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# Exploring Modeling as a Context to Support Content Integration for Chemistry and Earth Science

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**ABSTRACT:** Rarely are scientific phenomena isolated to a single discipline such as biology, chemistry, physics, Earth science, or others. Rather, these phenomena span multiple disciplines and often require bringing together content and understandings from multiple disciplines to engage with or explain the target phenomena. This study uses a model-based explanations framework to explore high school students' abilities to integrate science content from the disciplines of chemistry and Earth science within the context of generating models to explain a local phenomenon—the urban heat island effect. Students experienced a multiweek instructional unit as part of a larger integrated curriculum that brings together chemistry and Earth science content and features local phenomena to engage students in the scientific practice of modeling. Quantitative and qualitative findings from this study demonstrate students' emerging proficiency with integrating science content, practices, and crosscutting concepts to explain a phenomenon. Students' model-based explanations tended to include phenomenon-relevant components (e.g., physical features of the phenomenon) and sequences (e.g., cause−effect relationships), but tended to include relatively fewer explanatory mechanisms. Implications related to the utility of modeling as a practice-based venue for integrating content from diverse science disciplines are also discussed.

**KEYWORDS:** *High School/Introductory Chemistry, Interdisciplinary/Multidisciplinary, Inquiry-Based/Discovery Learning, Student-Centered Learning, Chemical Education Research*

**FEATURE:** Chemical Education Research



## INTRODUCTION

Citizens are being asked to make ever more complex and pivotal decisions related to scientific issues that have far reaching impacts on society and the environment. What are appropriate individual and society responses and actions related to a global pandemic? What are the potential costs and benefits of additional oil pipelines? How can humans reduce our impact on Earth systems? What does a sustainable energy future look like? Stakeholders can pose evidence-based answers to each of these questions that are quickly rebutted by others with counter-evidence and counter-arguments. Nevertheless, these are the challenging questions we wish to prepare current and future generations to answer and hope that strong scientific literacy is a contributing factor in the push toward solving these complex problems. Key to navigating these challenges is a deep understanding of science concepts drawn from a variety of disciplines. When considering complex science phenomena impacting society, it is difficult and at times arbitrary to classify the phenomena within a single scientific discipline. The global phenomenon of climate change has, for example, connections to climate science that would appear in a typical Earth science curriculum, and connections to the products and reactants of chemical processes and reactions that would appear in a typical chemistry curriculum.[1] In this way, many scientific phenomena are inherently interdisciplinary and require the coordination of multiple disciplines for a more complete understanding. While chemistry may be referred to as the "central science" there are rarely opportunities for students to connect chemistry to other science disciplines.[2] Therefore, using engaging phenomena to anchor school science curricula allows students opportunities to bring together concepts from multiple disciplines to reinforce and deepen learning and promote the development of their broader scientific literacy and see cross-disciplinary connections.[1,2]

## BACKGROUND

The Framework for K-12 Science Education[3] and the Next Generation Science Standards[4] encourage the use of phenomena-based instruction to engage students in relevant and meaningful learning experiences. The structure of the NGSS is grounded in a three-dimensional approach that brings together disciplinary core ideas, crosscutting concepts, and science and engineering practices that support such a phenomena-based approach. Further, the disciplinary core ideas of NGSS are drawn from life science, physical science, and Earth science, while the crosscutting concepts and science

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and engineering practices span these domains, which in part supports content integration. In this way, the current policy documents related to US science education are consistent with promoting and supporting an integrated approach to students' development of scientific literacy to aid in addressing pressing scientific issues. This structure of the standards encounters challenges, however, in the practical context of high school science education.[5] Specifically, most states, districts, or schools tend to offer a three-year course sequence comprising biology, chemistry, and physics. Thus, two competing factors complicate implementation of the NGSS: (1) the standards subsume chemistry and physics within a single domain of physical science,[6] yet schools offer two separate courses; and, (2) the standards specifically emphasize Earth science, which is rarely offered at the high school level.[6,7] These two factors contribute to the siloing of Earth science and physical science, whereas NGSS reform seeks to bring content areas together. With the increasing adoption and implementation of the NGSS across states, school districts are faced with the challenge of addressing the life science, physical science, and Earth science disciplinary core ideas within systems that typically do not offer Earth science courses.[6,7] In response, many districts have taken an integrated approach that brings Earth science core ideas and performance expectations into more traditionally offered courses such as biology, physics, or chemistry.

The challenge of integrating seemingly disparate disciplines within the context of NGSS can be supported through a focus on crosscutting concepts, which have the potential to serve as a lens for viewing, understanding, and helping shape explanations of phenomena. Given the complexity of integrated phenomena, the crosscutting concept "systems and system models" has particular relevance.[8] Identifying a system of interest within a broader, more complex phenomenon is often useful in helping to isolate relationships of the specific system while also considering how matter or energy moves into or out of the system. When considering phenomena at the intersection of chemistry and Earth science, students are afforded the opportunity to engage in this type of systems thinking, particularly with respect to environmental sustainability and the interactions between natural and human systems.[9,10] Using a systems-based approach contextualizes chemistry content from an ecocentric perspective that engages students with relevant problems that establish a need for actually learning core chemistry content.[9] Within systems thinking literature, a system is described as a model that includes (a) components or parts, (b) interconnections between those components, and (c) a purpose[2,11] as well as understanding that phenomena are positioned within broader contexts. Embracing systems thinking perspectives can be useful for organizing curricula and learning experiences. However, essential to this approach is providing opportunities for students to make their understandings of various systems visible through the use of science practices. Creating models is one such approach well suited for thinking about systems.

Developing and using models is one of eight science and engineering practices identified within the NGSS.[4] Scientific models are defined as diagrams, drawings, physical replicas, mathematical representations, analogies, and computer simulations that serve as tools for representing scientific ideas and explanations.[12] Engaging students in modeling practices and model-based reasoning has been shown to support students' development of conceptual understanding of phenomena[13−15] as well as support students' linking aspects of the phenomena through cause−effect relationships.[16] Similar to systems thinking frameworks, such as the systems thinking hierarchical model,[10] the model-based explanations framework[14,16] suggests evaluating students' models based on the inclusion of components, sequences, and explanations, which align to the components, interconnections, and purpose aspects related to systems thinking. In this way, when students develop a model of a phenomenon, they are identifying the aspects of the system and how those aspects interact to contribute to the observed phenomenon. Thus, the model is intended to help students understand and interpret complex systems.[2]

Classroom environments that bring together integrated content knowledge, crosscutting concepts such as "systems," systems thinking, and science practices such as modeling, can be established pedagogical approaches that emphasize engaging phenomena as an instructional feature.[2,17] This approach to learning is typified by three-dimensional strategies from NGSS reform goals that integrate the dimensions of disciplinary core ideas, crosscutting concepts, and science and engineering practices.[18,19] The National Science Teaching Association further endorses the use of three-dimensional teaching and learning, suggesting that classrooms and curricula that center on three-dimensional lessons and units actively engage students in the practices of science (e.g., collecting and analyzing data, and developing and refining models) to support students' development of deeper and more meaningful understanding of core disciplinary content[13,18,20] and broader crosscutting concepts such as systems and cause and effect relationships. Modeling scientific phenomena at the intersection of chemistry and Earth science provides a venue for students to illustrate connections between macro- and microscale processes, while also emphasizing the interconnections among scientific disciplines. Research literature suggests that students are able to create meaningful models, but often need additional support when integrating content domains within the practice of modeling.[21]

In the context of the current study, modeling the urban heat island phenomena (the observation of relatively warmer temperatures in urban areas compared to nearby suburban or rural areas) serves as an opportunity for students to connect microprocesses of energy absorption related to properties of matter for different materials, based on specific heat or surface albedo, or energy transfer through photosynthetic or transpiration processes, to more cumulative macroprocesses of differential heating and cooling within an urban setting or geographic region. This curricular focus on an engaging and locally relevant phenomenon brings together chemistry and Earth science core ideas and crosscutting concepts, within the practice of creating scientific models. Therefore, the students' creation of scientific models within a science classroom serves as an approach to three-dimensional teaching and learning by bringing together one or more disciplinary core ideas, crosscutting concepts, and science practices.[13] We contend that modeling also serves as a venue for content integration when core ideas from different science disciplines (e.g., chemistry and Earth science) are brought together in coordination to explain a scientific phenomenon.

## THEORETICAL FRAMEWORK

This study is grounded in constructivist views of learning, whereby students develop understanding through the active process of connecting their existing scientific knowledge with


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ideas that emerge during new experiences. In this way, learning involves students interacting with their physical and social surroundings.[22,23] This view of learning is operationalized within this study by providing students opportunities to bring together their initial ideas and those introduced through the curricular experiences to develop understanding of a particular phenomenon, which is then illustrated via a student-created model. The phenomenon-based modeling task allows students to engage with disciplinary core ideas, crosscutting concepts, and science practices to support the process of integrating new and existing ideas to articulate how they understand the modeled phenomenon to occur.[16] Additionally, modeling as a science practice allows students' thinking to become visible through the various components and sequences included within the models which further illustrate the connections students are constructing between key aspects of the modeled phenomenon. To further support students in building connections, the learning experience centers on a phenomenon drawn from students' local environment. The use of a locally relevant phenomenon builds on students' lived experiences and helps connect classroom learning experiences with their day-to-day understanding of the local phenomenon. The locally relevant phenomenon has the potential to motivate students to engage in the coordination or equilibration of new data and ideas developed during curricular activities with their own personal understanding and first-hand experiences with the phenomenon to build stronger connections.[19]

## ■ PURPOSE

In response to state adoption of NGSS, a large mid-Atlantic school district has developed a new high school chemistry curriculum that integrates Earth science and chemistry content. The curriculum leverages locally relevant phenomena that incorporate chemistry and Earth science core ideas to engage students in three-dimensional learning experiences with an emphasis on modeling practices. The purpose of this study is to investigate students' thinking related to integrated chemistry and Earth science involving complex phenomenon through the science practice of modeling.

### Research Questions

The data collected as part of this study address the following research question:

In what ways do students incorporate components, sequences, and explanatory features in models of local scientific phenomena at the intersection of chemistry and Earth science?

## ■ METHODS

This exploratory study was completed as part of a larger, three-year project to develop and implement a new integrated chemistry and Earth science curriculum for the district's high school chemistry course. While the course is being implemented throughout the school district, the present data were drawn from the classrooms of development team teachers (DTTs). These teachers engaged in curriculum development activities during the school year to help test and refine the new integrated curriculum. As part of their curriculum implementation efforts, DTTs also agreed to provide classroom artifacts to the research team for analysis purposes. Given various logistical constraints and challenges associated with the district context—specifically, student attendance and the consent/assent process—the data set consists of 76 student models of the urban heat island phenomena collected from across the classrooms of the six participating DTTs, which represents approximately 20% of students in those classrooms. These models represent a one-time snapshot of students' thinking near the end of the target instructional unit. A subset of approximately 15% of the students ($n$ = 12) from across the DTT classrooms, also provided initial models that served as matched pre/postunit model pairs for additional analyses.

### Participants

This study was conducted in a large-urban school district in the Eastern US. The district serves over 20,000 high school students and is a majority−minority district with the student body comprising 77% African American students, 14% Hispanic/Latinx students, and 8% White students. The student participants in this study are representative of the district as a whole. Data for this study were collected and are shared in a manner consistent with the consent/assent protocols of the managing institutional review board under which this study was conducted.

### Instructional Context

As described above, the partner school district where this study was conducted is amidst a systemic reform effort to develop and implement, district-wide, a new integrated curriculum that brings together chemistry and Earth science core ideas and performance expectations to align their district courses and curriculum with the state's recent adoption of the NGSS. Previously, the district did not offer Earth science as a standalone course at the high school level, so like other districts, chose to develop an integrated curriculum to address the content of the Standards and meet the needs of all district students.

The resulting curriculum is broken into seven smaller units with each unit bringing together chemistry and Earth science content to support the integrated experience. The curriculum includes units that address typical chemistry content, such as properties of matter, chemical reactions, stoichiometry, etc. The focal unit for this study is unit 6, Thermochemistry, which incorporates NGSS disciplinary core ideas related to energy (e.g., HS-PS3) and systems (e.g., HS-ESS2). The overarching question for this unit is *What determines the temperature in [our city]?* During the four-week unit, students explore more traditional chemistry topics, such as endo/exothermic processes, calorimetry, specific heat, and energy transfer (conduction, convection, radiation). These topics are further contextualized and also addressed within the context of the urban heat island (UHI) phenomena. The school district is located in a high-density urban setting that regularly experiences the impacts of the urban heat island phenomena, that has resulted in early release days from school due to high temperatures in school buildings.

Earth science and chemistry ideas are addressed in the unit within this UHI context. A series of lessons in the unit supports students' exploration of heat wave data from urban and rural locations within their hometown, students collect temperature data of various surfaces and materials within their school yard to make connections with surface albedo, properties of materials, and evaporative cooling. The unit also includes investigations related to heat capacity of urban building materials (e.g., brick, concrete, stone). Throughout these experiences, students develop various models and arguments to help explain connections between the chemistry of their city and the UHI phenomenon.


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**Components**

| Level | Descriptor |
|---|---|
| **0** | No relevant components included |
| **1** | One component involving energy (e.g., energy source, energy arrows of incoming radiation or internal energy of an object) OR<br>One component involving Earth system (e.g., bodies of water, Earth surface layer, plant life, atmosphere) OR<br>One component of anthropogenic effects (e.g., buildings, cars, industrial activity) |
| **2** | More than one component from any combination of categories (energy, Earth system, anthropogenic) |
| **3** | At least one component from each of the three categories (energy, Earth system, anthropogenic) |

**Sequences**

| Level | Descriptor |
|---|---|
| **0** | No sequences included |
| **1** | Includes one sequence (link between two components) involving absorption (e.g., Sun's energy absorbed by buildings/objects/bodies of water, photosynthesis in plants) or reflection (e.g., off buildings or natural surfaces) or radiation (e.g., conduction, convection, objects/materials emitting thermal energy |
| **2** | Includes two different sequences from two different categories of either absorption, reflection, radiation |
| **3** | Includes three different sequences, at least one from each absorption, reflection, radiation |

**Explanations**

| Level | Descriptor |
|---|---|
| **0** | No links between sequences |
| **1** | *General*: different materials absorb, reflect, transfer, or radiate energy differently (e.g., differences between buildings and trees; differences in color of objects) |
| **2** | *Properties of matter*: differences in absorption, reflection, transfer, and radiation of energy influence the temperature of objects (compares temp of diff. color objects., compares temp of natural materials versus human-made materials) |
| **3** | *Energy cycling*: energy interactions between natural and human-made systems exacerbate warming and cooling processes by creating imbalances in incoming/outgoing energy within the system and result in warming or cooling |

**Figure 1.** Model-based explanation rubric, specific to urban heat island phenomenon.

## Data Collection and Analysis

Data for the present study are derived from student models generated pre- and postunit to explain the urban heat island phenomenon. Students completed an initial model, prior to the instructional unit, where they were asked to show how energy flows into and out of an urban system (visualized by an urban landscape) and how energy is transferred within the system. Near the conclusion of the instructional unit, students once again completed a model to explain how the temperature of their city is impacted by the features of the city leading to the UHI phenomenon.

## Model-Based Explanations Analysis Framework

Our analysis of the students' models was shaped by the model-based explanations framework.[14,16] Within this study, students were tasked with developing a model that accounts for why their city becomes so hot. Zangori and Forbes[14] suggest that models demonstrating an understanding of a phenomenon with explanatory power, depict the essential "elements, relationships, and connections of the phenomenon" according to the model-based explanations framework (p. 963). In this way, the models illustrate the students' conceptual understanding and link the concrete and observable aspects of the phenomenon with theoretical and mechanistic processes that drive the phenomenon. According to the model-based explanations framework, there are three key aspects of explanatory models: components, sequences, and explanatory process. Zangori and Forbes[14] describe those aspects as follows: components are the elements represented within the model; sequences are the recognition of connections and relationships between the represented elements; and explanatory processes are the causal mechanisms underlying represented cause and effects. This analytic framework also reinforces the theoretical framework guiding the study by providing a focus on how the students' model representations of a phenomenon illustrate the progressive building of ideas from base level or intuitive aspects of the phenomenon (e.g., components) to more sophisticated aspects of the phenomenon (e.g., sequences and explanations).[22,23]

In the present study, students' models were scored using a rubric developed by the authors based on the model-based explanations framework.[16] The rubric was divided into three subscales reflecting the components, sequences, and explanations aspects of this framework (see Figure 1). These subscales are also aligned to the systems thinking literature with regard to students identifying relevant components, interconnections, and purposes of various systems.[10] For this study, *components* are considered words, images, or symbols used as a piece or aspect of the model-based explanation (e.g., buildings, roads, green space). Sequences are cause and effect relationships demonstrating a linkage between two or more components (e.g., energy flow, absorption, reflection).


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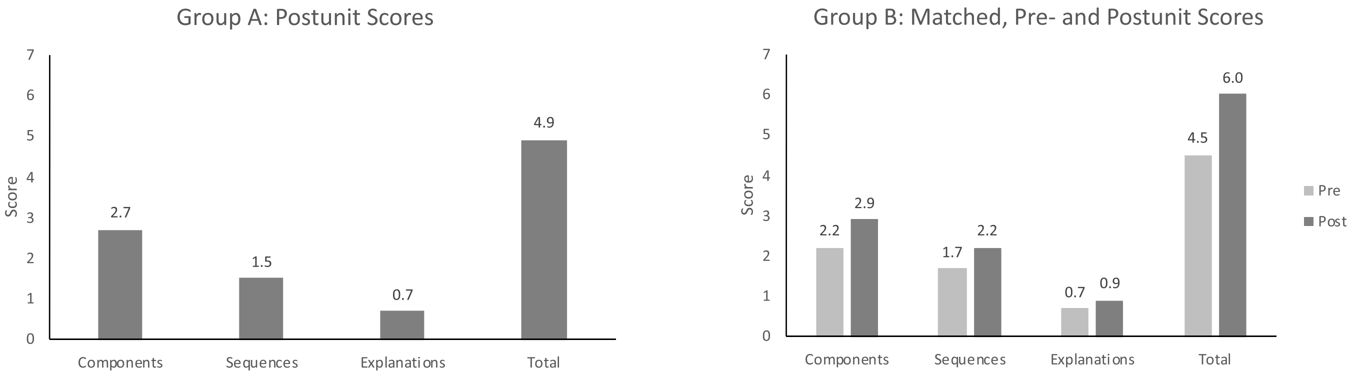


**Figure 2.** Model-based explanation scores for all postunit models (Group A, $n$ = 76) and matched pre- and postunit models (Group B, $n$ = 12).

Explanations are multiple sequences linked together generating the model's explanatory power (e.g., different properties of matter).[24] Each subscore was criterion-reference scored along a three-point scale. A 20% sample of the collected learning artifacts was used to assess the validity of the rubric's scoring criteria. Interrater reliability was calculated using an intraclass correlation ($ICC_{components}$ = 0.920; $ICC_{sequences}$ = 0.955; $ICC_{explanation}$ = 1.00), which indicated strong reliability of the rubric and agreement between raters.[25] Student assessment scores were then entered and analyzed using SPSS software to conduct descriptive analyses and parametric and nonparametric tests to assess changes in scores from pre- to postunit as well as differences in subscale performance when creating models.

## ■ RESULTS

### Student Performance on Modeling Task

Two separate analyses were conducted using the model data sets. The Group A data set ($n$ = 76) included postunit UHI models from the end of the unit 6 lesson sequence; the Group B data set ($n$ = 12) includes a subset of students from Group A that also provided matched, preunit UHI models. Figure 2 shows the average scores for the components, sequences, and explanation scores for each group based on the relevant data collection time point.

The distribution of scores for the postunit models within Group A suggest different performances across the subscales associated with the model-based explanations framework used for analyses. Paired samples $t$ tests were conducted within Group A to determine any potential difference between the subscales (see Table 1). The differences between each subscale score within Group A was small, but statistically significant, indicating that students scored highest on the components subscale, followed by the sequences subscale, and finally the explanation subscale.

Prior to conducting similar analyses within Group B, we first compared the average scores from the larger Group A data set with the smaller Group B data set that represented matched pre- and postunit models. Using a nonparametric Mann−Whitney test to compare the postunit models of Group A as a whole and the subset that forms Group B, there were small but significant differences in the overall score ($Z$ = −2.75, $p$ < 0.01) and on the sequences subscale specifically ($Z$ = −3.06, $p$ < 0.01). Like Group A, the pattern in scores across the subscales for Group B was similar to statistically significant differences between each subscale (see Table 2) indicating that students scored highest on the components subscale, followed by the sequences subscale, and finally the explanation subscale. Taken together, this analysis suggests reasonably similar performance of the Group B subset to the larger whole of Group A.

Additional analyses were conducted within Group B to determine any potential differences between the pre- and postunit scores. Given the sample size associated with Group B, a nonparametric Wilcoxon signed-rank test was conducted to compare student scores pre (M = 4.5) and postunit (M = 6.0). Students' scores on the model-based explanation task improved overall by 1.5 points (17%). This improvement on the postunit models was statistically significant and represented a moderate effect, $Z$ = −2.3, $p$ = 0.02, $r$ = 0.66. Follow-up pairwise comparisons at the subscale level illustrate that the overall significant growth on the model-based explanation task is most attributable to significant growth on the component subscale ($Z$ = −3.0, $p$ < 0.01, $r$ = 0.87), while raw scores moved in a positive direction for the sequence and explanation subscales those changes were not statistically significant.

**Table 1. Pairwise Comparisons of Model-Based Explanation Subscales for All Postunit Models within Group A**

| | Comparison by Subscale ($n$ = 76) | |
|---|---|---|
| Subscale | Components[a] | Sequences[a] |
| Sequences | $t(75)$ = 12.78 | |
| Explanations | $t(75)$ = 19.58 | $t(75)$ = 7.75 |

[a]Paired-samples $t$-test; $p$ < 0.001.

**Table 2. Pairwise Comparisons of Model-Based Explanation Subscales for Matched Pre- and Postunit Models within Group B**

| | Comparison by Subscale ($n$ = 12) | | | |
|---|---|---|---|---|
| | Components[a] | | Sequences[a] | |
| Subscale | $Z$ | $p$ | $Z$ | $p$ |
| Preunit | | | | |
| Sequences | −2.12 | 0.03 | | |
| Explanations | −2.81 | 0.01 | −2.24 | 0.03 |
| Postunit | | | | |
| Sequences | −2.46 | 0.01 | | |
| Explanations | −3.27 | <0.01 | −2.88 | <0.01 |

[a]Nonparametric Wilcoxon signed-rank test.



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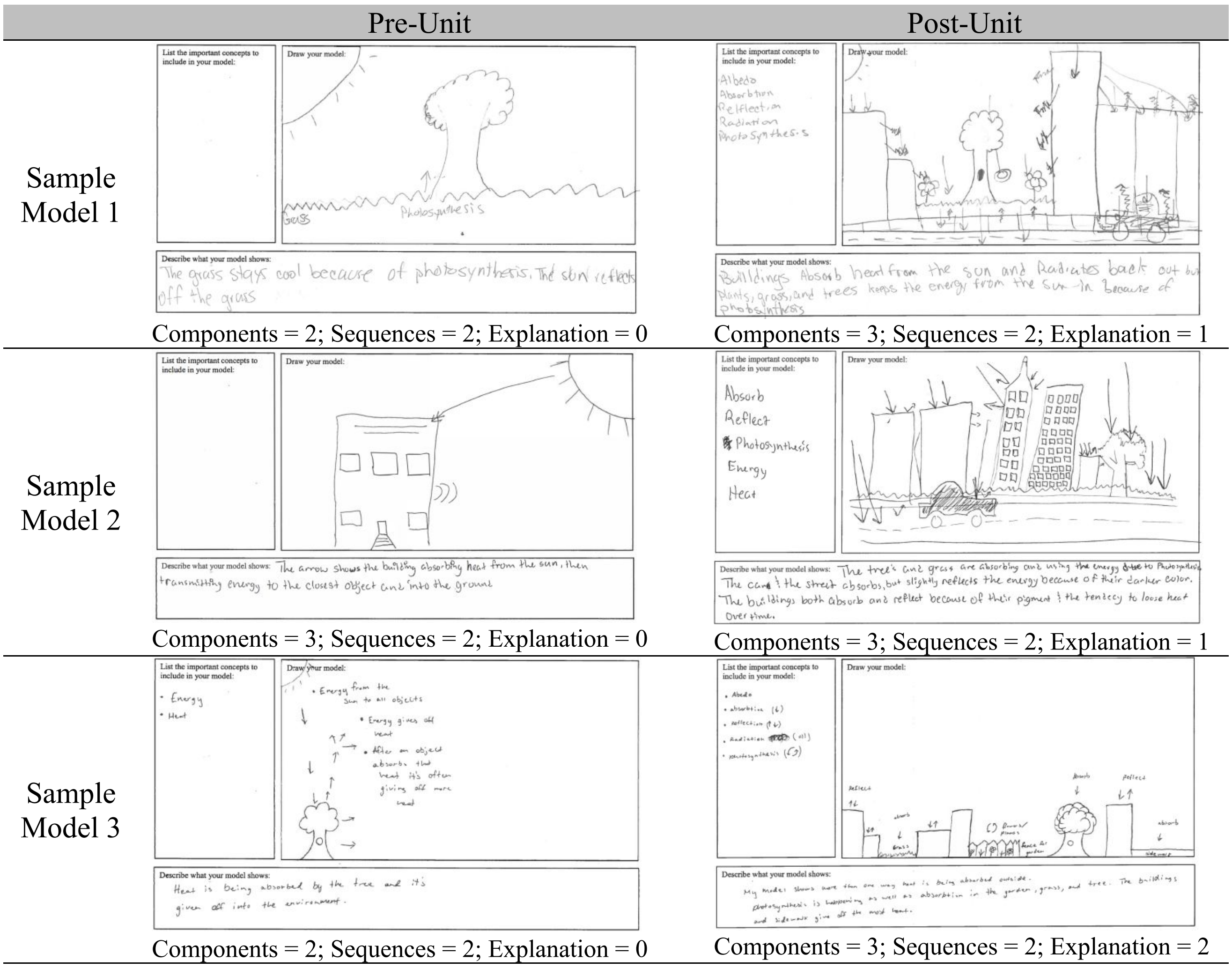


**Figure 3.** Pre- and postunit sample models from three students with subscale scores identified.

## Modeling and Content Integration

The sample models in Figure 3 illustrate the types of models that students created when explaining the impact of the UHI phenomena and what makes their city so hot. Each of these individual models demonstrate students relatively strong ability to identify the various components of the UHI phenomenon (e.g., an energy source, Earth system component, and/or human system component) and increasing difficultly identifying cause-effect relationships (e.g., energy processes—absorption, reflection, emission, radiation, or transfer), and explanatory mechanisms within their models (e.g., general differential behavior of materials, specific properties of matter influencing energy processes, or interactions between Earth and human systems). In each of the postunit models, students were able to identify components of the UHI phenomenon from each of the three general component categories. With regard to sequences, or cause-effect relationships, students' postmodels tended to include increased numbers of relationships, which are often illustrated via arrows representing different energy processes. These increasing numbers of arrows, while perhaps simplistic on the surface, suggest that students have developed increased understanding of how heat energy interacts with a variety of surface and material types. Typically, preinstruction models are descriptive with little explanatory power; these models do not offer a mechanism for different temperatures of objects or how/why their urban surroundings might become hot. However, the postinstruction models have a tendency to include some indication of differing behavior of the Earth or human system components based on their properties. For example, students illustrate higher energy absorption by darker objects (and state such in their written descriptions—see sample 2) and less energy or sunlight reflected off those objects. Similarly, darker or solid surface objects are associated with energy radiation (often indicated by a "squiggly" arrow), which suggests different energy interactions or properties between hard and soft surfaces. Finally, students do not associate high levels of reflection or radiation with Earth system components such as trees or grass and indicate those components absorb energy to be used in the chemical process of photosynthesis.

One of the goals of the curriculum unit was to provide students opportunities to bring together their understanding of chemistry content and Earth science content to explain a local phenomenon. The sample models in Figure 3 illustrate students' emerging connections between the cause−effect relationships they identified with the properties of matter linked to those relationships. The students point out that the color or pigment of a material or a material's "tendency to loose [sic] heat over time" (sample model 2, postunit) are related to the way that the material absorbs or reflects heat


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energy. The students stop short of providing more microscale explanations of why that may be or how atomic structure connects to those macro-scale observations. Further, students recognize the different ways that energy interacts with natural or Earth system components and human-system materials. In this way, students are beginning to demonstrate interconnections between Earth and human systems and the ways that humans impact broader Earth systems such as climate, local temperature, and the ways that energy moves within a complex system. Yet again, students stop short of explaining the interconnections of these systems from a total "energy budget" perspective with regard to a balance of energy-in and energy-out of the observed system. While not a direct corollary, there are opportunities for stronger connections to energy transfer concepts typically addressed within chemistry activities that feature calorimetry or conservation of energy topics.

## ■ LIMITATIONS

The results of this study should be considered with respect to their potential limitations. The findings presented here were derived from an instructional context situated within a large urban center and featured a local phenomenon that may not have broader applicability in other contexts. Phenomena-based instruction, should leverage local phenomena to support student motivation and engagement. While the UHI phenomenon served that purpose within this study, it may not serve as an equally engaging phenomenon across diverse contexts, where the UHI effect is not observed as part of some students' lived experiences. In those situations, there are likely other relevant local phenomena that would have a similar appeal with applicability to those students' lived experiences. Therefore, students engaging in modeling activities around UHI within contexts where that phenomenon is not observed, may or may not exhibit similar results as this study. Additionally, we acknowledge that such contextual factors coupled with a relatively small sample size may not result in broad scale generalizations of the findings of this study. However, it is important to note that locally relevant phenomena are key to increased student engagement, thus what is perhaps a limitation of this study is also an essential feature for meaningful curricula.

## ■ DISCUSSION

The students in this study were provided opportunities to integrate their understanding of chemistry topics and Earth science topics in the context of model-based explanations of the urban heat island phenomenon as part of the school district's efforts at implementing NGSS-related reforms. In doing so, students had an authentic platform to link constructs together to make sense of a complex phenomenon, constructing a scientific explanation to parts of their lived experience in the city. On the basis of quantitative analyses, students in this study, specifically those in Group B, demonstrated significant improvement in their model-based explanations over the span of the curriculum unit. Similar to other studies centered on practice-oriented three-dimensional interventions, students did well to identify components and sequences, the more basic features of the modeling practice[14,16] – analogous to providing a simple claim or single piece of supporting evidence in an argument—but struggled in comparison to include strong explanatory power of the UHI phenomenon within their models. This finding within a model-based explanation context is consistent with results across the modeling literature,[13,15,24] the work of Zangori et al.[14,16] specifically, and is not all that different from other interventions based on science practices. Particularly, in practice-based interventions that emphasize scientific argumentation, students often do well to propose claims and use supporting evidence, but lag in their ability to include high-quality reasoning or justifications for their arguments.[26−28] In this way, explanatory aspects of models and justification within a scientific argument serve similar purposes of connecting students' ideas back to broader guiding principles of the disciplines. However, these parallels highlight challenges of three-dimensional and practice-based pedagogies that seek to engage students in the work of scientists, via practices, while also connecting to the broader content of the science disciplines. Students in this study were able to successfully engage in practices as a way to describe a phenomenon; however, explicitly articulating the underlying scientific theories, laws, or properties that serve as mechanisms for understanding particular phenomenon is considerably more challenging. In other words, students demonstrated greater proficiency in identifying the various components, but struggled more with the conceptual linkages needed to ascend to a great systems-level approach in making meaning of the phenomenon. We also note that the students tended to not include key aspects related to systems thinking such as the articulation of feedback loops or the nested nature of components of the target phenomenon.[9] Thus, additional instructional attention should be paid to encouraging students to consider the iterative and cyclical effects of system components and sequences that can build explanatory power and further refine their systems-level thinking.

A particularly powerful aspect of this study was the use of a locally relevant phenomenon. The urban heat island effect is very real to the students of this school district. It is not uncommon for students to receive early release days from school due to extreme temperatures, which is exacerbated by many of the districts' schools not having air conditioning in the buildings. The authentic phenomenon represented by the UHI allowed students to connect their own intuitive knowledge about how and why the city heats up to more scientific explanations related to energy absorption, reflection, and radiation, which supports students in the construction of scientific ideas on top of their initial or existing knowledge and personal experiences.[22] It is well-known that wearing lighter color clothing can help mitigate the effects of being outdoors in direct sun. So, while students likely know or have experienced this similar phenomenon, there may not be an accompanying scientific explanation for why dark and light clothing have different impacts on body temperature. However, students are then able to connect this knowledge from their personal experience to their UHI explanations by referring to the role of "pigment" in bricks absorbing heat or illustrating how light and dark colored cars heat up differently through the processes of reflection or absorption. In this way when phenomena are purposefully chosen to engage students with connections to their existing knowledge, it provides a clear access point for learning and an entry point for connecting new science ideas to more informal, experiential, or intuitive understanding.[22,23]

Another contextual aspect of this study is the need for schools and districts to craft curriculum to address the disciplinary core ideas embraced by the NGSS, which are


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become more widely adopted across the US. As districts explore strategies for integrating content related to Earth systems, opportunities arise to integrate such content into more traditional and existent course structures. In the curriculum reform effort underway in this study, the district chose to integrate Earth systems content into the high school chemistry course. Through the use of local phenomena at the intersection of chemistry and Earth science, students have begun to integrate aspects of both chemistry and Earth systems thinking to explain interdisciplinary phenomena. The analysis above suggests that students' thinking in this integrated context is just developing as an emerging proficiency, but through continued engagement with integrated content across the secondary science curriculum (e.g., biology, chemistry, physics), signals promise for supporting students' continued development of systems thinking and developing a deeper understanding of the crosscutting concepts across the science disciplines.

## IMPLICATIONS

The present study was conducted within a larger, school district-led effort to develop and implement an integrated Earth science and chemistry curriculum that engages students in three-dimensional learning experiences by leveraging local phenomena. The results of this work suggest an emerging proficiency among students to develop model-based explanations about phenomena. Key to that progress is a curriculum that engages students with personally relevant and meaningful phenomena. While this approach has worked for our team and students within the local district, it is important that broad scale curriculum development efforts remain flexible and adaptable to local contexts in order to support responsive classroom practices.

Further, this study provided students with an opportunity to generate models; however, it is also important to also ensure that students develop an understanding of why they are being asked to create a model. This study provides evidence of students' abilities to identify aspects of a phenomenon through models, but there is little evidence that students' understanding of the purpose of models was enhanced. In this way, students did not necessarily develop metamodeling knowledge.[12,29,30] Science education literature is replete with examples of the need to explicitly teach about the epistemic aspects of scientific knowledge. Likewise, addressing students' metamodeling knowledge is crucial for supporting their development related to the practice of modeling and building their understanding of epistemic commitments of science and models. Additional studies focused on the interplay of students' modeling practices, metamodeling knowledge, and integration of disciplinary content would provide insight for supporting students' growth and development in these areas. Particularly as they relate to critical local phenomena.

It is also well-known that curriculum development and implementation at the scale of a large school district takes considerable time and effort by district staff, teachers, and many times outside contributors such as consultants or researchers—as was the case in this project. Further, it can take multiple rounds of implementation and refinement before positive shifts are realized at the classroom instruction level as well as at the level of student learning outcomes. This study serves to illustrate that even during prolonged reform within a school district, positive student learning and development can occur at the early stages within the implementation process. As such, those early developments serve as guideposts for continued refinement of curricular experiences. During the reform effort, it is also critical to acknowledge the centrality of the classroom teacher in enacting and sustaining the reform process. Teachers are the direct conduit between the goals of the district and the subsequent classroom experiences of the students.[31] Therefore, it is paramount that teachers receive the necessary support and professional learning opportunities to shift their practice to align for the broader reform.

As a community, science educators have a renewed interest and focus on engaging students in learning experiences that integrate multiple disciplines and require students to use science practices when learning science content. This multidimensional approach to teaching and learning is not without challenges from instructional, assessment, and learning perspectives. On the basis of the current study, we suggest that engaging students in practices such as scientific modeling is a fruitful approach for supporting three-dimensional teaching and learning that serves as a productive venue for students to bring together ideas from diverse science disciplines. Using modeling when learning about phenomena helps support students' integration across disciplines. Further, these activities help make students' thinking visible, not only to themselves, but also their peers and teachers. In this way, scientific modeling at the disciplinary boundaries of Earth science and chemistry can serve as a reflexive learning activity and provide insight for responsive instructional practice.

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### Notes

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