will rise, impacting people who live on the coast*. d. Earth's atmosphere will thin, especially in the Southern Hemisphere.
Mitigation and adaptation strategies	13. Data collected by scientists indicate that the average global temperature is rising and will continue to rise in the foreseeable future. What actions could people in your community take to reduce the negative impacts of climate change? a. Buy organic produce like fruits and vegetables. b. Prevent litter and pollution from entering rivers and oceans. c. *Plant more trees or reduce the number of trees being cut down*. d. Banning chemicals that break down ozone in the earth's ozone layer.