Abstract

Title of Document: A PROCESS FOR DEVELOPING AND REVISING A LEARNING PROGRESSION ON SEA LEVEL RISE USING LEARNERS' EXPLANATIONS

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The purpose of this study was to explore the process of developing a learning progression (LP) on constructing explanations about sea level rise. I used a learning progressions theoretical framework informed by the situated cognition learning theory. During this exploration, I explicitly described my decision-making process as I developed and revised a hypothetical learning progression. Correspondingly, my research question was: What is a process by which a hypothetical learning progression on sea level rise is developed into an empirical learning progression using learners' explanations? To answer this question, I used a qualitative descriptive single case study with multiple embedded cases (Yin, 2014) that employed analytic induction (Denzin, 1970) to analyze data collected on middle school learners (grades 6-8). Data sources included written artifacts, classroom observations, and semi-structured interviews. Additionally, I kept a researcher journal to track my thinking about the learning progression throughout the research study.

Using analytic induction to analyze collected data, I developed eight analytic concepts: participant explanation structures varied widely, global warming and ice melt cause sea level rise, participants held alternative conceptions about sea level rise, participants learned about thermal expansion as a fundamental aspect of sea level rise, participants learned to incorporate authentic scientific data, participants' mental models of the ocean

varied widely, sea ice melt contributes to sea level rise, and participants held vague and alternative conceptions about how pollution impacts the ocean. I started with a hypothetical learning progression, gathered empirical data via various sources (especially semi-structured interviews), revised the hypothetical learning progression in response to those data, and ended with an empirical learning progression comprising six levels of learner thinking. As a result of developing an empirically based LP, I was able to compare two learning progressions on the same topic. By comparing my learning progression with the LP in Breslyn, McGinnis, McDonald, and Hestness (2016), I was able to confirm portions of the two learning progressions and explore different possible pathways for learners to achieve progress towards upper anchors of the LPs through targeted instruction. Implications for future LP research, curriculum, instruction, assessment, and policy related to learning progressions are presented.

A PROCESS FOR DEVELOPING AND REVISING A LEARNING PROGRESSION ON SEA LEVEL RISE USING LEARNERS' EXPLANATIONS

By

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Chapter One: Problem Statement

Current reforms in science education are centered upon the recently released Next Generation Science Standards (NGSS; NGSS Lead States, 2013). In turn, the NGSS are based on recent science education research. In particular, the NGSS authors gave learning progressions research a central role (see appendices E & F of the NGSS). The centrality of learning progressions in the NGSS and current science education reform efforts underscores the need for researchers to improve the quality and coherence of learning progressions research.

Science learning progressions are generally defined as descriptions of the increasingly sophisticated ways that learners can think about a science topic over time (Duschl et al., 2007). Many in the science education community currently view them as popular and fashionable educational resources (Duncan & Gotwals, 2015; Duschl, Maeng, & Sezen, 2011; Lehrer & Schauble, 2015; Shavelson, 2009; Smith & Wiser, 2015). Researchers have praised LPs as a potential guide for curriculum development that leads learners towards more sophisticated thinking in both disciplinary practices and content knowledge (Berland & McNeill, 2010; Songer, Kelcey, & Gotwals, 2009). Researchers have also touted LPs as a resource to help teachers use knowledge of learner understanding to make instructional decisions (Alonzo & Steedle, 2008; Berland & McNeill). Additionally, researchers have proclaimed that learning progressions are a “promising” tool for developing meaningful assessments (Alonzo & Steedle; Berland & McNeill). In sum, the science education research community is exploring learning progressions because LPs may have the potential to allow educators to coordinate curriculum, instruction, and assessment in an effective way (Duncan & Hmelo-Silver, 2009; Duschl et al., 2011; Duschl et al., 2007; Shavelson).

However, many researchers have criticized the way that learning progression researchers have studied LPs (Duncan & Gotwals, 2015; Duncan & Hmelo-Silver, 2009;

Duschl et al., 2011; Ford, 2015; Lehrer & Schauble, 2009; Lehrer & Schauble, 2015; Shavelson, 2009; Shea & Duncan, 2013; Sikorski & Hammer, 2010; Hammer & Sikorski, 2015; Smith & Wiser, 2015). For example, Shavelson cautioned that learning progression research is particularly susceptible to "data fitting" as researchers may be tempted to ignore natural variation or individuality in learner thinking. Duncan and Hmelo-Silver identified ambiguity in the methods of validating learning progressions and the notion of "validity" in the context of LP research. Duschl et al. (2011) described a "flurry of competing perspectives" on learning progressions.

Currently, different researchers are using the construct learning progressions in different ways (Berland & McNeill, 2010; Duncan & Gotwals, 2015; Duschl et al., 2011; Lehrer & Schauble, 2015; Shavelson, 2009; Smith & Wiser, 2015). Duschl et al. distinguished between *evolutionary LPs* and *validation LPs*, which differ in regards to the ways that researchers appeared to view conceptual change. Alternatively, Shavelson distinguished between *curriculum and instruction LPs* and *cognition and instruction LPs*. Shavelson explained that researchers begin with a logical analysis of a science topic when developing a curriculum and instruction LP, while they begin with a psychological analysis of cognition when developing a cognition and instruction LP. In contrast, Berland and McNeill explained that some researchers use LPs as "developmental progressions," while others use LPs to mean descriptions of levels of complexity of scientific knowledge and practices. The key distinction between these two perspectives is that the former assumes that LP pathways are developmentally inevitable, while the latter emphasizes the role of instruction (Berland & McNeill).

As the previous discussion makes clear, there are a variety of different ways that researchers are carrying out LP research. There are also a variety of different ways in which researchers are characterizing and classifying LP research. Such diversity underscores the need for researchers to be clear and explicit when sharing their findings with others. Clarity and explicitness will allow the science education community to critique aspects of LP research such as the ways in which researchers are viewing conceptual change, relying on logical/psychological analyses, or considering the psychological development of learners.

Shea and Duncan (2013) identified an important aspect of LP research that remains unclear. The researchers explained that LP researchers have not clearly explained how they have made modifications to learning progressions based on empirical data. A notable exception to this criticism is Alonzo and Steedle (2008), who explained how they used empirical data to make modifications to a learning progression on force and motion. Another exception is Shea and Duncan, who explained how they made modifications to a learning progression on genetics. However, most LP researchers merely present their learning progression products without clearly explicating their thinking as they changed their LP models over time (e.g., Berland & McNeill, 2010; Furtak, 2012; Duncan, Rogat, & Yarden, 2009; Gunckel, Covitt, Salinas, & Anderson, 2012; Jin & Anderson, 2012; Lehrer & Schauble, 2000; Mohan, Chen, & Anderson, 2009; Schwarz et al., 2009; Songer et al., 2009). My study addressed this gap in the literature and provided a clear example of a process by which a researcher can modify a hypothetical LP and begin the process of validation in response to collected data on learner thinking.

Statement of the Problem

The problem that my research study addressed was that LP researchers have not been sufficiently explicit when explaining how they have developed their learning progressions. Specifically, they have not been explicit about how they have made modifications to their learning progressions based on empirical data. LP researchers often present the products of their studies without being clear about how these products were created. These LP products usually take the form of tables describing different levels of learner thinking.

For example, Mohan et al. (2009) presented six different tables describing increasingly complex ways that learners might describe carbon cycling on Earth. Table 1 from Mohan et al. characterized lower level accounts as those that view food or flames as enablers for natural processes in animals and upper level accounts as those that include processes like photosynthesis, respiration, and combustion. Similarly, Table 6 presented examples of learner responses that represented each of the four levels of the learning progression.

Mohan et al. (2009) described the method in which they developed the levels of their LP. The researchers used "exemplar workbooks" based on a stratified random sample of student responses to written assessments. Student responses were transcribed into spreadsheets and sorted. Mohan et al. explained that they sorted student responses based on

> common characteristics, such as how students described and identified materials, whether or not they attempted to conserve matter, and what scales they used in their responses. We grouped and then ordered the responses from least to most sophisticated, allowing us to identify initial patterns. One or two student responses were chosen as representative examples of similar-type responses. We used the patterns and exemplar responses to suggest initial Levels of Achievement. (p. 683)

Mohan et al. then used the exemplar workbooks as the basis for all future LP development, refinement, and validation.

Unfortunately, Mohan et al. (2009) did not analyze the *ways in which participants talked* about carbon cycling (Lehrer & Schauble, 2009). Mohan et al. did not explain to readers how the researchers made judgments about "how students described and identified materials." Additionally, readers do not know how the researchers made decisions about whether or not learners attempted to conserve matter. Finally, readers do not know how Mohan et al. evaluated "what scales [learners] used in their responses." It is concerning that the researchers were unclear about how they interpreted student language during this process, since language use is both culturally and contextually dependent, and this interpretation could be an important focus of debate among researchers (Leach & Scott, 2003).

Gunckel et al. (2012) and Jin and Anderson (2012) described their processes of LP development, refinement, and validation in a similar way. All three of these studies presented examples of student language and how it was analyzed and classified into LP levels *after* the learning progression had been created. However, the researchers failed to explain how they used student language to develop the levels in the first place. Thus, Gunckel et al., Jin and Anderson, and Mohan et al. (2009) all serve as examples of LP research that lacked clarity in terms of how researchers have made decisions about modifications to an LP based on empirical data.

Similar to Mohan et al. (2009), Berland and McNeill (2010) presented a table that clearly defined the characteristics of student argumentation at different levels of complexity and sophistication. However, unlike Mohan et al., Berland and McNeill did not create exemplar workbooks to develop the levels of their learning progression. Rather, the researchers explained that their learning progression was based on both prior research and a logical analysis of the discipline. For example, the researchers wrote,

> As their arguments increase in complexity, we focus on this defense with the expectation that students will first include evidence and second include their reasoning. This order is based on the second author's empirical work finding that students are more likely to include evidence than reasoning (McNeill et al., 2006). In addition, this order makes definitional sense: The reasoning component is designed to explain how the evidence supports the claim. One must therefore have evidence before they can have reasoning. (p. 773)

Berland and McNeill based their claim about the order of their learning progression on both evidence (the second author's previous work) and reasoning (a logical analysis of the discipline). However, the reasoning is not really an explanation of how the evidence supports the claim. The reasoning explaining how the evidence was interpreted was presented in another article (McNeill, Lizotte, Krajcik, & Marx, 2006)—an article that is not labeled as learning progressions research. Consequently, Berland and McNeill did not clearly explain how the researchers used empirical data to create and modify the levels of a learning progression.

The above example represents the way in which Berland and McNeill (2010) explained how they developed their learning progression on argumentation. After explaining and describing their learning progression product, they presented examples of student responses, much like Jin and Anderson (2012). Both of these studies used their learning progression products to evaluate the "levels" of the student responses, and they also used these responses to illustrate the levels of the LP. However, neither study clearly explained to readers how the researchers used empirical data to develop and modify their learning progressions.

A final example is Duncan et al. (2009). Unlike the research discussed above, Duncan et al. did not collect or analyze any empirical data to develop a learning progression on genetics. Rather, the researchers based their learning progression on an analysis of science education standards and prior learning research. As the researchers themselves pointed out, this learning progression on genetics needed to be refined and validated using empirical data. While Shea and Duncan (2013) made important progress in clearly explaining how they used empirical data to make additions to the genetics learning progression, the LP is far from refined or validated. The researchers involved in this project need to present the research community with significantly more empirical data, along with how these data were used to modify or support the learning progression, before the learning progression can be considered empirically grounded. Moreover, the LP research community would benefit from additional examples of how researchers are developing LPs based on empirical data, as this is a critical gap in the literature.

Purpose

The purpose of this study was to explore the process of developing a learning progression on constructing explanations about sea level rise. During this exploration, I explicitly described my decision-making process as I developed and revised a hypothetical learning progression. Correspondingly, my research question was: What is a process by which a hypothetical learning progression on sea level rise is developed into an empirical learning progression using learners' explanations? This study used qualitative case study methods in order to answer this question.

My study was an embedded single-case study with individual learners as the embedded units of analysis (Yin, 2014). The single case was the learners as a whole, whose thinking was represented by the learning progression. I collected empirical data on middle school learners (grades 6-8) through written artifacts, audio-recorded interviews, and observations. Additionally, I kept a researcher journal as a data source to track my thinking about the learning progression throughout the research study. I analyzed all data collected during this study using analytic induction (Denzin, 1970) and through the lens of the learning progressions theoretical framework.

Theoretical Framework

The overarching theoretical framework for my study was learning progressions. Learning progressions are related to "learning trajectories," a well-developed area of research in mathematics education, as well as the rich tradition of research that has focused on the way that learners' ideas develop over time (Duncan & Gotwals, 2015; Duschl et al., 2011; Duncan

& Hmelo-Silver, 2009). However, in science education, learning progressions is an emerging theoretical framework based on the notion that learners can develop increasingly sophisticated ideas about a science topic over a period of several years.

My study employed the learning progressions theoretical framework described in the research synthesis report *Taking Science to School* (Duschl et al., 2007) and represented in the *Journal of Research in Science Teaching's* special issue (McGinnis & Collins, 2009), as well *Science Education's* special issue (Ford, 2015), on learning progressions. Duschl et al. defined learning progressions as

> descriptions of the successively more sophisticated ways of thinking about a topic that can follow one another as children learn about and investigate a topic over a broad span of time (e.g., 6 to 8 years). They are crucially dependent on instructional practices if they are to occur. (p. 219)

Duschl et al. (2007) argued that four core characteristics separate learning progressions from other developmental sequences or standards documents:

1. LPs utilize current research on children's learning.
2. LPs address the interaction of the NRC's four "strands of scientific proficiency" and involve learners in meaningful questions and investigations of the natural world.
3. LPs organize conceptual knowledge around core ideas.
4. LPs recognize multiple sequences of learning and web-like growth (i.e., not all learners will follow the same learning pathway).

Ultimately, LPs are intended to coordinate curriculum, instruction, and assessment, representing an improvement over status-quo instruction (Duncan & Hmelo-Silver, 2009; Duschl et al.; Shea & Duncan, 2013).

However, Duschl et al. (2011) and Shavelson (2009) have distinguished among different ways of conducting LP research, even though most researchers claim to employ the definition of LPs from *Taking Science to School* (Duschl et al., 2007). Duschl et al. (2011) distinguished between *evolutionary LPs* and *validation LPs*, while Shavelson distinguished between *curriculum and instruction LPs* and *cognition and instruction LPs*. In my study, I defined LPs in accordance with Duschl et al.'s (2011) notion of evolutionary LPs. Evolutionary LPs are characterized by a view of conceptual change that seeks to build on learners' current understandings in a productive way. Rather than viewing learners' developing ideas as concepts that need to be replaced by scientifically accurate ones, evolutionary LPs view learners' developing ideas as a useful intermediate understanding. I also defined LPs in accordance with Shavelson's notion of curriculum and instruction LPs. According to Shavelson, the "validity" of curriculum and instruction LPs depends on the context of teaching and learning. The development of curriculum and instruction LPs is best achieved through the collaboration of teachers and researchers, since context is critically important to learning. Additionally, such collaborations will expand our knowledge about how teachers can use LPs in classroom practice.

The situated cognition perspective, which is related to Shavelson's (2009) notion about the contextual validity of a learning progression, further informed my learning progressions theoretical framework. Robbins and Aydede (2009) defined situated cognition as "a picture of mental activity as dependent on the situation or context in which it occurs" (p. 3). Brown, Collins, and Duguid (1989) argued that knowledge is dependent upon the activities, context, and culture in which it is developed. While formal school teaching frequently ignores these factors in learning, the theory of situated cognition calls for teaching and learning methods that explicitly address them. As Putnam and Borko (2000) explained, how a person learns knowledge and/or skills, as well as the situation in which the learning occurs, are critical components of what is learned.

In my study, situated cognition learning theory (Brown et al., 1989; Putnam & Borko, 2000; Robbins & Aydede, 2009) helped me to better understand two important aspects of teaching and learning about sea level rise. First, learner understanding of sea level rise is dependent upon the activities, culture, and context of classroom instruction, which are embedded in the activities, culture, and context of the learners' lives. Second, learners' abilities to apply their understandings of matter and energy in a given context will vary. This variation can be explained using situated cognition learning theory because learners' abilities to apply their learning to a construct like sea level rise are dependent upon learners' instructional experiences with that construct. Naturally, these instructional experiences will vary from construct to construct and so, too, will learners' performances.

Significance

Learning progression research is currently occupying a central role in science education reform efforts, as evidenced by recent education reform documents. The research synthesis report *Taking Science to School* (Duschl et al., 2007) dedicated an entire chapter to learning progressions. Learning progressions were also prominently featured in *A Framework for K-12 Science Education: Practices, Crosscutting Concepts and Core Ideas* (National Research Council, 2011). Since this framework was the immediate precursor to the *Next Generation Science Standards* (NGSS, NGSS Lead States, 2013), learning progressions are also prominently featured in the NGSS. Appendix E of the NGSS makes the relationship between these standards and learning progressions explicit. The NGSS authors explained that, following the vision of the *Framework*, the NGSS were intended to increase the coherence of K-12 science education in that it views learning as a "developmental progression." Correspondingly, Appendix E outlined the progressions of "increasing sophistication of student thinking" about disciplinary core ideas from grades K-12 that can be found in the NGSS, while Appendix F presented progressions of how students should engage in eight different scientific practices at each grade band. Fittingly, these progressions very much resembled the typical products of LP research—the tables that LP researchers use to present their learning progressions in published journal articles (e.g., Berland & McNeill, 2010; Mohan et al., 2009).

The centrality of learning progressions in current science education reforms underscores the need for LP researchers to be clear, explicit, and transparent when sharing their research with others through publications. Learning progression products can only be as good as the process used to develop, refine, and validate them. Unless researchers are clear, explicit, and transparent about how they carried out this process, it is difficult to support the legitimacy of learning progressions. Additionally, clear examples of how LP researchers engage in this process will invite critique. Critique of LP development will allow opportunities for improvement in LP research, as researchers continue to work towards better and better models of how learner thinking about a given topic can develop over time.

The present research study will contribute to the improvement of LP research by clearly explaining a process for modifying a learning progression on constructing explanations about sea level rise based on empirical data collected from middle school learners (grades 6-8). As I explicitly explained my decision-making in developing the learning progression, I allow others to critique my thinking. Additionally, I provided other researchers with an example of LP development that can serve as a guide for future learning progression research projects.

Definition of Major Concepts and Terms

Table 1

Definitions of Major Concepts and Terms

Global Climate Change	The change in global climate caused by greenhouse gases in the atmosphere

Global Warming	The increase in global temperatures caused by greenhouse gases in the atmosphere—a major component of global climate change
Sea Level Rise	The rise in local or global average sea level caused by global warming and climate change
Thermal Expansion	The expansion of water volume as temperature increases due to the greater spacing of water molecules
LP Revision	The process of clarifying and improving a learning progression through small changes in response to empirical data
LP Development	The process of constructing and modifying a learning progression, which can include constructing the initial hypothesis for an LP, LP revision, and LP validation
LP Validation	The process of evaluating a learning progression as a theoretical construct

Positionality

I defined my positionality in terms of two intertwined roles. First, I was an experienced high school and middle school science teacher. Second, I was a doctoral student in science education who studied learning progression research extensively. Related to my role as a doctoral student was my work as a graduate assistant for MADE CLEAR (Maryland and Delaware Climate Education Assessment and Research), a National Science Foundation funded project. Over the past six years, my teaching experiences informed both my doctoral studies and my work as a graduate assistant. Likewise, my doctoral studies and work as a graduate assistant informed my teaching.

From fall 2005 to spring 2011, I taught all levels of high school chemistry, including Advanced Placement (AP) Chemistry, at a public high school in suburban Maryland. The way I think about science is very much from a chemistry perspective. However, in the fall of 2013, I began teaching seventh grade science at a public middle school in suburban Maryland. The course was primarily concerned with biology, though chemistry concepts were a secondary focus. Consequently, I gained experience with both a different age of learners (seventh graders, as opposed to tenth, eleventh, and twelfth graders) and different subject matter (biology, as opposed to only chemistry). In the fall of 2014, I moved back to the high school where I previously taught to teach Honors Chemistry. I returned to the high school level with a greater appreciation for where my students are coming from, what they have learned previously, and how their thinking has evolved over time as they have transitioned from middle school to high school.

I believed that my two very different teaching experiences provided me with an uncommon opportunity to experience teaching and learning about science at a range of levels of complexity and sophistication. I taught my seventh graders about atoms and molecules differently than I taught my tenth graders in Honors Chemistry. Similarly, I taught my tenth graders in Honors Chemistry differently than I taught my eleventh and twelfth graders in AP Chemistry. Correspondingly, learners at different ages interact with my teaching in different ways. Such is the substance behind learning progressions. My teaching experiences positioned me to understand how learners make sense of a science topic at different levels of complexity and sophistication, which can be described by the levels of an LP.

As a doctoral student, I studied learning progression research extensively. Before reading LP research, I did not give much thought to how learners' ideas developed over time. I had little idea about what my students had learned in elementary and middle school. Consequently, my conception of teaching and learning was insufficiently narrow.

However, the research literature I read during my doctoral program enhanced my appreciation of science teaching and learning at all levels. In fact, this literature was a primary factor in accepting a teaching position in a middle school. In my teaching practice, I have frequently thought about how I can apply what I have learned from science education research. And, my teaching experiences have affected the way that I have read this research. In a similar way, my teaching experiences affected the way that I approached this learning progression research study.

As mentioned earlier, my role as a doctoral student included work as a graduate assistant on the MADE CLEAR project. In my role as a MADE CLEAR graduate assistant, I wrote literature reviews, presented on learning progressions at a climate change professional development academy for science educators, and drafted hypothetical learning progressions on three different climate change topics. These climate change topics were sea level rise, the urban heat island effect, and extreme weather. This study can be seen as a continuation of my work on the initial hypothetical learning progression on sea level rise.

When studying the literature on learning progressions, I was frustrated to discover that many researchers were not clear about how they developed their learning progressions. I felt that my research study helped address this gap in the literature. Qualitative methods allowed me to describe the process of developing the learning progression in detail and provided clear examples of how I interpreted learners' language use in the process.

Limitations

One important limitation of this study was the fact that it was a single case study. As Yin (2014) wrote, "In general, criticisms about single-case studies usually reflect fears about the uniqueness or artifactual conditions surrounding the case (e.g., special access to a key informant)" (p. 64). Thus, it was a limitation of this study that it only represented one context, which might contain features that are dissimilar to other contexts. This uniqueness may have limited my ability to perform analytic generalization, which aims to extend the findings of a single case to suggest the way that learners may think in a general sense.

There were also several limitations to the data sources that I used in my study. One data source was interviews, which have the limitations of inaccuracies due to poor recall, response bias, and reflexivity (Yin, 2014). These same limitations applied to the written artifacts data source, since these written artifacts involved participants responding to questions in a similar way to interviews.

Another data source was observations, which have the limitations of selectivity and reflexivity (Yin, 2014). Selectivity was a limitation because it was impossible for me to pay attention to all relevant events that occurred in the classroom (Yin). Instead, I needed to selectively choose only those events that I perceived to be relevant to the case study. I used an observation protocol to focus my attention on these events (please see Appendix B for the observation protocol). Reflexivity was a limitation because the research participants may have acted differently because they were aware that they were part of my research study (Yin).

Assumptions

An assumption of this study was that the levels of a learning progression can accurately describe learners' conceptions of sea level rise. Sikorski and Hammer (2010; Hammer & Sikorski, 2015) challenged this assumption, suggesting that it might be impossible to diagnose a learner as occupying a single level on a learning progression. Sikorski and Hammer (2010) pointed out that Alonzo and Steedle (2008) and Steedle and Shavelson (2009) found inconsistencies between the levels of a force and motion learning progression and learner performance on a related instrument.

Alonzo and Steedle (2008) suggested that the levels of their force and motion LP might not adequately describe learners' knowledge. For instance, the researchers found that learners performed differently across different problem contexts, even though these problems were supposed to assess the same concept. Consequently, learners appeared to be at two different achievement levels at the same time. Steedle and Shavelson (2009) found that learners did not apply a coherent set of ideas when responding to the diagnostic test designed by Alonzo and Steedle (2008). Steedle and Shavelson's finding also provided insight into an idea that Schwarz et al. (2009) proposed. Schwarz et al. explained that the goal of their study was "to explore to what extent knowledge about modeling can be abstracted from the specific modeling contexts in which it is developed" (p. 636). It is questionable as to whether or not knowledge can be abstracted from specific contexts to create the qualitatively distinct levels of a learning progression. It is likely that learners would appear to be at multiple levels of the modeling learning progression depending on the conceptual context of an assessment (Lehrer & Schauble, 2009).

Sikorski and Hammer (2010) took this further, suggesting that no learning progressions can accurately classify learner understanding. The researchers argued that describing learner ideas using coherent, qualitatively different levels is inaccurate. However, other researchers would argue that such thinking misunderstands the purpose of a learning progression (Lehrer & Schauble, 2009; Duschl et al., 2007).

As Lehrer and Schauble (2009) cautioned, LPs are only models and should not be taken too literally. As models, LPs

> do not just illuminate, they also eliminate information. Contemporary theories of learning and development demonstrate that variability in performance is the rule, not the exception, so it is unlikely that individual students will comply by tucking neatly into the levels proposed in a LP. Context, task, and support (as well as a host of other factors) affect a student's performance. Our field once made the mistake of taking stage theory too seriously, an error we should avoid repeating. (p. 731)

LP research must carefully consider the role of context in relation to instruction, learning, and assessment when constructing, refining, and validating learning progressions. Such considerations have particularly important implications for the role of learning progressions in designing large-scale assessments, which run the risk of grossly misdiagnosing learner achievement (Alonzo & Steedle, 2008).

Similar to Lehrer and Schauble (2009), Duschl et al. (2007) reflected that LPs must ultimately fail to some degree. The researchers argued that “no organizational scheme can fully capture the organization of a child’s knowledge or its connections with her practices, with systems and phenomena in the material world, and with developmental changes over time” (p. 222). Rather than take on a task of perfectionism, LP research necessarily makes compromises that highlight some aspects of learner thinking while obscuring, and perhaps misrepresenting, others (Duschl et al.). However, LP research ultimately aims to guide curriculum and instruction by illuminating developmental steppingstones (Shea & Duncan, 2013; Smith & Wiser, 2015). For educators, these steppingstones can serve as both diagnostic tools and instructional targets. In this way, learning progressions can allow educators to facilitate more productive learning experiences than those currently achieved under status-quo instruction (Duschl et al.).

Chapter Summary

Learning progressions play a central role in current science education reforms, including the recently released Next Generation Science Standards (NGSS Lead States, 2013). However, learning progression researchers have not been sufficiently clear when explaining how they have developed their learning progressions based on empirical data on learner thinking. The purpose of my study was to address this gap in the literature, exploring the process of developing a learning progression on constructing explanations about sea level rise. This study used qualitative case study methods in order to understand how middle school learners (grades 6-8) construct explanations about sea level rise. I collected empirical data on learner thinking through written artifacts, audio-recorded interviews, and observations. Additionally, I kept a researcher journal as a data source to track my thinking about the learning progression throughout the research study. I analyzed all data collected during this study using analytic induction (Denzin, 1970) and through the lens of the learning progressions theoretical framework.

One product of this study was an empirically grounded learning progression. This learning progression was a model of learner thinking, which highlighted some aspects of learner thinking, while obscuring others (Lehrer & Schauble, 2009; Duschl et al., 2007). Rather than provide an exhaustive description of learners' ideas, LPs aim to identify developmental steppingstones in learner thinking. These steppingstones can serve as both diagnostic tools and instructional targets, allowing educators to facilitate productive learning experiences (Duschl et al.; Lehrer & Schauble, 2012; Shea & Duncan, 2013; Smith & Wiser, 2015).

A second product of this study was a description of the process used to develop the learning progression. This description included a detailed accounting of each modification made to the learning progression during this process. This description addressed a gap in the literature that Shea and Duncan (2013) identified. Specifically, LP researchers have not clearly explained how they have made modifications to LPs based on empirical data.

Chapter Two: Literature Review

In this literature review, I present a comprehensive review of the literature on learning progressions in science education. After discussing LP research more generally, I discuss ways of distinguishing among learning progressions. Next, I describe different methods of developing, refining, and validating a learning progression. Finally, I discuss the role of assessment and instruction in LP research.

Learning Progressions in Science Education

In the research synthesis report *Taking Science to School*, Duschl et al. (2007) defined learning progressions as

> descriptions of the successively more sophisticated ways of thinking about a topic that can follow one another as children learn about and investigate a topic over a broad span of time (e.g., 6 to 8 years). They are crucially dependent on instructional practices if they are to occur. (p. 219)

The ways in which learners can think about a science topic do not only include conceptual knowledge. They also include the scientific practices involved in constructing that knowledge, such as making measurements, representing data, modeling, and constructing explanations.

Alonzo and Steedle (2008) wrote that learning progressions originated from the work of Mark Wilson and colleagues from the University of California, Berkley. The researchers explained, “Learning progressions rely upon cognitive science research on how students learn a particular concept to describe a path (or set of paths) that students might take in moving from novice to expert understanding” (p. 390). Alternatively, Duschl et al. (2011) explained that learning progressions grew out of advances in cognitive and sociocultural psychology, scaffolding of learning with tools and technologies, the adoption of “assessment for learning” instructional strategies, and other work. Regardless of its origins, many science education researchers have advocated learning progression as a way to guide instruction, assessment, curriculum, and the development of long-term learning goals (Alonzo & Steedle; Berland & McNeill, 2010; Duschl et al., 2007; Ford, 2015; Furtak, 2012; Gunckel et al., 2012; Lehrer & Schauble, 2009; Lehrer & Schauble, 2015; Shea & Duncan, 2013; Shea & Duncan, 2015; Smith & Wiser, 2015; Songer et al., 2009).

Though LP researchers often reference the definition of learning progressions from *Taking Science to School* (Duschl et al.; 2007), the *Journal of Research in Science Teaching's* (2009) special issue on learning progressions, as well as *Science Education's* special issue on learning progressions (Ford, 2015), represented the diversity of conceptions of LPs present in the research literature (Duncan & Hmelo-Silver, 2009). Duncan and Hmelo-Silver explained that the special issue comprised research articles employing "different perspectives about the structure and grain size of LPs, the relationship between instruction and the theoretical progression, and what it means to validate a LP" (p. 308). For example, Songer et al. (2009) viewed instructional interventions as critical for validating their learning progression, while Mohan et al. (2009) validated their learning progression using learners who have experienced status quo instruction. Learning progressions also diverge significantly with respect to features such as the integration of science concepts and practices, views of conceptual change, and the role of assessment (Duschl et al., 2011). This literature review analyzes these differences for the purpose of identifying, describing, and comparing the various theoretical approaches employed in LP research.

Ways of distinguishing among learning progressions. Duschl et al. (2011) distinguished between "validation LPs" and "evolutionary LPs." These two categories of learning progressions were closely related to the models of conceptual change that researchers employed in developing them. The validation LPs tended to employ a "misconception-based *fix it* view" of conceptual change, while evolutionary LPs employed a “productive misconception-based *work with it* view” of conceptual change. Duschl et al. distinguished among LPs using these categories according to the way that the researchers defined the lower/upper anchors, designed instructional interventions, and developed formative assessments to measure progress along the LP.

Duschl et al. (2011) found that the dominant mode of LP research was to guide students along an LP with an upper anchor that represents canonical scientific understandings and/or expert scientific practices. According to Duschl et al., this represents the *fix it* view of conceptual change, which is commonly found in *validation LPs*. Far less common were *evolutionary LPs*. In contrast to validation LPs, evolutionary LPs involve developing “more sophisticated ways of understanding and applying targeted knowledge to contexts of use” (p. 156)—sometimes referred to as “developing more productive understanding” (Shea & Duncan, 2013, p. 26).

An example of a validation LP is found in Duncan et al. (2009). Duncan et al. developed a learning progression on genetics that outlines ideas that learners are supposed to adopt at three different grade bands (5-6, 7-8, and 9-10). The researchers acknowledged that learners tend to have certain conceptions about genetics, such as the view that genes are direct instructions for traits. However, Duncan et al. claimed that “such views result in shallow and un-mechanistic reasoning that does not account for the biological mechanisms that link genes to traits” (p. 657). Rather than considering learner’s intuitive ideas as productive conceptual landmarks, Duncan et al. dismissed learner conceptions as shallow. This is in contrast to Lehrer and Schauble (2012), who viewed learners’ everyday knowledge about biological diversity as a productive resource for developing scientific explanations.

Duncan et al. (2009) presented conceptual progressions of eight big ideas in genetics, labeled A to H. Though some of these progressions reflect increasingly sophisticated understandings (B, D, G, and H), others could read as explanatory text in a high school textbook. For example, big idea A reads

> Level 1: Humans, animals, plants, fungi, and bacteria have genes (genetic information in their cells).
>
> Level 2: The genetic information is found in the chromosomes of cells. Most sexually reproducing organisms have two sets of chromosomes. All cells of an organism have the same two chromosomal sets (except sex cells).
>
> Level 3: Genes are nucleotide sequences within the DNA molecule. DNA molecules make up chromosomes that make up our genome. (p. 660)

The most striking feature of big idea A is its lack of parallel structure. Level 1 states that different organisms have genes, level 2 explains what chromosomes are, and level 3 defines genes. Alternatively, all three levels of big idea B begin with either "Different cells have" (levels 1 and 2) or "All cells have" (level 3). The parallel structure of big idea B allows Duncan et al. to describe how learners' understandings about a single idea are developing over time. Berland and McNeill's (2010) LP on argumentation is exemplary in terms of using parallel structure in order to describe increasingly complex and sophisticated understandings.

Songer et al.'s (2009) biodiversity LP is another example of a validation LP because it involves a continuous, linear sequence of ideas that learners adopt over time—it focuses on the elaboration of previously held concepts (Duschl et al., 2011). Like Duncan et al. (2009), the learning progression lacks parallel structure among levels. For example, level 1 (grade 4) includes ideas such as "only a small fraction of energy at each level of a food chain is transferred to the next level," while level 2 (grade 5) includes ideas such as "an area has a high biodiversity if it has both high richness and abundance" (p. 626). Since these ideas (and other ideas in each level) are unrelated, they cannot possibly become more sophisticated from levels 1 to 3. Rather, they simply represent the different pieces of knowledge that learners should accumulate over time as they progress through a conceptual sequence.

Unlike Duncan et al. (2009) or Songer et al. (2009), Alonzo and Steedle (2008) incorporated learners' alternative conceptions into their force and motion LP. However, the authors also considered understanding as more "sophisticated" when it was more "correct" (Duschl et al., 2011; Sikorski & Hammer, 2010). For example, the table representing the most current version of Alonzo and Steedle's LP explicitly stated the common errors that impede learner progress along the LP.

Mohan et al. (2009) is an example of an evolutionary LP that views children's conceptions as potentially productive. The researchers discussed the development of an LP that progresses from learners' informal accounts of carbon cycling (level 1) to model-based accounts (level 4) of carbon cycling. Mohan et al. explained that "level 2 reasoning is itself a substantial intellectual accomplishment because students at this level begin to delve into the hidden mechanisms" (p. 693). What makes Mohan et al. an evolutionary LP is its *work with it* view of conceptual change, as evidenced in the preceding quote. Moreover, the authors placed a particular emphasis on how learners *make sense* of the world, and how this thinking can *evolve* over time. Duschl et al. (2011) explained that evolutionary LPs, like Mohan et al., include middle levels that can be used to bolster meaning making through instructional interventions.

Shavelson (2009) proposed an alternative way to distinguish among LP research studies. He characterized learning progression research as following two distinct but interconnected paths. One path, termed the *curriculum and instruction road*, begins with a logical analysis of content to develop a learning progression (e.g., Songer et al., 2009). Alternatively, the *cognition and instruction road* starts with a psychological analysis of cognition related to content. Researchers traversing this second path might ask questions such as, "How can we use knowledge about cognition to build instruction that improves the chances of all students learning to high levels...*what do the paths look like in between novice* *and expert* and how might they inform curriculum, teaching and assessment?" (p. 5). Though framed in different ways, there are significant similarities between Duschl et al.'s (2011) *evolutionary LPs* and Shavelson's *cognition and instruction LPs*. Both types of LPs place a particular emphasis on learner thinking and how this thinking can be leveraged to achieve progress in terms of how learners understand a topic.

Shavelson (2009) argued that cognition and instruction LPs might not accurately reflect cognition and that learners might not grow their knowledge in the linear way that these LPs describe. The author also questioned whether cognition and instruction LPs can be useful in designing curriculum, instruction, and assessment. To support this point, Shavelson cited the work of Alonzo and Steedle (2008) and Steedle and Shavelson (2009), to show that learner knowledge appeared to depend greatly on context. Cognition and instruction LPs, by their nature, do not place a particular emphasis on the context of curriculum, instruction, or assessment.

Alternatively, Shavelson (2009) explained that curriculum and instruction LPs are closely aligned with curricular specifications or the development of instructional units (e.g., Lehrer & Schauble, 2000). Shavelson compared these LPs to Bruner's (1960) vision of the spiral curriculum. Like the spiral curriculum, curriculum and instruction LPs are constructed based on a logical analysis of the discipline. The LP researcher also "psychologizes" how learners might develop the ideas cognitively over time, though this process is secondary.

According to Shavelson (2009), most curriculum and instruction LPs have not been validated with empirical data. However, the author suggested that, based on his own research, the "validity" of these learning progressions depends on the context of teaching and learning. For example, a teacher using guided inquiry might have learners who appear to follow the learning progression closely, but a different teacher using discovery teaching methods might not. Shavelson advocated the continued development of curriculum and instruction LPs through teaching experiments with teams of collaborating teachers and researchers. He argued that this research would expand both our knowledge about validating and refining learning progressions and our knowledge about how teachers can use LPs in classroom practice.

The structures or formats of LPs. Another way to distinguish among learning progressions is based on their structures or formats. Learning progressions are often organized into multiple strands, components, or dimensions, each representing different aspects of the LP topic (Alonzo & Steedle, 2008). For example, Duncan et al. (2009) organized their genetics LP into 8 big ideas that address two questions about genetics:

1. How do genes influence how we, and other organisms, look and function?
2. Why do we, and other organisms, vary in how we look and function? (p. 657).

Alternatively, Mohan et al. (2009) organized their carbon cycling LP into four dimensions—life, materials, scale, and models. Berland and McNeill's (2010) argumentation LP is organized into three dimensions, labeled instructional context, argumentative product, and argumentative process. Furtak's (2012) natural selection LP is divided into two conceptual structures—variation and differential survival/reproduction. The natural selection LP also has an additional "horizontal axis," which Furtak explained was a product of participant teachers' involvement in the LP development process.

Each component of an LP is structured into qualitatively different "levels" of achievement, and these levels are labeled with whole numbers (e.g., 1 is the lowest level, 4 is the highest level, and 2 and 3 are intermediate levels). A single level typically groups together related ideas with the assumption that a learner understands these ideas as a coherent set (Alonzo & Steedle, 2008). In other words, if a learner has achieved level 2 understanding, then he or she understands all of the ideas that level 2 comprises. However, in practice, researchers find that this assumption is often violated, since learners appear to achieve different levels of performance with respect to different dimensions of LPs or even different ideas within one dimension of an LP (Alonzo & Steedle; Berland & McNeill, 2010; Duncan & Gotwals, 2015; Gunckel et al., 2012; Lehrer & Schauble, 2012; Mohan et al., 2009; Steedle & Shavelson, 2009).

Alonzo and Steedle's (2008) force and motion LP describes learner thinking related to four different kinds of problems (force, no force, motion, and no motion), which can be viewed as the dimensions of the force and motion topic. The LP has five levels (labeled 0-4), with level 0 representing ideas that are "way off track." Interestingly, the authors created a sublevel labeled "A" (e.g., 2A) to clarify that learners at levels 2 and 3 could potentially share the notion that moving objects can contain the force that carries them along. Finally, the LP includes anticipated errors in thinking at each of the lower levels (1-3).

Schwarz et al. (2009) described a learning progression on modeling organized into two dimensions. These dimensions were labeled as

1. The generative nature of models as tools for explaining and predicting
2. The dynamic nature of models as improving new understanding.

Within each dimension, the authors categorized student performance into four levels (1-4). Schwarz et al. described the four levels of student performance for the first dimension of their LP (see *Table 3* in Schwarz et al., p. 640). Schwarz et al.'s learning progression describes how learners view, construct, and use modeling practices. However, it also indicates what learners *do not* do at the lower levels of the LP.

A more intricate and detailed version of a learning progression is seen in Lehrer and Schauble (2012). The authors divided their LP on evolutionary theory into three strands—variability, ecosystems, and change. Within each strand, the LP has 7 levels, with each level representing a consequential shift in learner thinking. Each level is further divided into sublevels labeled with letters (e.g., 4A to 4E). For each sublevel, the researchers provided both a learning performance that describes what learners can do with their understanding, as well as multiple examples of authentic learner statements representing each learning performance.

As a final example, Gunckel et al. (2012) developed a learning progression on water in socio-ecological systems. The authors divided the LP into five components, which they called the five elements of scientific accounts—structures and systems, scales, scientific principles, representation, and human dependency. Like Mohan et al. (2009), Gunckel et al. divided each dimension of their LP into four qualitatively different levels of achievement, labeled 1-4. Level 1 describes the informal accounts that learners bring to school, while level 4 describes societal expectations of environmentally literate citizens. The authors summarized,

> Lower level explanations and predictions portray water as primarily available for people to use and that people can change and control the quality and location of water to meet their needs. Accounts at level 2 depict water and people as part of larger environmental systems. Level 3 accounts suggest that people's actions can have impacts on these systems. Level 4 accounts recognize that environmental systems operate according to the physical laws of nature and that the capacity of environmental systems to provide fresh water is limited. (p. 860)

Similar to both Schwarz et al. (2009) and Mohan et al., the authors not only described what learners are able to do and understand at each level, but they also pointed out what learners do not do or understand (see *Table 2* in Gunckel et al., p. 854). As Wilson (2009) explained, this practice helps researchers to define student understanding at each level, as well as clearly distinguish between levels.

Grain size and LP levels. The grain size or level of descriptive detail of an LP is also a useful way of distinguishing among LPs. Lehrer and Schauble (2009) explained that the grain size of a learning progression usually translates into the number of levels that an LP comprises. However, Shea and Duncan (2013) suggested that differences in grain size among LPs are sometimes related to differences in the time span that an LP covers (e.g., grades 5-7 vs. grades K-12), which is directly related to the "scope" of an LP. Alonzo and Steedle (2008) suggested that as the scope of an LP increases, it becomes less feasible to provide detailed descriptions of learner thinking.

Because of the limited scope of their work, Plummer and Krajcik (2010) actually labeled their description of learning about celestial motion as a "learning trajectory"—a concept borrowed from the mathematics education research community. The authors explained, "We found learning trajectories to be a useful tool in describing our work on celestial motion because the focus is on a smaller grain-size than current learning progression work" (p. 770). Specifically, Plummer and Krajcik described a learning trajectory of "earth-based observational patterns," which the authors hoped might contribute to the eventual development of a learning progression on a "full model" of celestial motion. Thus, some researchers consider learning trajectories as components of learning progressions that involve a finer grain size and smaller scope.

There are trade-offs to consider when deciding upon the grain size of a learning progression. Too fine a grain size may not provide enough summary or generalization to help guide educators in making instructional decisions (Lehrer & Schauble, 2009). On the other hand, LP's with too large a grain size may lack explanatory power. Additionally, Lehrer and Schauble (2015) commented that the motivations for LP research affect the grain size of LP descriptions. LP research motivated by a need to produce large-scale assessments tends to develop LPs comprising broader categories, which are easier to measure in a reliable way. Alternatively, LP research motivated by a desire to explore new approaches to teaching and learning science would develop more detailed LP levels with a finer grain size.

In the case of Lehrer and Schauble (2012), the authors developed an LP on evolutionary theory comprising seven "rather detailed" levels. The authors explained that they were specifically aiming for a grain size that was suitable to guide instruction. In contrast, Lehrer and Schauble (2009) criticized Mohan et al. (2009) for developing a carbon cycling LP with only four levels, which they felt had "a grain size that may not provide much leverage for guiding the particulars of instruction" (p. 733).

During the development of an LP, researchers must make decisions about grain size when they add, consolidate, and/or remove levels based on student data (Shea & Duncan, 2013). This process is complicated when learner performance falls outside the boundaries of an LP's hypothesized levels. Shea and Duncan provided guidance for researchers making decisions about grain size when data on learner thinking is messy: "The heuristics for adding levels, removing, or combining levels posit that grain size is determined in terms of cognitive and instructional productivity" (p. 25). The authors suggested that a level should exist if it highlights a meaningful conceptual shift that can be promoted through teaching. In other work, these conceptual shifts are referred to as developmental milestones, landmarks, or benchmarks (Lehrer & Schauble, 2012). Shea and Duncan further explained that while an LP defines these important conceptual shifts or benchmarks, LPs do not exhaustively describe every incremental understanding that learners might achieve.

Integration of science concepts and practices. In *Taking Science to School*, Duschl et al. (2007) explained that a primary goal of LPs is to develop in learners both conceptual knowledge and understanding of scientific practices. Thus, Duschl et al. (2011) were surprised to find that most LP studies have failed to integrate concepts with practices (e.g., Alonzo & Steedle, 2008; Berland & McNeill, 2010; Plummer & Krajcik, 2010; Schwarz et al., 2009). However, some exemplary studies have successfully merged concepts and practices (e.g., Mohan et al., 2009; Lehrer & Schauble, 2012). Wiser, Smith, Doubler, and

Asbell-Clarke (2009) also included more than just concepts in their LP, including modeling practices, mathematical understandings, and use of representational tools (Sikorski & Hammer, 2010).

There is also a notion among researchers that LPs should be designed to coordinate forms of knowledge with epistemology, or the ways in which scientists construct knowledge (Duschl et al., 2007; Lehrer & Schauble, 2009; Smith & Wiser, 2015; Songer et al., 2009). This notion is evident in Smith, Wiser, Anderson, Krajcik, and Coppola (2004), which described a learning progression related to three central questions:

1. What are things made of and how can one explain their properties?
2. What changes and what stays the same when things are transformed?
3. How do we know? (p. 10)

The third question, "How do we know," directly addresses the epistemological bases of the ideas in questions one and two. Moreover, the LP considers involving learners in grades K-2 with developing their own measuring systems for length, which necessitates an exploration of the relationships between knowledge construction and epistemology (Duschl et al.). Smith and Wiser argued that the interaction between science content and epistemology should be central to LP research because these aspects of learning science are closely intertwined.

Alternatively, other learning progressions have focused on the development of conceptual knowledge without consideration of the scientific practices involved in constructing that knowledge. For example, Plummer and Krajcik (2010) discussed a learning progression for celestial motion without consideration of scientific practices. Similarly, Alonzo and Steedle's (2008) force and motion LP did not consider scientific practices.

Sikorski and Hammer (2010) argued that LPs that focus on learner attainment of increasingly "correct" answers about science concepts might impede learners' development of scientific practices. For example, rather than using available evidence to assess ideas, learners may assess ideas according to their alignment with canonical science knowledge. Such learning is in discord with current understandings among many science educators, who have generally moved towards a focus on learners' productive engagement in disciplinary practices, even though these practices might involve non-canonical accounts of phenomena (Sikorski & Hammer). Examples of LPs that view non-canonical learner accounts of phenomena (specifically, carbon cycling, water movement, and energy) as productive are found in Mohan et al. (2009), Gunckel et al. (2012), and Jin and Anderson (2012). As mentioned earlier, Lehrer and Schauble (2012) also recognized learners' everyday knowledge about biodiversity as "productive resources" for developing scientific explanations in their LP on evolutionary theory.

Lehrer and Schauble (2012) integrated a variety of scientific practices in their LP on evolutionary theory. For example, level 4A of the ecosystems strand involves questioning, 4B involves modeling, and 4C involves measurement. Each practice is fully contextualized in learners' understandings of conceptual knowledge about ecosystems.

At the other end of the spectrum from content-only LPs, some learning progressions have focused on developing an understanding of scientific practices in a domain-general manner without connection to specific science concepts. For example, Schwarz et al. (2009) discussed a learning progression on scientific modeling detached from any particular conceptual knowledge. Interestingly, the authors argued for the importance of the integration of the practice of modeling with metaknowledge about that practice. However, they ignored considerations about the conceptual context in which learners are developing their understandings about modeling. Schwarz et al. admitted, "The influence that specific contexts have on learning scientific practices is, of course, critical" (p. 635). Consequently, the authors were left to wonder whether learners demonstrated level 1 modeling because they held less sophisticated views of modeling or because they lacked content knowledge about phenomena such as evaporation. Schwarz et al.'s work would have been improved if they had integrated three strands of modeling instead of two:

1. Elements of modeling practice
2. Metaknowledge about models
3. Disciplinary knowledge relevant to models (e.g., phase changes of matter)

Similar to Schwarz et al. (2009), Berland and McNeill (2010) developed a generalized learning progression on argumentation. Though the authors recognized instructional context as an important dimension of argumentation, instructional context did not include the conceptual knowledge that was the focus of instruction. Consequently, the authors failed to explore the role that content knowledge had on a learner's ability to coordinate claims, evidence, and reasoning.

As a final example, Songer et al. (2009) took a relatively novel approach in designing their LP. In contrast to LPs that fully integrate conceptual knowledge and scientific practices, Songer et al. constructed two distinct but parallel components of their biodiversity LP—one on content knowledge and the other on inquiry reasoning. The authors recognized the importance of integrating content and inquiry reasoning knowledge, so they emphasized that all of their LP products reference both components of the learning progression. Additionally, the authors explained,

> In our work we did not integrate the content and inquiry reasoning progressions into one template to acknowledge our previous work (Songer, 2006) that suggests that the fostering of 'more sophisticated way of thinking about a topic' might suggest a cyclical path along our inquiry reasoning progression even if it suggests a linear path along our content progression. In other words, in an ideal curricular unit manifested from our progressions, students could be working with one level of the inquiry reasoning progression (e.g., intermediate) many times in combination with different

focal points along the content progression. (p. 613)

Thus, the authors suggested that, though related, learning about scientific concepts is fundamentally different than learning about scientific practices.

Sikorski and Hammer (2010) suggested that Songer et al.'s (2009) approach misses the complexity of the interaction between conceptual knowledge and scientific practices. Similarly, Lehrer and Schauble (2009) hoped that Songer et al. would elaborate on what they considered complexity of explanation. Lehrer and Schauble explained, "We suspect that complexity interacts with the nature of the knowledge of biodiversity being assessed, and a syntactic definition may miss this interaction" (p. 732). Sikorski and Hammer agreed, stating that inquiry practices and conceptual understanding cannot be separated from one another.

Methods of developing a learning progression. In general, the process of developing a learning progression begins with researchers identifying the core science ideas that the learning progression will address (Duschl et al., 2007). Next, researchers identify a potential sequence of ideas that could lead to an understanding of a particular topic, drawing upon standards documents, previous research studies, and/or their own evaluation of the science discipline. After drafting an initial hypothetical LP, researchers then begin the work of refining and validating the learning progression using data on learner thinking. This final step is an ongoing process of iterative cycles involving messy data and difficult decision-making (Shea & Duncan, 2013).

Alonzo and Steedle (2008) described a similar, though somewhat less general method for developing an LP. The authors explained that the LP development process starts with expectations for what learners should ultimately know about a construct, which can be based on standards documents or prior learning science research. These expectations represent the upper end of the LP. Lower levels of the LP can be based on research related to learner ideas about the construct. These ideas can be "misconceptions" or productive ideas that support further learning. Learner ideas are grouped based on similarities, and these groups are ordered in a logical way to create a hypothetical learning progression. This hypothetical learning progression represents "a current idea about how student understanding develops" and should be revised as the researcher analyzes new data. After creating a preliminary LP, the researcher can develop items to assess students' levels of achievement. Data from administering the assessments can be used to revise both the instrument and the learning progression.

Furtak (2012) took a relatively novel approach to developing an LP for natural selection that positioned teacher participants as co-researchers. The learning progression served as the centerpiece of the teachers' professional development experience. Furtak hypothesized an early version of the LP based on previous research, and the LP was revised based on teachers' ideas and analysis of student work. A significant benefit of Furtak's work is that it sheds light on how classroom teachers may actually use learning progressions for formative assessment purposes. Interestingly, Furtak found that four out of six teacher participants used the LP to identify and "squash" students' alternative conceptions, rather than to make inferences about student thinking in order to inform their instruction.

In contrast to Furtak (2012), Gunckel et al.'s (2012) LP development process was more typical. As part of the same research group, their method of LP development was quite similar to Mohan et al. (2009) and Jin and Anderson (2012). Gunckel et al. explained that their LP for water was developed and refined through iterative cycles of assessment and analysis over a 6-year period. The authors began with hypothesized upper and lower anchors, which they used to develop assessments that elicit learner thinking. Based on the assessment data, the authors developed the intermediate levels of the LP, and they continued to revise LP levels throughout each design cycle. During this process, Gunckel et al. created "exemplar workbooks" that represented clusters of learner ideas, which could be "used to distinguish between qualitatively different patterns in student accounts" (p. 852). Ultimately, each exemplar workbook came to represent a discrete level of achievement on the learning progression. These workbooks not only served to develop and refine the LP, but they were also used as diagnostic tools to assign learners to levels of achievement.

Regardless of a researchers' process for developing a learning progression, all researchers must necessarily begin with the same critical decision. They must identify a science topic that is worthwhile and in the spirit of learning progression research. Generally, learning progression research has defined worthwhile topics as those that are considered central to the scientific disciplines.

Identifying a learning progression topic. Duschl et al. (2007) wrote that learning progressions should address the core ideas in science. Core ideas are those that have the greatest explanatory power and scope. They provide central frameworks for further learning in science, and so they are presumably the most important to teach. Duschl et al. named atomic-molecular theory and evolutionary theory as examples of the types of core ideas that LP research should address.

Researchers have interpreted the notion of core ideas in science in a variety of ways. Some researchers have selected topics that are very general, such as force and motion (Alonzo & Steedle, 2008), evolutionary theory (Lehrer & Schauble, 2012), genetics (Duncan et al., 2009), argumentation (Berland & McNeill, 2010), and modeling (Schwarz et al., 2009). Others have selected more specific topics, such as natural selection (Furtak, 2012), water in socioecological systems (Gunckel et al., 2012), carbon cycling in socio-ecological systems (Mohan et al., 2009), and biodiversity (Songer et al., 2009). However, regardless of which LP topic is selected, researchers have felt the need to justify their topic choice explicitly. For example, Furtak explained, "The concept of natural selection is a disciplinary core idea in biology" (p. 1189). Similarly, Lehrer and Schauble called evolutionary theory one of the most central concepts in biology. Gunckel et al. argued that providing model-based accounts of water's movement through socio-ecological systems is critical for environmental science literacy. Mohan et al. made the same argument for the importance of learners understanding carbon cycling in socio-ecological systems. In contrast, Songer et al. cited the presence of the biodiversity topic on the 2006 Programme for International Student Assessment.

Duschl et al. (2011) found that LP topics are generally decided upon based on either perceived disciplinary importance or inclusion in standards documents. However, such decisions ignore two key features of learning. First, learning is context specific (Brown et al., 1989; Putnam & Borko, 2000; Robbins & Aydede, 2009), a notion supported by LP research (e.g., Alonzo & Steedle, 2008; Berland & McNeill, 2010; Duschl et al., 2007; Schwarz et al., 2009; Sikorski and Hammer, 2010; Steedle & Shavelson, 2009). Second, learning is meaningful to learners to varying degrees based on their varying "personal and cultural resources or different instructional histories" (Duschl et al, 2007, p. 221). Thus, researchers would be justified in considering LP topics that are situated in the specific contexts in which learners find learning meaningful. These LP topics could still fulfill the purpose of aligning with standards documents and addressing scientific constructs of disciplinary importance. However, they could also facilitate learning that is both socially and culturally relevant for learners.

Contextual learning progressions. Currently, there is a gap in the literature exploring *contextual learning progressions* (R. McGinnis, 2011, personal communication), which situate learning within contexts that aim to minimize variation in learner achievement in relation to the learning progression. Situated cognition learning theory (Brown et al., 1989; Putnam & Borko, 2000; Robbins & Aydede, 2009) can be used to support the notion of contextual learning progressions because situated cognition posits that mental activity is dependent on the situation or context in which it occurs (Robbins & Aydede), which includes factors such as the instructional histories and cultures of learners (Brown et al.). Situated cognition calls for teaching and learning which explicitly addresses instructional context. How a person learns knowledge and/or skills, as well as the situation in which the learning occurs, are critical components of what is learned (Putnam & Borko).

The dominant mode of learning progressions research to date has been to portray a solely cognitive theory of learning (e.g., Alonzo & Steedle, 2008; Duncan et al., 2009; Gunckel et al, 2012; Jin & Anderson, 2012; Mohan et al., 2009; Songer et al., 2009). Employing a cognitive perspective, researchers have developed learning progressions on general topics, such as force and motion (Alonzo & Steedle), which can be applied to a variety of conceptual contexts. For example, in Alonzo and Steedle, learners were asked to apply their understanding of force and motion to contexts including a stone thrown in the air, a box sitting on a table, and a puck sliding across a frictionless surface. Steedle and Shavelson (2009) found that learner performance on tasks varied greatly and depended on the context in which their knowledge was to be applied.

In contrast, a learning progression that takes context into account, would expect this variation. Contextual learning progressions, using situated cognition learning theory (Brown et al., 1989; Putnam & Borko, 2000; Robbins & Aydede, 2009), define both the conceptual and instructional contexts of teaching and learning. In agreement with Shavelson (2009), the validity of these learning progressions will depend on these contexts. My study includes consideration of situated cognition learning theory as a way to more fully understand how learners learn about an environmental phenomenon (i.e., climate change) that has differing observable consequences (e.g., sea level rise, drought, enhanced urban heat island effect, extreme weather) in the diverse contexts in which learners live.

Contextual learning progressions should be related and compared to more general learning progressions with the goal of describing the “multiple sequences of learning and web-like growth" that different learners experience under different settings (Duschl et al., 2007). To date, LP studies have developed learning progressions that assume that learners will follow a single learning pathway (though many researchers have raised questions about this assumption; e.g., Jin & Anderson, 2012). A learner's sociocultural background is treated as irrelevant in terms of the way that learners develop increasingly sophisticated ideas about a given topic over time. However, there is reason to question whether or not this is the case.

An example of a learning progression that does take a learner's sociocultural background into account and is set in a specific context was reported in Breslyn et al. (2016), a study which I coauthored. Breslyn et al. reported on the development of a learning progression on sea level rise, an observable consequence of climate change that is relevant to learners living in coastal regions. Since my dissertation study is also about developing a learning progression on sea level rise, I have the opportunity to compare two different learning progressions on the same topic. Comparing two learning progressions on the same topic is an understudied area of LP research and represents a gap in the literature, which my study can address.

Research is also needed to compare learning progressions on general topics that are assumed to generalize to all learners and learning progressions on more specific topics that attend more closely to learners' sociocultural contexts. For example, learning progressions research would benefit from exploring how a more general learning progression on argumentation (Berland & McNeill, 2010) compares to a contextual learning progression on constructing explanations (a form of argumentation) about sea level rise. Moreover, researchers can learn from comparing and contrasting two different context-specific learning progressions, such as an LP on the movement of water on Earth (Gunckel et al.) and an LP on sea level rise. Comparing and drawing connections among LPs from a variety of different research projects will allow researchers to better understand the variety of ways that learning can happen about a given topic or set of related topics.

Drafting an initial hypothetical LP. After selecting a learning progression topic, researchers can then hypothesize the first draft of a learning progression. Schwarz et al. (2009) explained that the first step in drafting an initial LP is to draw out the implicit understandings that the learning goals entail and organize them into a coherent framework. However, learning progressions also typically incorporate research describing learners' various conceptions at different ages (Alonzo & Steedle, 2008; Mohan et al., 2009). Additionally, researchers tend to draw on standards documents to construct initial hypotheses (e.g., Alonzo & Steedle; Songer et al., 2009). In many cases, researchers combine these approaches to varying degrees.

Perhaps one of the most thorough explanations of drafting an initial hypothetical LP is found in Songer et al. (2009). Songer et al. explained that they began the LP development process by engaging scientists in lengthy conversations about core ideas in science. After working with the scientists, the authors chose evidenced-based reasoning and biodiversity as the core ideas of their learning progression. These decisions were also based upon definitions of scientific literacy found in standards documents (Duschl et al., 2007), the researchers' own prior research, and the perceived importance of biodiversity in a world with a changing climate. After choosing the focal ideas for the LP, Songer et al. continued to work with the scientists to consider the ways in which state and national standards address their focal topics. They also discussed how learners could be supported in developing more complex understandings about the focal ideas. The product of these discussions was an initial hypothetical LP, which was then used to generate assessments, which were then used to refine the learning progression.

Other researchers begin drafting learning progressions by defining the lower and upper anchors (Gunckel et al., 2012; Jin & Anderson, 2012; Mohan et al., 2009). In the following sections, I will discuss how researchers have defined these anchors. First, I will focus on how researchers have defined the lower anchors of learning progressions.

How researchers have defined lower anchors. The lowest level of a learning progression generally represents the ideas and reasoning of learners entering school (Duschl et al., 2007). This is known as the *lower anchor*. Lower anchors of learning progressions are often based on macroscopic (easily visible) or everyday experiences (Duschl et al., 2011). Duschl et al. (2011) posited that stronger LPs tend to have lower anchors that are accessible to learners.

Duschl et al. (2011) raised concerns about the lower anchor presented in Duncan et al. (2009), suggesting that it might not be accessible to younger learners. The lower anchor was intended for learners in grades 5-6 and required them to possess "sophisticated interdisciplinary awareness of chemical and physical interactions at a molecular level and of unobservable entities of cellular and molecular processes" (p. 152). Duschl et al. suggested that a more accessible lower anchor would pay more attention to how children construct meaning and would perhaps involve more "macro-type-properties" of genetics.

Schwarz et al. (2009) defined the lower anchor of their modeling LP with a general description of learner thinking, followed by an illustrated example of learner performance. The authors explained,

> At level 1, students construct and use models that show literal illustrations of a single phenomenon, depicting only observable features, rather than attempting to explain the phenomenon. Students at this level view models as a means of describing the phenomenon to others, rather than explaining why it occurs. This initial level can be seen in many of the elementary students' initial modeling process, and in some aspects of middle school students' work. (p. 640)

In this description, the authors are tying level 1 thinking to a particular grade band—elementary students. However, the authors acknowledge that level 1 performance is also observed in middle school students. Indeed, larger cross-sectional research studies have found significant overlap among grade bands in terms of reaching different levels of LP achievement, including the lower anchor (e.g., Mohan et al., 2009). See Mohan et al. (*Figure 3*, p. 692) for a graphical distribution of LP achievement among participants in that study.

How researchers have defined upper anchors. The highest level of a learning progression is referred to as the upper anchor**.** The upper anchor describes what students should know at the end of a learning progression (Duncan & Hmelo-Silver, 2009; Duschl et al., 2011). Thus, where the lower anchor represents beginning learners' ideas about a topic, the upper anchor represents disciplinary understandings and societal expectations (Mohan et al., 2009).

Duschl et al. (2011) discussed what they call the "abstractness issue," which refers to the upper anchors of learning progressions being inappropriately abstract. The authors found that upper anchors were often too abstract in learning progressions tied to college readiness or curricular frameworks. They also found that the abstractness issue was a concern in learning progressions that aimed for scientists' understandings of concepts and/or practices in early grades. Duschl et al. argued that the upper anchors of LPs should have targets that are based on obtainable societal expectations rather than scientifically accurate conceptual frameworks.

Interestingly, many LP research studies have found little or no evidence of upper anchor performance from their data sources (e.g., Gunckel et al., 2012; Jin & Anderson, 2012; Mohan et al., 2009; Schwarz et al., 2009). While in some cases this finding might stem from Duschl et al.'s (2011) abstractness issue, in others, it might be more closely related to research design. For example, Mohan et al. employed a cross-sectional research design to investigate learner accounts of carbon cycling under "status-quo" instruction. The researchers suggested that their current work on instructional interventions related to carbon cycling may allow more learners to achieve upper anchor understandings.

How researchers have defined the middle levels. In addition to hypothesizing lower and upper anchors of learning progressions, researchers must also propose intermediate understandings that represent coherent networks of ideas and/or practices (Duschl et al., 2007). Duschl et al. pointed out that some of these intermediate understandings might not look like the ideas making up the upper anchor, yet they are critical to developing more sophisticated understandings.

Shea and Duncan (2013) commented that it is the middle levels that truly define a learning progression. The authors explained that these middle levels represent *hypotheses* about how learner knowledge develops over time, and each intermediate level of an LP describes "productive bridging understandings" that can be leveraged during instruction. However, Shea and Duncan added that learners' ideas might not align neatly within the borders of an LP's hypothesized levels. Consequently, the researcher must make important decisions about how to modify the structure and content of the learning progression. These decisions involve adding, consolidating, and/or removing levels from the original learning progression.

Refining and validating learning progressions. Common to LP research studies is the notion that the development of a learning progression is an "iterative process" (Shea & Duncan, 2013; Schwarz et al., 2009; Alonzo & Steedle, 2008). According to Duschl et al. (2007), this iterative process

> requires one to synthesize results from disparate (often short-term) studies in ways that begin to address questions of how longer term learning may occur; learning progressions suggest priorities for future research, including the need for engaging in longer term studies based on best bets suggested by these research syntheses; and they

present research results in ways that make their implications for policy and practice apparent. (p. 220)

Indeed, long-term, longitudinal research studies investigating how individual learners or a cohort of learners develop thinking about a topic over time are absent from the literature. However, researchers have expressed the belief that this is the direction in which LP research needs to focus its attention (e.g., Alonzo & Steedle, 2008). Though researchers have not yet conducted long-term longitudinal studies on learning progressions, researchers have begun collecting empirical data that informs the refinement and validation of LPs.

There is a subtle but important distinction in the literature between *refinement* of a learning progression and *validation* of a learning progression. Alonzo and Steedle (2008) provided a clear example of this distinction when they explained that their work comprised preliminary revisions in response to empirical data—this is considered LP refinement. LP refinement is the process of clarifying and improving a learning progression through small changes. On the other hand, Alonzo and Steedle explained that "full validation" is a more substantial activity requiring longitudinal studies that track how learner understanding develops over time. An important component of this validation process would be to study learning about an LP topic under different instructional and curricular contexts to examine whether or not the proposed learning progression describes learner thinking in an accurate way. As Shavelson (2009) commented, the "validity" of a learning progression depends on the context.

Duncan and Hmelo-Silver (2009) discussed the validation of a learning progression in terms of evaluating the LP as a theoretical construct. However, the researchers reflected that the meaning of "validity" is ambiguous in the context of learning progressions. Duncan and Hmelo-Silver wrote,

> A valid progression implies that the underlying cognitive model of learning holds true in different instructional settings and for different learners. However, learners bring with them unique experiences and knowledge and it is not yet clear how LPs can take into account these different learner histories. (p. 608)

Researchers have attempted to deal with this issue with LP validity in different ways.

For example, Jin and Anderson (2012) used a deductive process to validate their LP on energy after first using an inductive process to draft an initial LP framework. The researchers used the levels of the initial LP framework as rubrics to rate learner responses. Jin and Anderson modified the indicators composing the LP framework in order to better distinguish among learner responses. In other words, Jin and Anderson considered the learning progression "more valid" when it was more effective for sorting learner responses into specific levels. Jin and Anderson also considered the presence of LP level indicators in interview data as validity evidence for the learning progression. In terms of LP validation, this research made the assumption that the underlying cognitive model of learning will hold true under different instructional contexts and for different learners.

Neumann, Viering, Boone, and Fischer (2013) also made the assumption that the LP will generally be valid across contexts. The researchers explained that LP development involves recurring cycles of empirical validation and theoretical refinement. In this case, Neumann et al. administered multiple-choice items about energy to a large number of learners and analyzed the data using Rasch analysis. Similar to Jin and Anderson, Neumann et al. evaluated the validity of the LP in terms of its ability to distinguish among learners. The researchers concluded, "We were able to confirm a general progression with respect to the levels described by four conceptions of energy (forms and sources, transfer and transformations, dissipation, conservation" (p. 184). For Neumann et al., they validated *the* learning progression for energy—instruction did not play an important role in the way that learners can develop over time.

Alternatively, Lehrer and Schauble (2012) did not use the word validation when discussing their learning progression on modeling evolution. Rather, the authors described "the rationale and structure for a learning progression to understand the development of modeling under supportive forms of instruction" (p. 701). In this case, the researchers emphasized the specific experiences of learners in their research and were interested in taking learners' differing instructional histories into account. For Lehrer and Schauble, 15 years of research conducted *in classrooms* was validity evidence for the learning progression. This validity evidence was derived from both shorter-term and longer-term studies set in a variety of instructional contexts. As the researchers explained, the learning progression is an "encapsulation of distinctive ways that children tend to think, based on observation and study of attempts to put these forms of teaching and learning into practice" (p. 705). Thus, the validity of a learning progression does not necessarily need to be achieved through a sophisticated cycle of assessment and corresponding statistical analysis (e.g., Neumann et al., 2013; Wilson, 2009). Instead, some researchers are working towards validating learning progressions through long-term, qualitative studies that specifically attend to the context of learning.

In summary, there is no one generally accepted way to validate a learning progression (Duncan & Hmelo-Silver, 2009). Researchers have attempted to validate and refine LPs using both quantitative and qualitative methods. Some researchers have explicitly discussed "validating" a learning progression, while other researchers have addressed the notion of validity in other ways. What is common to all learning progression research is the notion that useful LPs must ultimately be based on empirical data.

These data are both quantitative and qualitative. However, researchers have found some data sources more useful than others. In the next section, I will discuss data sources in learning progression studies, as well as their potential usefulness in refining and validating learning progressions.

Data sources. Researchers have used a variety of data sources in developing their learning progressions. See *Table 2* (below) for examples of data sources found in various LP studies.

Table 2

Data Sources Used in Various LP Research Studies

LP Research Study	Data Source
Alonzo & Steedle (2008)	Ordered multiple-choice items, open-ended written assessment items, think-aloud interviews, interviews
Berland & McNeill (2010)	Classroom discourse
Duncan et al. (2009)	None
Furtak (2012)	Clinical interviews, whole-class assessment conversations
Gunckel et al. (2012)	Open-ended written assessment items
Jin & Anderson (2012)	Open-ended written assessment items, clinical interviews
Lehrer & Schauble (2012)	Small group interviews, classroom artifacts (e.g., student drawings), classroom observations
Mohan et al. (2009)	Open-ended written assessment items, clinical interviews
Plummer & Krajcik (2010)	Clinical interviews
Schwarz et al. (2009)	Open-ended written assessment items, clinical

	interviews, classroom discourse
Shea & Duncan (2013)	Open-ended written assessment items, student artifacts, classroom observations
Songer et al. (2009)	Open-ended written assessment items, multiple-choice items
Steedle & Shavelson (2009)	Ordered multiple choice items
Gotwals & Songer (2013)	Open-ended written assessment items, think-aloud interviews, clinical interviews

Table 2 shows that researchers often use multiple data sources when developing learning progressions. Gotwals and Songer (2013) argued for the importance of collecting multiple data sources, especially in the initial phases of LP development. The authors explained, "It is imperative that we gather rich and varied sources of data about the nuances of students' understanding and learning through written work, think-alouds, interviews, and other data sources (such as curricular interventions)" (p. 623). In their study, Gotwals and Songer found that think-alouds and clinical interviews allowed them to examine the abilities of learners to reason and use evidence in ways that multiple-choice and written assessment items did not.

Other researchers have agreed that some data sources are better for eliciting learner thinking than others. For example, Mohan et al. (2009) explained that open-ended written assessment items allowed them to capture a diversity of learner ideas, in contrast to multiple-choice items. However, the authors found it challenging to develop open-ended items that would illicit sufficient understanding from both younger learners (grade 4) *and* older learners (high school). Gunckel et al. (2012) also found that open-ended assessment items were difficult to write in a way that is equally accessible to learners at all levels of the learning progression. The authors suggested that interviews would allow them to gain a deeper understanding of learners' ideas in future studies. Similarly, Jin and Anderson (2012) found that clinical interviews were most effective in predicting learners' abilities.

Alonzo and Steedle (2008) found that ordered multiple-choice (OMC) items allowed for more precise and valid diagnosis of a learner's level on the force and motion LP than did parallel open-ended response items. Interestingly, the authors found that the OMC items elicited conceptions similar to those expressed during clinical interviews. Alonzo and Steedle suggested that the multiple answer choices on the OMC served a similar function to clinical interview probes. These answer choices, like interview probes, gave participants ideas to consider and compare to other ideas.

In the OMC format, each of the answer choices represents a particular level of the learning progression. For example, if participants choose the first answer choice, then their thinking is in line with level three of the learning progression. Or, if they choose the second answer choice, then their thinking is in line with level one of the learning progression. This format of OMC items allows for the efficient diagnosis of learners along the LP when clinical interviews are not a practical option. Also of note, Alonzo and Steedle (2008) found "genuine discrepancies" between data obtained from think-aloud interviews and clinical interviews. Such discrepancies introduce additional challenges to researchers attempting to triangulate data sources to better understand learner thinking in relation to an LP topic.

Moving from data to refinement. Detailed descriptions of the messy process of data analysis during LP refinement or validation are largely missing from the literature (Shea & Duncan, 2013). Shea and Duncan acknowledged that Alonzo and Steedle (2008) clearly explained how the researchers used data on learner thinking to modify the levels of their hypothetical LP on force and motion. However, the authors argued that the field needs additional examples of the process of LP refinement. Studies are needed that explore challenges in data analysis, as well as researcher decision-making during the LP refinement process. Researchers must be more open and explicit about how they collect their data, how they compare these data to other data, and how they use this analysis to justify decisions about modifying the language and structure of LP levels.

In response to this gap in the literature, Shea and Duncan (2013) provided insights into how they refined an LP on genetics using learner data from clinical interviews and written artifacts. During this refinement process, they used the following heuristic: "Levels should be added when the new ideas are directly related to the construct, represent an important conceptual shift, and/or afford instructional leverage" (p. 13). Indeed, Shea and Duncan added additional levels to their genetics LP to incorporate students' alternative conceptions, but did not remove or modify levels from their original LP. Additionally, Shea and Duncan included a level zero to represent no knowledge of proteins or cells. This action is logical since there is an important difference between learners who have no knowledge of a topic and those who have alternative conceptions about a topic.

In contrast to Shea and Duncan (2013), Gunckel et al. (2012) mostly presented the product of their LP refinement process. The authors explained, "During interpretation, students' responses were analyzed and results were used to inform revision of the learning progression. Using empirical results, we were able to better articulate lower anchor and intermediate levels of student achievement" (p. 852). While Gunckel et al. described the details of how they clustered items and developed exemplar workbooks to define levels of achievement, the authors did not provide examples of their decision-making during this process, nor did they discuss the complexities of differentiating between qualitatively different patterns in learner ideas. Such discussions are especially important for the development of intermediate levels of achievement, which Songer et al. (2009) referred to as the "messy middle."

Deciding on LP dimensions. Similar to the process of creating and modifying the levels of an LP, researchers must also make difficult decisions about how to organize an LP into dimensions. Schwarz et al. (2009) explained that they organized their modeling LP into two dimensions because these dimensions "emerged" as a useful way to organize the data analyses in terms of the "four elements" of modeling practice. Additionally, Schwarz et al. provided a summary argument for how these two dimensions helped the researchers address their commitment to reflective practice. However, they did not provide examples of learner data that illustrate how these dimensions emerged. Thus, the reader is left to trust that the authors have made logical, rather than arbitrary, decisions about the dimensions of the modeling LP.

In contrast, Alonzo and Steedle (2008) did carefully explain how the dimensions of their force and motion LP evolved over the course of three related research studies. The authors explained that their LP topic involves two very closely related ideas—the conditions under which an object is in motion and the conditions under which it is at rest. The authors expressed uncertainty about whether or not learner understanding of these closely related ideas develops in concert, and they cited literature to support this uncertainty (Finegold & Gorsky, 1991). Thus, these ideas needed to be separated to more accurately describe learners' conceptual frameworks. Ultimately, Alonzo and Steedle decided to distinguish among four types of problems on their learning progression—force, no force, motion, and no motion. In support of their decision to create these four different LP dimensions, Alonzo and Steedle commented that the dimensions were useful in terms of writing and scoring assessment items, and they provided examples of learner ideas to support this claim.

Furtak (2012) explained that she based the dimensions of her natural selection LP on prior work (Catley, Lehrer, & Reiser, 2005). In their work on an evolutionary theory LP, Catley et al. divided natural selection into six conceptual structures, though Furtak chose to focus on only two of these—variation and differential survival/reproduction. She selected variation as a dimension because of the strong research base into learners' alternative conceptions about this topic, while she selected differential survival/reproduction because it "emerged" as a topic of focus among participant teachers during the LP development process. Additionally, Furtak supported her decisions by pointing out that both of these dimensions are represented in the Next Generation Science Standards (NGSS Lead States, 2013).

As the above examples illustrate, researchers justify their decisions about an LP's dimensions in a variety of ways. These include references to standards documents, analyses of science disciplines, prior research, and analyses of empirical data. The strongest arguments for LP dimensions are those that begin with references to standards documents, analyses of sciences disciplines, and/or prior research, but then respond to empirical data as it is collected (e.g., Alonzo & Steedle, 2008). When explaining how they have responded to empirical data, researchers should provide and analyze examples that support their decisions.

Assessment and instruction. There are two final aspects of LP research that are prominent in the literature—assessment and instruction. Learning progressions are seen as a promising framework for developing meaningful large-scale and classroom-based assessments that are grounded in how learners develop understanding over time (Alonzo & Steedle, 2008). LPs are also intended to coordinate assessment with both curriculum and instruction (Duschl et al., 2007).

Assessment. Shea and Duncan (2013) explained that the grain size of an LP needs to support assessment of learner understanding for the purpose of informing ongoing instruction. Shea and Duncan cited Songer et al.'s (2009) biodiversity LP as an example of an LP that supported frequent assessment (weekly). However, Shea and Duncan acknowledged that such a fine grain size is impractical for large-scale assessments. Moreover, Lehrer and Schauble (2015) commented that LPs that avoid too many distinctions among levels are better suited for large-scale assessments because broad categories can be measured more reliably.

Songer et al. (2009) explained that assessments are essential for learning progressions because they allow researchers to measure learner understanding at multiple levels over time. According to the authors, these measurements allow researchers to make claims about the validity of learning progressions. Additionally, Songer et al. found that assessments tied to their biodiversity LP were able to detect a greater range of learner performance than traditional assessments.

Alonzo and Steedle (2008) emphasized the assessment aspect of research on their force and motion LP. Over the course of three studies, the authors refined their learning progression after having participants answer various versions of an instrument containing ordered multiple-choice (OMC) and open ended (OE) items. Additionally, the authors had a subset of participants think aloud when responding to items, and then engaged them in clinical interviews to clarify their thinking. The authors thoroughly coordinated these four data sources to draw conclusions about learner thinking and the usefulness of each data source to better understand learners' ideas.

Alonzo and Steedle (2008) found various challenges in assessing a learners' level on their learning progression using the four data sources. First, learners did not respond consistently to similar problems set in different contexts. Therefore, both classroom and large-scale assessments should assess learner understanding across multiple contexts. Second, during interviews, the researchers learned that participants responded differently to assessment items related to classroom activities. Third, learners did not share a common understanding about the meanings of certain scientific words (e.g., force), which may have influenced the way they interpreted and responded to some items. This finding raises validity issues for LP assessments, since it may be difficult to write items that have the same meaning for learners at different levels. Researchers developing assessments for learning progressions should use interviews to ensure that assessments are capturing the thinking of learners with different interpretations of scientific words (Alonzo & Steedle).

Alonzo and Steedle (2008) concluded that clinical interviews provided the best picture of learner thinking, though they acknowledged that interviews are impractical for non-research settings. So, it was an encouraging finding that the OMC items were "reasonably" effective in estimating the learners' ideas expressed during clinical interviews. Alonzo and Steedle suggested that the common learner conceptions serving as incorrect responses serve a similar function to interview probes. This feature distinguishes OMC from traditional multiple-choice items.

Finally, a major challenge that remains for learning progression research is to better understand how classroom teachers can use LP-based formative assessments to guide instruction. Researchers have expressed the idea that an important next step for LP research is to provide teachers with tools to respond to learner ideas (Furtak, 2012; Gunckel et al., 2012). Gunckel et al. explained that assessment data "could help teachers target instruction to students' starting points and support them in progressing towards the next level of achievement" (p. 863). Similarly, Furtak wrote, "Clearly, learning progressions need to be accompanied by other supports to help teachers adapt their instructional practices" (p. 1206). However, the researchers failed to provide specifics about how teachers can support learners in progressing along an LP or how teachers should adapt their instructional practices. Future studies should explore how LP researchers can work with teachers to use LP-based assessments to make inferences about learner thinking. Additionally, they should clearly describe examples of instructional moves that teachers can make to support learner progress along a learning progression.

Instructional interventions. When defining learning progressions in *Taking Science to School*, Duschl et al. (2007) explained that LPs are crucially dependent on instructional practices, and most learners are not able to progress along the proposed learning sequences under traditional instruction. However, the authors were hopeful that appropriate instruction *could* allow most children to attain a good understanding of the scientific frameworks and practices described in learning progressions. Duschl et al. (2011) pointed out that most of the LP studies considered in their literature review did not report on instructional interventions, even though many researchers agree with the importance of instruction-assisted learning in LPs.

However, Duschl et al. (2011) did offer the work of Furtak (2009) and Furtak, Morrison, and Henson (2010) as examples of LP research with appropriate instructional interventions. Duschl et al. (2007) hypothesized that instruction that involves having learners gather and represent data, reason about what the data mean, and apply key ideas to new situations would help learners advance along a learning progression. Moreover, such learning must take place over sustained periods of time—longer than the 2 to 3 months during which instructional interventions typically occur.

Shea and Duncan (2013) argued that LP revision needs to occur in classroom contexts through targeted instruction guided by learning progressions. The authors suggested, “It may be that the specific designs of curriculum unit(s) used in an implementation study to refine an LP (as in our LP) result in particular patterns of progress and that a different design would yield different results” (p. 28). Specifically, Shea and Duncan wondered whether an LP’s lower and upper anchors would remain the same using different instructional interventions, but intermediate steps would vary. Given this notion, the authors questioned whether or not Mohan et al.’s (2009) LP based on status-quo instruction was a “reasonable” research endeavor. Similarly, Lehrer and Schauble (2009) argued that LPs that describe student knowledge and abilities under status-quo instruction will tend to promote low expectations for learners, while those LPs tied to instructional interventions can inspire improvement in science education. Moreover, Lehrer and Schauble (2015) argued that merely describing what students have traditionally been taught misses the opportunity to reexamine our assumptions about what and how students learn. When instruction is intentionally designed to build on children's existing ideas, concepts that have traditionally been considered too difficult for children could possibly come within reach.

Yet, Mohan et al.'s (2009) research provides the baseline that is needed to answer the numerous questions about the instructional dependence of LPs that Shea and Duncan (2013) raised. Mohan et al. explained that their curriculum development and instructional intervention studies are in progress. Without first investigating the status of learner understanding under traditional instruction, researchers will not be able to claim with certainty that their work represents progress. Moreover, in their carbon cycling LP, Mohan et al. did not appear to set the "low expectations" that Lehrer and Schauble (2009) warned about, considering the fact that the vast majority of learners did not demonstrate level 4 achievement.

In line with Mohan et al. (2009), Alonzo and Steedle (2008) suggested that future studies on their force and motion LP should investigate learning under different instructional contexts. Such studies would explore the relationships among curriculum, learner responses to assessment items, and the proposed learning progression. Alonzo and Steedle hypothesized that classroom instruction can help learners transfer underlying principles about force and motion to a variety of situations, addressing issues of consistency across different problem contexts.

However, Lehrer and Schauble (2009) raised valid concerns about studies that focus on instructional interventions. For instance, the authors wondered about Songer et al. (2009), “Whether similarity in format between the embedded assessments and the curriculum support may account for most of the effects reported in relation to a comparison group” (p. 732). As Alonzo and Steedle (2008) found, learner performance on assessment is closely related to context, and classroom activities have a particularly strong influence on how learners perceive assessment items. Along these lines, Lehrer and Schauble pointed out that learners experiencing the instructional intervention in Songer et al. had the advantage of being familiar with the format of the assessments. These assessments involved the coordination of evidence and claims, and this familiar format may have cued their successful performance. Such “intervention only” approaches run the risk of conflating learner understanding with learner familiarity with assessments tied to the curricular interventions. Moreover, studies with intervention and control groups must engage learners in clinical interviews in order to investigate how participants are interpreting assessment items and how these interpretations are related to classroom instruction.

Additionally, Duncan and Gotwals (2015) raised concerns about the potential confounding effects of instruction on the validation of an LP’s assumptions. In the hypothetical case of an LP study that shows little progress in student learning, the researchers asked, “How are we to know whether the assumptions of the LP regarding expected learning are inappropriate or whether the specific instructional intervention (and its enactment) has fallen short of promoting the sort of learning reflected in the LP?” (p. 414). In this case, there is tension in determining the source of discrepancy between anticipated progress and the empirical data. Thus, Duncan and Gotwals argued that LP research must treat the instructional intervention and its implementation as a variable, along with the LPs assumptions. Developing an LP using only one instructional approach does not allow researchers to test this variable, so Duncan and Gotwals advocated that LP researchers test multiple instructional interventions during LP development.

Conclusion. This review of learning progression literature indicates that the theoretical approaches guiding LP research vary with respect to views on instruction, assessment, and conceptual change. Additionally, researchers have taken a variety of approaches to developing and structuring learning progressions. Regardless of the theoretical approaches employed in LP research, several important challenges remain.

First, researchers should be more explicit about their decision-making process when developing LPs. Second, researchers should further investigate the role of context in describing meaningful learning about a topic. Third, researchers must explore and describe how teachers can productively respond to learners' conceptions as they relate to a learning progression. Fourth, researchers must continue to design and investigate a variety of instructional interventions that aim to advance learners along an LP, comparing these interventions to traditional instruction. Finally, researchers should engage in long-term longitudinal studies to track how understanding actually develops for individuals over a long time span.

Chapter Summary

In this chapter, I presented a comprehensive literature review on learning progressions. I described the various approaches of different LP researchers and identified several challenges remaining in LP research. These challenges include researchers being more explicit about how they make decisions when developing LPs and further investigating the role of context in learning progressions. My study will address both of these challenges by explicitly describing my decision making process in developing a contextual learning progression on constructing explanations about sea level rise.

Chapter Three: Methodology

The purpose of this study was to explore the process of developing a learning progression on constructing explanations about sea level rise. During this exploration, I explicitly described my decision-making process made revisions to the learning progression based on collected data. Correspondingly, my research question was: What is a process by which a hypothetical learning progression on sea level rise is developed into an empirical learning progression using learners' explanations? This study used qualitative case study methods in order to answer this question. My case study design was a descriptive single case study with multiple embedded cases (Yin, 2014). In this chapter, I will discuss the research setting and participants, justify the use of a case study methodology, describe data collection and analysis procedures, and address issues of validity and reliability.

Case Study Justification

This study employed case study methodology because I was seeking to provide an in-depth description of how learners think about a topic. In this case, the goal was to describe how learners construct explanations about sea level rise. As Yin (2006) explained, the case study approach is appropriate to achieve an in-depth understanding when addressing a descriptive or explanatory question. Yin added that case studies allow the researcher to collect data in natural settings. This feature of case studies aligned well with my approach to learning progression research because I was seeking to understand learners' ideas and language use in the natural setting of a science classroom (a real life context).

Yin (2014) explained, "A case study is an empirical inquiry that

- investigates a contemporary phenomenon (the "case") in depth and within its real-world context, especially when
- the boundaries between phenomenon and context may not be clearly evident" (p. 16).

Yin added that a researcher would conduct a case study when the goal is to understand a real-world case and when contextual conditions are important to this understanding. In my study, I was interested in exploring several contextual features of the case, such as the instructional history of the learners.

Yin's (2014) case study approach also aligns well with situated cognition learning theory (Brown et al., 1989; Putnam & Borko, 2000; Robbins & Aydede, 2009), which informed this study. The reason I used a case study approach is that it allowed me to attend to details about the context of teaching and learning about sea level rise, which situated cognition posits are critical to understanding what has been taught and learned. When revising the sea level rise learning progression, I sought to make connections between instructional conditions and learners' developing understandings explicit.

During my classroom observations of the targeted instruction on sea level rise, I observed the conditions under which learners' prior knowledge was activated, how learners worked as a community to interpret authentic data on sea level rise, and how their ideas about matter and energy were applied to the novel context of sea level rise. Previous learning progression studies have not attended to the contextual conditions of teaching and learning (e.g., Alonzo & Steedle, 2008; Mohan et al., 2009; Duncan et al., 2009), which limits our understanding of the relationship between instruction and a learner's progress along a learning progression.

Yin's (2014) definition of case study research also included a second component. Yin wrote,

> A case study inquiry
>
> - copes with the technically distinctive situation in which there will be many more variables of interest than data points, and as one result

- relies on multiple sources of evidence, with data needing to converge in a triangulating fashion, and as another result
- benefits from the prior development of theoretical propositions to guide data collection and analysis. (p. 17)

A case study involves the collection of multiple sources of data, such as direct observations, interviews, audiovisual material, documents, and physical artifacts (Creswell, 2007; Yin). In my study, I collected multiple sources of data—written artifacts, audio-recorded interviews, and direct observations. I analyzed these data to construct a description for my case study report.

This study was an embedded single-case study with individual learners as the embedded units of analysis (Yin, 2014). The single case was the learners as a whole, whose thinking was represented by a learning progression. However, I collected empirical data on the thinking of individual learners through interviews, written artifacts, and direct observations. For this reason, individual learners served as embedded subunits within the single case study. The case was bounded by both time and place, as well as by instructional context. The case study included sixth, seventh, and eighth grade learners attending the same public middle school for the 2014-2015 school year.

Finally, Yin (2006) identified an important feature of the case study approach that was particularly useful for my learning progression study. Yin explained that case studies often involve the simultaneous collection and analysis of data, which allows the researcher to modify data collection plans while still in the field. Since I entered the field with limited experience with how learners construct explanations about sea level rise, it was critical for me to adjust data collection as I gained preliminary insights on learner thinking. For example, I found that learner explanations might have been limited on the baseline written assessment because the space designated for learner responses did not fill the entire paper. On subsequent written assessments, I increased the amount of space designated for learner responses so as not to unintentionally limit participant responses. Additionally, when giving the baseline assessment, I found that learners benefited from having access to scientific data on sea level rise when constructing scientific explanations about sea level rise. Consequently, I provided learners with data in the form of graphs as they completed subsequent written assessments and as they participated in interviews.

Case Selection and Description

As explained above, this study was an embedded single-case study of a group of learners with individual learners as the embedded units of analysis (Yin, 2014). The case was bounded because it comprised sixth, seventh, and eight grade learners taking a science course at a single public middle school during the 2014-2015 school year. The sixth and seventh graders learned about sea level rise as a real-world application of atomic-molecular theory and phase transitions. The eighth graders learned about sea level rise as part of a course that focused on Earth Space Systems. Additionally, all of the participants were developing their abilities to engage in the scientific practice of constructing explanations from evidence throughout the 2014-15 school year, as this was an instructional focus for all science teachers at the school. Since sea level rise is a socioscientific issue involving uncertainty, it was a useful context for learners to develop their abilities to construct explanations based on available evidence.

Participants. Participants in the study included sixth, seventh, and eighth grade students taking a science course in a single middle school located in a Mid-Atlantic state. The middle school was a public school in a large school district serving students in grades 6-8. It was located in a suburban area just outside of a major city. School enrollment was between 700 and 800 students, with approximately equal division among the three grades. The school was racially and ethnically diverse, though Caucasian students made up just over half of the population. Hispanic, Asian, and African-American students also made up large percentages of the population (greater than 10% for each group). The science classes at this middle school were not differentiated into different levels (e.g., gifted and talented, on-level). All students not taking a "self-contained" science course were enrolled the same science course.

In addition to the student participants, I also worked with three participating teachers. I knew all three of these participating teachers prior to beginning my research study, and they were willing and enthusiastic to participate in the research study. My previous relationships with these teachers, as well as my familiarity with their approaches to teaching, helped us collaborate closely as a teacher-researcher team. As a team, we worked to plan and carryout data collection and the targeted instruction on sea level rise that participants experienced.

Case Study Protocol

Yin (2014) explained that the case study protocol contains both the instrument to be used in the study and the procedures and rules to follow when using the protocol. Yin also explained that using a protocol is an important way to increase the reliability of a case study, as it guides the researcher in carrying out data collection. The protocol includes four sections:

1. An overview of the case study
2. Data collection procedures
3. Data collection questions
4. A guide for the case study report

Creating a protocol prior to collecting data for a case study focuses the research and helps to anticipate potential problems (Yin).

Overview of the case study. The overview of the case study includes the rationale for selecting the case, the theoretical propositions being examined, and the broader theoretical relevance of the study (Yin, 2014). The rationale for selecting this particular case was my privileged access to the study participants. During the 2013-14 school year, I was a seventh grade science teacher at the middle school participating in my study. Because of my relationships with the staff at the school, I had the ability to include participants from the sixth, seventh, and eighth grades.

As Shavelson (2009), Lehrer and Schauble (2015), and Duschl et al. (2011) argued, learning progressions will be most useful when they are developed within real classrooms in the context of a specific curriculum or teaching intervention. Shavelson explained, “Our research suggests that context—in this case teacher and teaching method—will greatly influence the validity of a learning progression interpretation of student performance” (p. 6). My relationships with the sixth, seventh, and eighth grade teachers involved in this study allowed me to work with them to target their instruction towards helping learners construct explanations about sea level rise. As Duschl et al. explained, the relationships between LPs and actual teaching and planning is understudied, and my research helped to address this gap in the literature.

Theoretical propositions. One theoretical proposition explored in this case study was that learners can be differentiated into qualitatively different levels of performance—the levels of the learning progression—and that learners will consistently demonstrate the same level of performance. While prior learning progression research has found that learners do not demonstrate the same level of performance consistently (e.g., Alonzo & Steedle, 2008; Steedle & Shavelson, 2009), this study described a *contextual learning progression*. Contextual learning progressions may potentially reduce the variability of learner performance on a learning progression because it necessarily reduces the contextual variability of learning tasks. In contrast, a learning progression on force and motion could apply to problems involving a hockey puck being pushed across ice, a stone being thrown into the air, or a box sitting on a table (Alonzo & Steedle).

An additional feature of the contextual learning progression in my study was that it fully integrated a scientific practice with a particular conceptual domain. Specifically, it integrated the practice of constructing scientific explanations with the conceptual domain of sea level rise science. Several researchers have argued that the integration of science practices with content knowledge is essential to the current definition of a learning progression (e.g., Duncan & Hmelo-Silver, 2009; Duschl et al., 2007; Jin & Anderson, 2012; Smith & Wiser, 2015). However, Duschl et al. (2011) reflected that most LP studies have failed to focus on both conceptual domains and the development of scientific practices. By integrating the practice of constructing explanations with the conceptual domain of sea level rise, I aimed to develop a learning progression that meets the research community's current definition of an LP. Additionally, I aimed to reduce the amount of variability in learner performance on the learning progression by narrowing the focus of the learning progression. Since the learning progression focused on a specific practice and a specific conceptual domain, I hoped to describe learner ideas using coherent and consistent levels of achievement.

A second theoretical proposition concerned expectations for the learning progression. These expectations were based on both the Next Generation Science Standards (NGSS Lead States, 2013) and prior science education research (Berland & McNeill, 2010; Gunckel et al., 2012; McNeill et al., 2006). The NGSS were particularly informative in developing a draft hypothetical learning progression on constructing explanations about sea level rise because the NGSS include "progressions" for both scientific practices and core disciplinary ideas. In developing the draft LP, I started by reviewing Appendices E and F of the NGSS. Specifically, I drew from the section of Appendix F labeled "Practice 6 Constructing Explanations and Designing Solutions." Also, I drew from the progressions of the following disciplinary core ideas from Appendix E: ESS2.C, PS1.A, PS3.A, and PS3.B. I chose to include these specific disciplinary core ideas because they are closely aligned with constructs related to sea level rise, such as the movement of water on Earth's surface, the thermal expansion of water, and the phase changes of water. In order to synthesize the ideas in the progressions from the NGSS appendices, I applied the descriptions of the explanation practice from Appendix F to the disciplinary core ideas from Appendix E.

In the table below, I present the hypothetical learning progression that is based on this synthesis. I used quotes to indicate when I used the exact wording from the NGSS. When quotes are not indicated, then I paraphrased or added language. To make the hypothetical learning progressions coherent and focused specifically on constructing explanations about sea level rise, I only included portions of the NGSS relevant to that topic. Also, I converted the grade bands for the learning performances (Grades K-2, Grades 3-5, Grades 6-8, and Grades 9-12) into levels 1 through 4 of the learning progression. I made this choice to align with other learning progressions research, which emphasizes that the levels of a learning progression are not necessarily aligned with particular grade bands (e.g., Berland & McNeill, 2010; Mohan et al., 2009).

Table 3

Initial Hypothetical Learning Progression (Note: Quotes indicate language taken directly from the NGSS)

	Description of Learning Performance
Level 1	Learners use "evidence and ideas to construct evidence-based accounts" of sea level rise. Learners know that "water is found in many types of places and in different forms on Earth." Learners also know that "matter exists as different substances that have observable different properties. Different properties are suited to different purposes. Objects can be built up from smaller parts."
Level 2	Learners use "evidence in constructing explanations that specify variables that describe and predict phenomena" related to sea level rise. Learners know that "most of Earth's water is in the ocean and much of the Earth's fresh water is in glaciers or underground." Learners also know that "because matter exists as particles that are too small to see, matter is always conserved even if it seems to disappear." Additionally, learners know that "moving objects contain energy. Energy can be converted from one form to another form."
Level 3	Learners construct explanations about sea level rise "supported by multiple sources of evidence consistent with scientific ideas, principles, and theories."

	Learners "apply scientific ideas, principles, and/or evidence to construct, revise, and/or use an explanation for" sea level rise. Learners know that "water cycles among land, ocean, and atmosphere, and is propelled by sunlight and gravity. Density variations of seawater drive interconnected ocean currents. Water movement causes weathering and erosion, changing landscape features." Learners also know that "the fact that matter is composed of atoms and molecules can be used to explain the properties of substances, diversity of materials, states of matter, phase changes, and conservation of matter." Additionally, learners know that "kinetic energy can be distinguished from the various forms of potential energy. Energy changes to and from each type can be tracked through physical or chemical interactions. The relationship between the temperature and the total energy of a system depends on the types, states, and amounts of matter."
Level 4	Learners construct explanations about sea level rise "supported by multiple and independent student-generated sources of evidence consistent with scientific ideas, principles, and theories." Learners "apply scientific reasoning, theory, and/or models to link evidence to the claims to assess the extent to which the reasoning and data support the explanation or conclusion." Learners know that "the planet's dynamics are greatly influenced by water's unique chemical and physical properties." Learners also know that "the sub-atomic structural model and interactions between electric charges at the atomic scale can be used to explain the structure and interactions of matter." Additionally, learners know that "the total energy within a system is conserved. Energy transfer within and between systems can be described and predicted in terms of energy associated with the motion or configuration of particles (objects)."

The hypothetical learning progression presented in *Table 3* was only an initial hypothesis about how learners construct explanations about sea level rise at different levels of sophistication. This initial draft was based solely on the expectations of the NGSS and was not based on empirical data on learner thinking about constructing explanations about sea level rise. After collecting and analyzing empirical data on learner thinking, I expected that I would be able to provide richer and more nuanced descriptions of learner performances, especially at the lower levels of the LP. Additionally, I expected that the learning progression would become more specific to the sea level rise construct, moving away from discussion of "matter" in a general sense towards a discussion of the matter involved in sea level rise.

Prior science education research also informed my expectations for the learning progression. Based on prior research, I expected that learners would only incorporate reasoning into their explanations at higher levels of the learning progression (Berland &

McNeill, 2010; McNeill et al., 2006). Second, I expected that learners will be better able to reason about matter on an atomic-molecular scale at higher levels of the learning progression (Gunckel et al., 2012). Combining these two expectations, I expected that higher levels of the learning progression would involve learners constructing explanations about sea level rise using reasoning that adheres to the principles of atomic-molecular theory. In contrast, I expected that lower levels of the learning progression would involve learners constructing incomplete explanations (Berland & McNeill; McNeill et al.) that attend to macroscopic or immediately visible features of matter (Gunckel et al.).

Data collection procedures. In this section, I will explain the types of evidence that were collected and a timeline of data collection activities. Additionally, I will describe procedures for protecting human subjects and storing data.

Types of evidence collected and timeline of data collection activities. The types of evidence that were collected were written artifacts, audio recorded interviews and transcripts, and direct observations. Additionally, I kept a researcher's journal in order to track my thinking during the study. For the seventh grade learners (n = 28), the first written artifact was a baseline assessment administered on December 2, 2014, prior to any instruction on sea level rise (please see Appendix A for the written assessment prompts). On February 2, 2015, a second written assessment was administered at the conclusion of a lesson on sea level rise. I was present in the classroom during this lesson on sea level rise and made direct observations for all five sections of seventh grade science included in this case study. During February and March, I conducted individual interviews with 7 seventh grade participants (2/19/15 to 3/12/15). All interviews were audio recorded.

Interviews were semi-structured and explored participants' everyday experiences with water and sea level rise. Interviews also explored participants' performances in constructing explanations about sea level rise verbally (see Appendix C for the interview protocol). Interview data were triangulated with data from written artifacts and direct observations.

Written assessments were also collected from sixth grade participants (n = 6) and eighth grade participants (n = 8), though data collection was less systematic, less organized, and less complete. Sixth and eighth grade learners also experienced a lesson on sea level rise, though I was not present during this lesson to make direct observations. However, I was able to conduct individual interviews with sixth grade participants (n = 5) and eighth grade participants (n = 7) during March 2015. For 4 out of 5 of the sixth grade learners, the interview occurred prior to any instruction on sea level rise. For all 7 of the eighth grade learners, the interviews occurred after the lesson on sea level rise. The data on sixth grade learners were useful in defining the lower levels of the learning progression, while data on eighth grade learners were useful in defining the higher levels of the learning progression.

Finally, I kept a researcher's journal to record my thinking about the learning progression throughout my research study. A primary goal of this research study was to provide a clear example of a process for developing a learning progression. My researcher's journal was helpful in describing and explaining modifications that I made to the descriptions of LP levels after analyzing collected data during this process.

Procedures for protecting human subjects. All data collected during this study were kept confidential to the extent permitted by law. All participants' identities were disguised through the use of pseudonyms in all written materials. Audio recordings, transcripts, written artifacts, and field notes collected during this study will remain private and will not be made publicly available. The audio-recorded data were transcribed for analysis by the researcher. Information was not recorded in such a manner that subjects can be identified, directly or through identifiers linked to subjects. The researcher kept track of which pseudonym represented each participant using a key on an electronic document saved on the researcher's computer using password protection. Audio files and transcript files were also stored on the researcher's computer using password protection. All electronic files will be destroyed after ten years. All participants were encouraged to ask the researcher questions throughout the duration of the study and were informed that they may withdraw from the study at any time without penalty.

Parent consent and student assent forms were provided to participants in the beginning of the school year prior to any data collection. Signed assent and consent forms were stored in my home until the completion of the study. All participants had access to a copy of the form and were informed that they could withdraw from the study at any time without penalty. Additionally, the students' science teachers were not aware of which students were participating in the study. In this way, students and parents were offered an extra assurance that student participation or non-participation in the study would in no way affect the student's grade or quality of instruction.

Data collection questions. Data collection questions are questions posed to the researcher, serving as a guide and reminder of the information that needs to be collected, as well as the reasons why the information needs to be collected (Yin, 2014). Each data collection question should be accompanied by the sources of evidence that are likely to address the question. The following were my data collection questions and the sources of evidence used to address each question.

1. What aspects of learners' *explanations about sea level rise* separate them into qualitatively distinct levels?
    - Written artifacts
    - Interviews
    - Direct observations

2. What aspects of learners' *conceptual understanding* of sea level rise separate them into qualitatively distinct levels?
    - Written artifacts
    - Interviews
    - Direct observations
3. What aspects of learners' *explanations* separate them into qualitatively distinct levels?
    - Written artifacts
    - Interviews
    - Direct observations
4. Are learners' performances in constructing explanations about sea level rise consistent across different learning tasks and sources of data?
    - Written artifacts
    - Interviews
    - Direct observations
5. When should a level of the learning progression be modified?
    - Researcher's journal
    - Written artifacts
    - Interviews
    - Direct observations

With the questions above, I needed to be careful to maintain my focus on the group of learners as a whole, though individual learners were the embedded subunits of analysis. As Yin (2014) explained,

> The questions should cater to the unit of analysis of the case study, which may be at a different level from the unit of data collection of the case study. Confusion will occur

> if, under these circumstances, the data collection process leads to an (undesirable) distortion of the unit of analysis…The common confusion begins because the data collection sources may be individual people (e.g., interviews with individuals), whereas the unit of analysis of your case study may be a collective…In this example, the protocol questions need to be about the organization, not the individuals. (p. 92)

I was able to avoid this confusion by focusing on developing the overall learning progression rather than simply exploring the thinking of each participant individually.

Guide for the case study report. This section served as a tentative outline for the case study report. The primary audience for my report was my dissertation committee. The substance of my report was the development of a learning progression from an initial hypothetical LP into an LP that is empirically based and partially validated. As indicated by my primary research question, I made this development clear and explicit in my case study report, justifying my decisions with empirical data collected from middle school participants. In particular, I focused on how and why I decided to create or modify different levels of the learning progression.

Data Analysis

One goal of my study was to make an analytic generalization (Yin, 2014) about the way that learners construct explanations about sea level rise at different levels of complexity. A second goal of my study was to make an analytical generalization about the way that a learning progression can be developed based on empirical data on learner thinking. Analytic generalizations are in contrast to statistical generalizations, which aim to describe a feature of some larger population. Instead, my analytical generalizations aimed to extend the findings of my single narrow case to a broader significance (Yin).

One strategy that I used when analyzing my data was to rely on theoretical propositions (Yin, 2014). As explained previously, these theoretical propositions are two-fold:

1. Learners can be differentiated into qualitatively different levels of performance—the levels of the learning progressions—and learners will consistently demonstrate the same level of performance.
2. Expectations for the learning progression are based on both the NGSS and prior learning research and are defined by the initial hypothetical learning progression (see table 3). Additionally, prior learning research suggested that higher levels of the learning progression will involve learners constructing explanations about sea level rise using reasoning that adheres to the principles of atomic-molecular theory (Berland & McNeill, 2010; Gunckel et al., 2012; McNeill et al., 2006).

These theoretical propositions guided and organized my case study analysis, indicating important contextual features to notice and what to look for in learner explanations.

A second strategy that I used when analyzing my data was to examine plausible rival explanations (Yin, 2014). A rival explanation that I examined was the notion that a learning progression *cannot* accurately describe learners' ideas. For example, Alonzo and Steedle (2008) suggested that the levels of their learning progression on force and motion might not adequately describe learners' knowledge. Sikorski and Hammer (2010) suggested that it is inaccurate to diagnose a learner as occupying a single level on a learning progression, since several studies have shown that learner performance is inconsistent across different learning task contexts (e.g., Alonzo & Steedle, 2008; Steedle & Shavelson, 2009). Thus, I analyzed my data with the assumption that learner performance cannot be classified into the coherent levels of a learning progression to explore whether or not my data supports this rival explanation.

To approach my qualitative data analysis in a systematic manner, I employed analytic induction (Denzin, 1970). Analytic induction has been the principal means by which qualitative researchers have developed and tested propositions about the nature of social life (Taylor, Bogdan, & DeVault, 2015). Moreover, analytic induction requires the researcher to formulate theories in a way that allows them to be tested through a deliberate search for negative cases (Silverman, 1985). It is a cyclical process of analyzing cases, redefining the phenomenon under study, and reformulating hypotheses (Denzin). Each negative case requires a redefinition of the phenomenon or a reformulation of hypotheses.

My first step in analyzing the written assessment, direct observation, and interview data was to develop initial codes and memos. For example, after reading each participant's claim, evidence, and reasoning on the baseline written assessment, I coded them by assigning a word or short set of words that classified these items (Lofland & Lofland, 1995; Taylor et al., 2015). These were my initial codes, which I then analyzed to determine which codes were "being used more than others and which topics and questions are being treated more than others" (Lofland & Lofland, p. 192). Through this process, known as focused coding, I was able to identify and elaborate on categories within selected codes, collapse codes, drop codes, and identify more important codes that were used to develop overarching ideas and analytic concepts. After developing initial codes, I engaged in focused coding to collapse and/or refine codes.

Along with developing and refining codes, I wrote memos to explain and elaborate on different codes (Lofland & Lofland, 1995; Taylor et al., 2015). I used elemental memos to describe analyses on relatively specific matters, I used sorting memos to analyze the elemental memos, and I used integrating memos to explain the relationships among sorting memos. Ultimately, integrating memos allowed me to develop analytic concepts.

In addition to developing analytic concepts, I also analyzed the written assessment data to inventory how participants used claim, evidence, and reasoning to construct their explanations about sea level rise. Specifically, I analyzed the structure of each explanation, including the participants' coordination of claim, evidence, and reasoning. I also analyzed how frequently specific codes could be applied to participant responses.

Validity and Reliability

Yin (2014) wrote about four principles of data collection, which can be used to establish the validity and reliability of a case study. These principles are using multiple sources of evidence, creating a case study database, maintaining a chain of evidence, and exercising care when using data from electronic sources. The first three of these principles were applicable to my case study and are further explained in the sections below.

Multiple sources of evidence. A major advantage of using case study methodology was the opportunity to use multiple sources of evidence (Yin, 2014). My rationale for collecting multiple sources of evidence was to achieve data triangulation. Data triangulation involves the coordination of multiple sources of data to develop converging lines of inquiry. Case study findings and conclusions are likely to be more convincing if they are based on several different sources of evidence, rather than just one. As Yin explained, "By developing converging evidence, data triangulation helps to strengthen the construct validity of your case study. The multiple sources of evidence essentially provide multiple measures of the same phenomenon" (p. 121). By using multiple sources of evidence (i.e., interviews, written artifacts, and direct observations), I improved the construct validity of my case study.

Case study database. I created and used an electronic case study database as a tool for organizing and documenting my data (Yin, 2014). The database comprised two separate sections—the evidentiary base (interview transcripts, written artifacts, and observation notes) and my written narrative report in response to the evidence. Maintaining the case study database improved the reliability of my study because it gives another researcher the opportunity to analyze my data and to draw his or her own conclusions independently at a later date.

Maintaining a chain of evidence. Maintaining a chain of evidence also increases the reliability of the information in a case study (Yin, 2014). Maintaining a chain of evidence is the principle that an external observer should be able "to follow the derivation of any evidence from initial research questions to ultimate case study conclusions" (p. 127). This principle also dictates that no evidence is lost, failing to receive appropriate attention when generating the findings of the case study. Thus, I made every effort to establish that I did not miss any important evidence and that my findings were based on all of the evidence available to me.

Trustworthiness

Rather than using terms such as validity and reliability, the quality of qualitative research is often framed as an issue of establishing *trustworthiness* (Brenner, 2006). Eisenhart (2006) explained, "If for some reason, representations are not considered trustworthy, then doubt is cast on the researcher's findings" (p. 573). Researchers can promote the trustworthiness of qualitative research by establishing that the researcher was present and directly participated in the scenes of action with the participants (Eisenhart). In the context of my study, I established my participation in the study through my direct observations of classroom instruction and through individual interviews with learners.

Chapter Summary

In this chapter, I justified my use of case study methodology to answer the research question and described the case study participants and context. Then, I described the case study protocol, including the overview of the case study, the data collection procedures, the data collection questions, and the guide for the case study report. Also, I described the procedures for analyzing data. Finally, I discussed issues of validity, reliability, and trustworthiness for the study. In the next chapter, I discuss the findings of my data analyses.

Chapter Four: Findings

In this chapter I report a description of the process I used to analyze empirical data to develop and begin the validation of a learning progression on students' scientific explanations about sea level rise. I begin this description by presenting my initial theory or hypothesis about how learners explain sea level rise (i.e., my initial hypothetical learning progression). My initial hypothetical learning progression is one of two generic propositions for my study. My other generic proposition is that learners will consistently demonstrate the same level of performance as described by the qualitatively different levels of the learning progression. As Lofland and Lofland (1995) explained, "The goal is, specifically, to formulate *generic propositions* that sum up and provide order in major portions of your data" (p. 182). Along with generic propositions, I also present the analytic concepts or themes that emerged during my data analysis. As Taylor et al. (2015) explained, "It is through concepts, accounts, and propositions that the researcher moves from description to interpretation and theory" (p. 183). In distinguishing between propositions and concepts, Taylor et al. explained that propositions are general statements grounded in the data that are either right or wrong. On the other hand, concepts are abstract ideas generalized from the data, which may or may not fit.

During the data analysis and writing processes, I employed analytic induction (Denzin, 1970) to test my theories about the ways learners explain sea level rise at different levels of performance. As Taylor et al. (2015) explained, qualitative researchers "develop and verify or test propositions about the nature of social life. The procedure of analytic induction has been the principal means by which qualitative researchers have attempted to do this" (p. 164). Moreover, Silverman (1985) explained that analytic induction requires the researcher to formulate theories in a way that allows them to be tested through a deliberate search for negative cases. Denzin (1970, p. 195) defined the six steps of analytic induction as follows:

1 A rough definition of the phenomenon to be explained is formulated.

2 A hypothetical explanation of that phenomenon is formulated.

3 One case is studied in light of the hypothesis, with the object of determining whether or not the hypothesis fits the facts in that case.

4 If the hypothesis does not fit the facts, either the hypothesis is reformulated or the phenomenon to be explained is redefined so that the case is excluded.

5 Practical certainty may be attained after a small number of cases have been examined, but the discovery of negative cases disproves the explanation and requires a reformulation.

6 This procedure of examining cases, redefining the phenomenon, and reformulating the hypotheses is continued until a universal relationship is established, each negative case calling for a redefinition, or a reformulation.

I constantly reformulated the draft SLR learning progression as the data analysis and writing processes unfolded. During this process, the initial hypothetical learning progression changed status and became an empirical learning progression.

In the first section of this chapter, I present findings about how the seventh grade learners (n = 26) constructed explanations about what causes SLR on the baseline written assessment. I also explain how I responded to those data to revise and reformulate the draft LP in order to fit the collected data. Next, I describe findings from the classroom observations of seventh graders learning about sea level rise, again reformulating the draft learning progression to fit the data. After discussing data from classroom observations, I present findings from the written assessments that participants completed at the conclusion of the observed lessons, and I once again redefine and reformulate the draft LP to fit the data.

After presenting my findings from the written assessments and classroom observations, I present further development of the learning progression based on interview data from a subset of sixth, seventh, and eighth grade participants. I began construction and reconstruction of the learning progression with the written assessments and classroom observations of the seventh grade participants, but then used interview data from participants of all three middle school grade levels to gain a richer and more nuanced understanding of how participants are learning to construct scientific explanations about sea level rise at different ages and grade levels. I also used interview data to begin the LP validation process using qualitative methods. During this validation process, I used the interview data in the following way:

1. First, I used the interview data to show how the data disconfirmed or contested portions of the learning progression, providing cogent student examples that support my claims (i.e., strike some pieces or rearrange them by level).
2. Second, I showed how my analysis of the student interviews confirmed portions of the learning progression, again providing cogent student responses for each of the portions that are confirmed.
3. Finally, I used interview data to add new (and therefore unexpected) material to the learning progression, providing cogent student examples to support my claims.

Initial Hypothetical Learning Progression—Prior to Data Collection

I conducted data analysis with two theoretical propositions in mind. As stated in Chapter Three, these theoretical propositions are:

1. Learners can be differentiated into qualitatively different levels of performance—the levels of the learning progressions—and learners will consistently demonstrate the same level of performance.
2. Expectations for the learning progression are based on both the NGSS and prior learning research, and they are defined by the initial hypothetical learning progression (see *Table 4*). Additionally, prior learning research suggested that higher levels of the learning progression will involve learners constructing

explanations about sea level rise using reasoning that adheres to the principles of atomic-molecular theory (Berland & McNeill, 2010; Gunckel et al., 2012; McNeill et al., 2006).

In *Table 4* below, as a reminder, I present the initial hypothetical learning progression.

Table 4

Initial Hypothetical Learning Progression (Note: Quotes indicate language taken directly from the NGSS)

	Description of Learning Performance
Level 1	Learners use “evidence and ideas to construct evidence-based accounts” of sea level rise. Learners know that “water is found in many types of places and in different forms on Earth.” Learners also know that “matter exists as different substances that have observable different properties. Different properties are suited to different purposes. Objects can be built up from smaller parts.”
Level 2	Learners use “evidence in constructing explanations that specify variables that describe and predict phenomena” related to sea level rise. Learners know that “most of Earth’s water is in the ocean and much of the Earth’s fresh water is in glaciers or underground.” Learners also know that “because matter exists as particles that are too small to see, matter is always conserved even if it seems to disappear.” Additionally, learners know that “moving objects contain energy. Energy can be converted from one form to another form.”
Level 3	Learners construct explanations about sea level rise “supported by multiple sources of evidence consistent with scientific ideas, principles, and theories.” Learners “apply scientific ideas, principles, and/or evidence to construct, revise, and/or use an explanation for” sea level rise. Learners know that “water cycles among land, ocean, and atmosphere, and is propelled by sunlight and gravity. Density variations of seawater drive interconnected ocean currents. Water movement causes weathering and erosion, changing landscape features.” Learners also know that “the fact that matter is composed of atoms and molecules can be used to explain the properties of substances, diversity of materials, states of matter, phase changes, and conservation of matter.” Additionally, learners know that “kinetic energy can be distinguished from the various forms of potential energy. Energy changes to and from each type can be tracked through physical or chemical interactions. The relationship between the temperature and the total energy of a system depends on the types, states, and amounts of matter.”
Level 4	Learners construct explanations about sea level rise “supported by multiple and independent student-generated sources of evidence consistent with scientific ideas, principles, and theories.” Learners “apply scientific reasoning, theory, and/or models to link evidence to the claims to assess the extent to which the reasoning and data support the explanation or conclusion.” Learners know that “the planet’s dynamics are greatly influenced by water’s unique chemical and physical properties.” Learners also know that “the sub-atomic structural model and interactions between electric charges at the atomic scale

	can be used to explain the structure and interactions of matter." Additionally, learners know that "the total energy within a system is conserved. Energy transfer within and between systems can be described and predicted in terms of energy associated with the motion or configuration of particles (objects)."

Based on my extensive reading of the LP literature, I anticipated that I would be able to provide richer and more nuanced descriptions of learner performances after collecting and analyzing empirical data on learner thinking. Additionally, I expected that the learning progression would become more specific to the sea level rise construct, moving away from discussion of "matter" in a general sense towards a discussion of the matter involved in sea level rise. Finally, I expected that I would need to reformulate the learning progression because my initial hypothesis about the learning progression would not fit the facts of the data I collected, as is required in the process of analytic induction (Denzin, 1970; Silverman, 1985; Taylor et al., 2015).

I began my data analysis by generating initial codes and memos in response to participants' baseline written assessments. Coding and memoing are the key activities I engaged in during data analysis. After reading each participant's claim, evidence, and reasoning on the baseline written assessment, I coded them by assigning a word or short set of words that classified these items (Lofland & Lofland, 1995; Taylor et al., 2015). These were my initial codes, which I then analyzed to determine which codes were "being used more than others and which topics and questions are being treated more than others" (Lofland & Lofland, p. 192). Through this process, known as focused coding, I was able to identify and elaborate on categories within selected codes, collapse codes, drop codes, and identify more important codes that were used to develop overarching ideas and analytic concepts.

For example, I placed all of the claims that participants made on the baseline written assessment into a table. In the column next to each claim, I assigned an initial code.

Table 5

Initial Codes for Claims on the Baseline Written Assessment

Participant	Claim	Initial Code
7-M-1	*Because of global warming melting ice therefore putting more water in the sea to increase sea level.*	Global warming, melting ice, more water
7-F-1	*Sea level rise is caused by change in the climate.*	Change in climate
7-M-2	*Sea level rises because poler ice caps melt wich makes the sea level rise*	Polar ice caps melt
7-F-2	*Global warming melts the polar ice caps, causing there to be more water in the ocean.*	Global warming melts polar ice caps, more water
7-M-3	*The increased sunlight from global warming melts the ice, putting more water in the oceans, so the sea level is rising.*	Increased sunlight from global warming melts ice, more water in oceans
7-F-3	*Through global warming glaciers and ice melts, going into the ocean, causing the sea level to rise.*	Global warming melts glaciers and ice, water goes into ocean
7-F-4	*Sea level rise is caused by increace in water in the oceans.*	More water in oceans
7-M-4	*The main cause of sea level rise is increased temperature.*	Temperature increase
7-F-5	*Sea level rise is caused by the artic glaciers melting due to global warming.*	Global warming makes arctic glaciers melt
7-F-6	*Waste that goes into the sea causes sea level rise.*	Waste added to ocean
7-M-5	*The cause of sea level rise is global warming*	Global warming
7-F-7	*The amount of rainfall and wind increases the sea level's hight.*	Increased rainfall and wind
7-M-6	n/a	n/a
7-F-8	*Global warming melts the ice caps, which means there is more water.*	Global warming melts ice, more water
7-M-7	*Sea level rise is caused by the melting ice berg*	Melting iceberg
7-F-9	n/a	n/a
7-M-8	*Sea level rise is caused by the melting of the polar ice caps.*	Melting polar ice caps
7-M-9	*Sea level rise is due to ice melting and adding more water*	Ice melting, more water in sea

	to the sea.	
7-M-10	*sea level rises due to the moon and polar ice caps*	Moon and polar ice caps
7-M-11	*Global warming from Methane releasing melts polar ice caps*	Global warming from releasing methane, melting polar ice caps
7-M-12	*The raise of atmospheric tempature causes sea level rise.*	Increasing atmospheric temperature
7-M-13	*Global warming causes sea level rise.*	Global warming
7-F-10	*Global warming*	Global warming
7-F-11	*The sea level is rising because of global warming*	Global warming
7-F-12	*I believe that sea level rise is caused and created by global warming.*	Global warming
7-F-13	*The gummy bear is smaller and grows higher*	Gummy bear grows
7-F-14	*The rise of the atmosphere causes the sea level to rise.*	Rise of atmosphere
7-M-14	*Sea level rise is caused from gradual global warming*	Gradual global warming

After labeling each claim with an initial code, I engaged in focused coding to collapse and/or refine codes. To do this, I created another table listing my initial codes for each participant. I reorganized these initial codes based on their similarities, and then created two other columns to show the development of my focused codes (which I refer to as axial and selective codes).

Table 6

Initial and Focused Codes for Claims on the Baseline Written Assessment

Initial Codes	Axial Codes	Selective Codes
Global warming, melting ice, more water	Global warming melts ice on Earth's surface and adds water to the sea	Melting ice on Earth's surface
Global warming melts polar ice caps, more water		
Global warming melts glaciers and ice, water goes into ocean		
Global warming melts ice, more water		
Increased sunlight from global warming melts ice, more water in oceans		
Ice melting, more water in	Ice melts on Earth's surface	

sea	and adds water to the sea	
Global warming from releasing methane, melting polar ice caps	Global warming melts ice on Earth’s surface	
Global warming makes arctic glaciers melt		
Melting iceberg	Melting ice on Earth’s surface	
Polar ice caps melt		
Melting polar ice caps		
Temperature increase	Global warming or climate change	Global warming or climate change
Change in climate		
Global warming		
Gradual global warming		
Increasing atmospheric temperature		
More water in oceans	More water in oceans	More water in oceans
Rise of atmosphere	Alternative conception	Alternative conception
Increased rainfall and wind		
Moon and polar ice caps		
Waste added to ocean		
Gummy bear grows	Confusion about topic of explanation	Confusion about topic of explanation

Using this coding procedure, I was able to see that many participant claims addressed the overarching idea of melting ice on Earth’s surface. Ultimately, this helped me to develop the analytic concept *global warming and ice melt cause sea level rise*.

Along with the initial and focused coding processes, I wrote memos in order to explain and elaborate on different coding categories (Lofland & Lofland, 1995; Taylor et al., 2015). Elemental memos are detailed analyses on a relatively specific matter, while sorting memos are more abstract analyses, which analyze the elemental memos. Finally, integrating memos are the most abstract type of memo, as they explain the relationships among sorting memos. Integrating memos are critical in developing the analytic concepts and generic propositions that emerge during the data analysis and writing processes.

For example, I wrote an elementary memo to explain how I was creating the initial codes for participant claims that appear in *Table 5*. This elementary memo is presented below:

When creating initial codes for the claims on the baseline written assessment, I tried to capture what the participants were saying succinctly but including all of the important details. For example, for participant 7-M-1's claim, "Because of global warming melting ice therefore putting more water in the sea to increase sea level," I created the initial code "global warming, melting ice, more water." The three phrases that make up this initial code represent the three important parts of his claim but do not include any extra language that might ultimately prevent me from seeing similarities between participant 7-M-1's claim and another participant's claim. Similarly, for participant 7-M-2's claim, "Sea level rises because poler ice caps melt wich makes the sea level rise," I created the initial code "polar ice caps melt." Again, this initial code preserves the important details of the participants claim without any distracting language.

While I used elementary memos for the initial stages of the data analysis process, I used integrating memos during the later stages of data analysis and while writing up my findings. For example, the integrating memo below shows my thinking as I further collapsed and refined my coding scheme for participant claims, evidence, and reasoning on the second written assessment:

I changed the coding scheme for the second written assessments to collapse codes and to combine the local and global data. Instead of presenting data on the four different questions on the second written assessments, I view it more as two different questions:

1. How have sea levels changed over the past 50 years? (globally or around the Chesapeake Bay)

2. How will sea levels change over the next 50 years? (globally or around the Chesapeake Bay)

> *I also collapsed many of the categories, recognizing that many of the codes were very similar. For example, most codes essentially said the same thing: sea level has risen or sea levels will rise. For the evidence and reasoning codes and tables, I collapsed the data in the same way. Also, I decided that it was not important to specify which locations are showing sea level rise (e.g., Baltimore, Manila) or which graph because the underlying concept was the same. Rather, many codes could be collapsed into the category "Graph(s) show sea level rise."*

To better present my findings from the second written assessments, I needed to combine and simplify the data so as not to distract the reader with an overwhelming number of codes and data tables. By finding more similarities among codes and participant responses, I was able to provide more convincing support for analytic concepts such as *participants learned to incorporate authentic scientific data*.

I employed matrices, which are the crossing of two lists, organized by rows and columns to diagram my coding processes (Lofland & Lofland, 1995). Specifically, I crossed the participants' responses with the codes I used to label them. These matrices are provided at the end of each discussion about a particular analytic concept/theme or a specific set of codes. In this study, I have used these matrices to incorporate quantitative data into my study to indicate how frequently a particular code was applied to participants' responses. As Silverman (1985) explained,

> Such counting helps to avoid the temptation to use merely supportive gobbets of information to support the researcher's interpretation. It gives a picture of the whole sample in summary form, highlighting deviant cases and encouraging further qualitative analysis of regularities. (p. 17)

For example, I created *Table 7* below to represent the number of times a participant's use of evidence on the second written assessment could be labeled with a particular code. The data in *Table 7* show, in summary form, that an overwhelming number of participants (18 out of 19) provided evidence from a graph or graphs that show sea level rise, which is strong support for the analytic concept *participants learned to incorporate authentic scientific data*.

Table 7

Inventory of Evidence for the Questions About How Sea Levels Have Changed Over the Past 50 Years (Globally or Around the Chesapeake Bay)

Code	Participant Names	Number of Participants
Graph(s) show sea level rise	7-M-1, 7-F-1, 7-F-2 7-M-13, 7-M-4, 7-F-8, 7-M-10, 7-F-1, 7-F-2, 7-M-6, 7-M-1, 7-M-3, 7-F-3, 7-M-6, 7-F-1, 7-M-2, 7-M-9, 7-F-11	18
Ice levels have decreased	7-M-2, 7-F-3, 7-F-6, 7-M-8, 7-M-10, 7-M-1	6
Graph(s) shows ocean warming	7-M-1, 7-M-13, 7-F-12, 7-M-13	4
Thermal expansion	7-F-3, 7-M-11	2
San Francisco sea level has risen little or decreased	7-M-2	1
Global warming has occurred over recent years	7-M-11	1
Sea levels will increase by 1 meter by 2100	7-M-13	1
Polar bear populations are shrinking	7-M-8	1

These quantitative data do not take the place of the collected qualitative data, but rather, enhances them and further refines my thinking in terms of what to look for when analyzing participant responses using qualitative methods.

Baseline Written Assessment Data

When analyzing participants' baseline written assessments, three major analytic concepts emerged. First, *participant explanation structures varied widely*. Second, many participant explanations could be labeled with the analytic concept *global warming and ice melt cause sea level rise*. Third, other participant explanations could be labeled with the analytic concept *participants held alternative conceptions about sea level rise*. For each of these three analytic concepts, I present cogent examples of participant responses that represent the analytic concepts. I also revisit these analytic concepts as I present my findings from the classroom observations, the second written assessments, and interviews.

Analytic concept: Participant explanation structures varied widely. Participants varied in terms of the structures of their explanations on the baseline written assessments. This variation affected the quality of participants' scientific explanations, as they included and coordinated claims, evidence, and reasoning to different degrees. Specifically, participants varied in regards to the ways in which they used claims to take a stance on the question asked, their use of appropriate and sufficient evidence to support claims, and their use of reasoning to connect evidence to claims. Moreover, participant explanations varied in terms of the overall coordination among claim, evidence, and reasoning. Consequently, the structure of scientific explanation emerged as a useful way in which to categorize learners at varying levels of performance. A less successful explanation would state a claim but would not support the claim with evidence and reasoning. In contrast, the most successful explanation would fully coordinate a claim with appropriate and sufficient scientific evidence and reasoning.

Participant 7-F-14's baseline written assessment exemplified an explanation that lacked proper support of a claim with sufficient and appropriate scientific evidence and reasoning. Her written assessment is shown below.

Write a scientific explanation that answers the question: What causes sea level rise?

Claim (Write a sentence that answers the question.)
The rise of the atmosphere causes the sea level to rise.

Evidence (Provide data that support your claim.)
When the atmosphere rises the sea level rises because the atmospher causes it.

Reasoning (Connect evidence to claim.)
The atmospher causes the sea level to rise.

Note: participant responses are italicized and are not edited for grammar or spelling.

Rather than provide evidence and reasoning to support her claim, participant 7-F-14 simply restated the claim that the atmosphere causes sea level rise.

In stark contrast, participant 7-M-4 provided a fully connected explanation, which coordinated claim, evidence, and reasoning. His written assessment is shown below.

> Write a scientific explanation that answers the question: What causes sea level rise?
>
> **Claim** (Write a sentence that answers the question.)
> *The main cause of sea level rise is increased temperature.*
>
> **Evidence** (Provide data that support your claim.)
> *Because of rising temperatures polar ice caps have been melting. Since there is a large amount of frozen water this causes sea level rise when it melts.*
>
> **Reasoning** (Connect evidence to claim.)
> *When temperature increases more of the polar ice melts causing sea level rise.*

Participant 7-M-4's claim stated that increased temperature is the main cause of SLR, which he then supported with two distinct pieces of evidence:

1. polar ice caps are melting
2. much of Earth's water is in the form of polar ice caps

Finally, participant 7-M-4 tied this evidence back to the claim by stating that as the temperature rises, these solid polar ice caps melt, which raises sea levels. Thus, participant 7-M-4 provided a high quality scientific explanation with a structure widely accepted in the science education research literature (e.g., McNeill et al, 2006; McNeill & Knight, 2013; Ryoo & Linn, 2014; Sandoval & Millwood, 2005; Songer et al., 2009; Swanson, Bianchini, & Lee, 2014; Zangori, Forbes, & Biggers, 2013).

After developing the analytic concept *participant explanation structures varied widely*, I conducted an analysis of how each seventh grade participant used and coordinated claims, evidence, and reasoning on the baseline written assessment. This analysis of the structure of learner explanations aligns with the work of McNeill et al. (2006), Sandoval and Millwood

(2005), Songer et al. (2009), Swanson et al. (2014), and many other science education researchers. McNeill et al. stated, “Our goal is to help students construct scientific explanations about phenomena where they justify their claims using appropriate evidence and scientific principles” (p. 54). For each baseline written assessment, learner responses were analyzed by answering “yes” or “no” to the following questions, which were identified as important components of a scientific explanation in the research literature:

1. Is a claim present that takes a stance on the question asked?
2. Does the learner justify his or her claim using appropriate evidence?
    - Is the evidence appropriate?
    - Is the evidence sufficient?
3. Does the learner include reasoning about scientific principles to explain the claim?
4. Does the learner connect the claim and evidence using scientific principles? In other words, does the learner use scientific principles to justify why the evidence supports his or her claim?

Before presenting the summary of my explanation structure analysis on the baseline written assessment, I provide examples to explain how decisions were made when answering each question.

Baseline written assessment for 7-M-1.

Write a scientific explanation that answers the question: What causes sea level rise?

Claim (Write a sentence that answers the question.)
Because of global warming melting ice therefore putting more water in the sea to increase sea level.

Evidence (Provide data that support your claim.)
There was a lot of scientific research showing that a lot of ice is melting making more water in the sea because global warming makes the planet hotter therefore making ice melt into the ocean.

Reasoning (Connect evidence to claim.)
Taking in that scientists researched for years about this, it shows that ice is actually melting and that the weather is getting warmer in the poles and making more ice melt.

In Participant 7-M-1's response, his claim was that global warming is causing sea level rise through ice melt, so I answered "yes" to the question about the claim taking a stance on the question asked. The participant's evidence about melting ice was appropriate because it aligned with the claim that global warming is causing the ice to melt. The participant's evidence was also sufficient, since he provided both the evidence that ice is melting and the evidence that the planet is hotter from global warming. The evidence supports both aspects of his claim. Therefore, I answered "yes" to the questions about whether the evidence is appropriate and sufficient. The participant's reasoning does use scientific principles to explain the claim because he explained that the temperature increase in the poles causes the melting phase change. Thus, I answered "yes" to the question about reasoning. Finally, I answered "yes" to the question about connecting the claim and evidence because the claim, evidence, and reasoning were all aligned with the idea that increasing temperatures are leading to ice melt, which causes sea level rise.

Baseline written assessment for 7-F-1.

Write a scientific explanation that answers the question: What causes sea level rise?

Claim (Write a sentence that answers the question.)
Sea level rise is caused by change in the climate.

Evidence (Provide data that support your claim.)
If there is a lot of rain at the sea and little amount of sun, then the water from the rain wont evaporize very fast. The sea level can rise also when there are large glaciers melting which increases the amount of water in the sea.

Reasoning (Connect evidence to claim.)
The less sun there is to evaporate the water the more water is left and the more huge glaciers melt the more the water in the sea which can also mean global warming is causing glaciers to melt at the sea.

In this response, the participant's claim was that a change in climate is causing sea level rise, so I answered "yes" to the question about the claim taking a stance on the question asked. The participant's evidence was hypothetical in nature and also contained the alternative conception that increased precipitation and less sunlight/evaporation are causing sea level rise. For both reasons, I answered "no" about whether the evidence was appropriate. Since the participant did not provide any concrete evidence to support the claim that a change in climate is causing sea level rise, I also answered "no" about whether the evidence was sufficient. However, the participant's reasoning does use scientific principles to explain the claim because she explained that the sun evaporates the water, and less sun will translate into less evaporation and more water left behind. She also explained that global warming will cause glacial ice melt, and the melted water will add to the sea. Both components of the explanation involve reasoning related to the conservation laws of energy and matter. Therefore, I answered "yes" to the question about reasoning. Finally, I answered "no" to the question about connecting the claim and evidence because the learner did not provide appropriate evidence supporting the claim.

Baseline written assessment for 7-F-12.

Write a scientific explanation that answers the question: What causes sea level rise?

Claim (Write a sentence that answers the question.)
I believe that sea level rise is caused and created by global warming.

Evidence (Provide data that support your claim.)
When I was watching tv once this ad came up that was saying how people (our world) are slowly killing ourselves because of pollution and global warming and that sea level rise was part of that process. The people in the ad were saying that global warming was causing many troubles in our world and I figure one of the troubles may be sea level rise.

Reasoning (Connect evidence to claim.)
Overall I believe that sea level rise is caused by global warming which I had gotten from a TV source.

In this response, the participant's claim is that global warming is causing sea level rise, so I answered "yes" to the question about the claim taking a stance on the question asked. The participant's evidence is not appropriate because it is not based on scientific data or direct observation, and it did not support the claim that global warming is causing sea level rise.

Rather, the participant simply restated the claim made in a television commercial. Thus, I answered “no” to the questions about whether the evidence is appropriate and sufficient. The participant’s reasoning does not use scientific principles to explain the claim because she merely restated the idea that her claim was based on the claim of a television commercial. So, I answered “no” to the question about reasoning. Finally, I answered “no” to the question about connecting the claim and evidence because the learner did not provide appropriate evidence or reasoning to support her claim.

Summary of explanation structures on baseline written assessment. *Table 8* below summarizes the structure of each participant’s written response on the baseline assessment. Two of the 28 seventh grade participants did not complete the baseline written assessment, yielding a total of 26 responses. In *Table 8*, I have indicated “n/a” for these two participants.

Table 8

Structures of Scientific Explanations on Baseline Written Assessments

Learner Name	Is a claim present that takes a stance on the question asked?	Does the learner justify his or her claim using appropriate evidence?	Does the learner justify his or her claim using sufficient evidence?	Does the learner include reasoning about scientific principles to explain the claim?	Does the learner connect the claim and evidence using scientific principles?
7-M-1	Yes	Yes	Yes	Yes	Yes
7-F-1	Yes	No	No	Yes	No
7-M-2	Yes	Yes	No	Yes	Yes
7-F-2	Yes	Yes	Yes	Yes	Yes
7-M-3	Yes	Yes	Yes	Yes	Yes
7-F-3	Yes	Yes	No	Yes	Yes
7-F-4	Yes	Yes	No	Yes	Yes
7-M-4	Yes	Yes	Yes	Yes	Yes
7-F-5	Yes	Yes	Yes	Yes	Yes
7-F-6	Yes	No	No	Yes	No
7-M-5	Yes	No	No	Yes	No
7-F-7	Yes	No	No	Yes	Yes
7-M-6	n/a	n/a	n/a	n/a	n/a
7-F-8	Yes	Yes	No	Yes	Yes

7-M-7	Yes	No	No	Yes	No
7-F-9	n/a	n/a	n/a	n/a	n/a
7-M-8	Yes	Yes	Yes	Yes	No
7-M-9	Yes	Yes	Yes	Yes	Yes
7-M-10	Yes	Yes	Yes	Yes	Yes
7-M-11	Yes	Yes	Yes	Yes	Yes
7-M-12	Yes	Yes	Yes	Yes	Yes
7-M-13	Yes	Yes	Yes	Yes	Yes
7-F-10	Yes	Yes	Yes	Yes	No
7-F-11	Yes	Yes	Yes	Yes	Yes
7-F-12	Yes	Yes	No	No	No
7-F-13	No	No	No	No	No
7-F-14	Yes	No	No	No	No
7-M-14	Yes	Yes	Yes	Yes	Yes
Total "Yes"	25/26 = 96%	19/26 = 73%	14/26 = 54%	23/26 = 88%	17/26 = 65%

The data indicate that 96% of learners stated a claim that takes a stance on the cause of sea level rise. Also, 73% of learners provided appropriate evidence to support the claim, while only 54% of learners provided sufficient evidence to support the claim. Finally, 88% of learners included reasoning about scientific principles to explain the claim and, 65% of learners used that reasoning to connect the evidence and claim.

Revisions to the initial hypothetical learning progression. The initial hypothetical learning progression expected learners to include in their explanations reasoning that adheres to the principles of atomic-molecular theory only at higher levels of the LP. However, on the baseline written assessment, learners were more likely to incorporate scientific reasoning (88%) than sufficient evidence (54%) or appropriate evidence (74%). These data support the notion that learners at lower levels of the LP *might* be likely to include scientific reasoning in their explanations, even when their use of scientific evidence is inappropriate and/or insufficient. Perhaps it is the inconsistency with which learners employ evidence and/or reasoning that should characterize lower levels of the LP. Moreover, many learners were not able to connect their claims and evidence using scientific principles. This inability should also characterize lower levels of the LP. Therefore, I decided to revise the first level of the LP to the following (changes are bolded):

> Learners **sometimes** use evidence and ideas to construct evidence-based accounts of sea level rise **and sometimes they rely more heavily on scientific reasoning to support their claims about sea level rise**. **Due to learners' inconsistent and/or incomplete use of both evidence and reasoning, learners often fail to connect their claims and evidence using reasoning that adheres to scientific principles.** Learners know that water is found in many types of places and in different forms on Earth. Learners also know that matter exists as different substances that have observable different properties. Different properties are suited to different purposes. Objects can be built up from smaller parts.

Similarly, level two could also be revised to describe inconsistency in using evidence and reasoning, though it is unclear how this inconsistency relates to a clear distinction between levels one and two, the two lowest levels of the learning progression. Based on my data analysis, level two should be changed to the following in order to indicate this uncertainty with which level two learners employ evidence and reasoning (changes are bolded):

> Learners use evidence **and/or scientific reasoning** in constructing explanations that specify variables that describe and predict phenomena related to sea level rise. Learners know that most of Earth's water is in the ocean and much of the Earth's fresh water is in glaciers or underground. Learners also know that because matter exists as particles that are too small to see, matter is always conserved even if it seems to disappear. Additionally, learners know that moving objects contain energy. Energy can be converted from one form to another form.

Analytic concept: Global warming and ice melt cause sea level rise. A second analytic concept that emerged from analysis of the baseline written assessment data was that most participants explained that *global warming and ice melt cause sea level rise*. Participants used such phrases as “Because of global warming melting ice” (participant 7-M-1), “Through global warming glaciers and ice melts” (participant 7-F-3), and “artic glaciers melting due to global warming” (participant 7-F-5).

This analytic concept emerged during the process of coding participants’ claims, evidence, and reasoning on the baseline written assessment. I began by creating initial codes for each participant claim, and then I revised the initial codes during the focused coding process (see appendix E for the matrices created during the coding process). I followed the same coding processes for the evidence participants used, and also for the reasoning that each participant used, on the baseline written assessments.

Participant 7-F-2’s baseline written assessment exemplifies the thinking expressed by many of the participants. Her response to the assessment is below.

> Write a scientific explanation that answers the question: What causes sea level rise?
>
> **Claim** (Write a sentence that answers the question.)
> *Global warming melts the polar ice caps, causing there to be more water in the ocean.*
>
> **Evidence** (Provide data that support your claim.)
> *1. The ice caps are melting, causing there to be more water in the ocean.*
>
> *2. If there is more water in the ocean, the sea level will rise because the ocean will over flow.*
>
> **Reasoning** (Connect evidence to claim.)
> *Global warming is making the Earth warmer, causing the ice caps to melt. After the ice caps melt, there will be more water in the ocean, causing sea levels to rise.*

Many participants, like participant 7-F-2, explained that global warming and/or higher temperatures are causing more ice on Earth to melt. Participants referred to the melting ice as “polar icecaps,” “ice,” “icecaps,” “glaciers,” “icebergs,” “ice in the North or South poles,” “giant ice caps in the North and South poles,” and/or “polar ice.” However, they generally used these terms for ice to refer to any ice in very cold places on Earth that should not be melting in the way that it is. Because temperatures have risen higher than they should have, this ice has melted more than it should have, and sea levels have risen higher than they should have.

Like participant 7-F-2's baseline written assessment, participant 7-M-3's baseline written assessment below demonstrates this line of thinking.

Write a scientific explanation that answers the question: What causes sea level rise? **Claim** (Write a sentence that answers the question.) *The increased sunlight from global warming melts the ice, putting more water in the oceans, so the sea level is rising.* **Evidence** (Provide data that support your claim.) *The avg. temp. has risen about 1 degree at the past 20 years or something. Fossil fuels are being used more.* **Reasoning** (Connect evidence to claim.) *Since global warming is increasing more ice will melt, causing sea levels to rise.*

Though participant 7-M-3 expressed the alternative conception that global warming is caused by increased sunlight, he still clearly explained that increased temperatures are causing ice to melt, which is causing sea level rise.

Participant 7-F-3's baseline written assessment also related global warming and melting ice to rising sea levels. In her response provided below, she emphasized her perspective that sea level has risen in a way that is not "normal" to her because global warming has increased the amount of melting ice.

Write a scientific explanation that answers the question: What causes sea level rise? **Claim** (Write a sentence that answers the question.) *Through global warming glaciers and ice melts, going into the ocean, causing the sea level to rise.* **Evidence** (Provide data that support your claim.) *Before global warming the sea level was normal and wasn't rising, but after global warming the sea level rose by many inches each day, because of ice melting.* **Reasoning** (Connect evidence to claim.) *When global warming melts ice and glaciers melt causing the ocean level to rise above the level it was before.*

Like participant 7-M-3, participant 7-F-3's response contained an alternative conception about sea level rise. Sea levels have not been rising by many inches each day due to global warming. However, the overarching idea remains the same: global warming is causing increased ice melt, which ultimately causes sea levels to rise to greater heights.

Analytic concept: Participants held alternative conceptions about sea level rise. A third analytic concept that emerged from the baseline written assessment data is *participants held alternative conceptions about sea level rise*. I have already discussed two such alternative conceptions in the previous section. Participant 7-M-3 explained that global warming involves increased sunlight, while participant 7-F-3 explained that sea levels are rising many inches each day. However, these alternative conceptions did not necessarily limit participants' abilities to construct productive explanations about what causes sea level rise. In both cases, the participants still employed the concept that global warming is causing increased ice melt, which is leading to higher sea levels.

Other alternative conceptions about sea level rise were not as scientifically normative, though they do have bases in everyday experience, logic, and even concepts in the eighth grade science curriculum. For example, participant 7-F-6 explained that waste added to the sea raises sea levels through weight displacement (a concept that is similar and related to volume displacement).

Write a scientific explanation that answers the question: What causes sea level rise?

Claim (Write a sentence that answers the question.)
Waste that goes into the sea causes sea level rise.

Evidence (Provide data that support your claim.)
When waste goes into the sea, the sea level starts to rise due to the weight of the waste.

Reasoning (Connect evidence to claim.)
When waste goes into the sea, the sea levels starts to rise due to the weight of the waste. Therefore, waste causes sea level rise.

Weight/volume displacement of water from human-added waste does not cause sea level rise in any significant way. However, this alternative conception does conform to scientific principles. When an object is added to water, it will sink when it is denser than water, and it will displace the water. The volume of the object will equal the increase in total volume of the water system. This alternative conception about human-generated waste also matches children's everyday experiences. When we get into a bathtub, our bodies displace the water in the tub, causing the water to rise to a greater height.

Participant 7-M-10 expressed an alternative conception about sea level rise that is closely related to concepts in the eighth grade science curriculum. In eighth grade, students learn about the Earth-moon system and the cause of the lunar tides, which participant 7-M-10 conflated with sea level rise. His baseline written assessment is presented below.

> Write a scientific explanation that answers the question: What causes sea level rise?
>
> **Claim** (Write a sentence that answers the question.)
> *sea level rises due to the moon and polar ice caps*
>
> **Evidence** (Provide data that support your claim.)
> *In some environment channels and in some books it states that the melting of polar Ice caps causes sea levels to rise. The moons gravitational pull also directs when sea levels rise or decrease. The moons gravity pulls water to where it is so the water rises or decreases*
>
> **Reasoning** (Connect evidence to claim.)
> *when the Ice melts more water goes into the sea increasing the sea level. The moons gravity pulls water towards it so when it's above the sea water gets pulled under it raising the sea level*

Like participants 7-M-3 and participant 7-F-3, participant 7-M-10 explained sea level rise in terms for melting ice, but he also included the moon's gravitational pull on the sea's water, indicating that he is unclear on what is meant by the sea level rise construct.

In the space below, I provide examples of participant claims, evidence, and reasoning from the baseline written assessment that involve a wide variety of alternative conceptions, indicating many different types and levels of understanding. First, I present claims that indicate alternative conceptions:

> 7-M-3: *The increased sunlight from global warming melts the ice, putting more water in the oceans, so the sea level is rising.*
>
> 7-M-10: *sea level rises due to the moon and polar ice caps*
>
> 7-F-6: *Waste that goes into the sea causes sea level rise.*
>
> 7-F-7: *The amount of rainfall and wind increases the sea level's hight.*
>
> 7-F-14: *The rise of the atmosphere causes the sea level to rise.*

Similarly, the following participant evidence on the baseline written assessment indicated alternative conceptions:

> 7-F-6: *When waste goes into the sea, the sea level starts to rise due to the weight of the waste.*
>
> 7-F-7: *The melting of ice berg (global warming in a sense) ice berg melt in the heat so where does the melted ice go? Exactly the ocean! the ocean takes all the water and with the extra water the ocean sea level rises.*
>
> 7-F-8: *The sea levels in the Atlantic Ocean have gone up as the weather went up.*
>
> 7-M-9: *In the national geographic television network, they had a segment on sea level rise. They said that due to global warming (heat getting trapped in the atmosphere) ice was melting and adding to the sea.*
>
> 7-M-12: *Anartica snow and icebergs are melting and causing heating of water and the water to rise.*
>
> 7-F-10: *The ice in the north and south pole is melting, which makes there be an overall higher sea level. It is predicted that it will get at least a foot higher in 5 years.*
>
> 7-F-14: *When the atmosphere rises the sea level rises because the atmospher causes it.*

Finally, the following participant reasoning on the baseline written assessment indicated alternative conceptions:

7-F-1: *The less sun there is to evaporate the water the more water is left and the more huge glaciers melt the more the water in the sea which can also mean global warming is causing glaciers to melt at the sea.*

7-M-2: *when people use cars, buses, and planes which causes exost which is carbon dixid which melts the ice*

7-F-6: *When waste goes into the sea, the sea levels starts to rise due to the weight of the waste. Therefore, waste causes sea level rise.*

7-F-7: *If the ocean is made of water, then rainfall will increase the water level.*

7-M-10: *when the Ice melts more water goes into the sea increasing the sea level. The moons gravity pulls water towards it so when it's above the sea water gets pulled under it raising the sea level*

These participant claims, evidence, and reasoning indicated a variety of different alternative conceptions. Participants 7-M-3, 7-F-3, and 7-M-10 provided explanations that aligned with the many other participants who explained SLR in terms of global warming and ice melt. However, they included the alternative conceptions that global warming involves increased sunlight (7-M-3), that sea levels are rising inches per day (7-F-3), and that the moon's gravity causes SLR (7-M-10). In contrast, other participants attributed SLR only to factors that represent alternative conceptions. For example, participant 7-F-6 used the concept of weight/volume displacement to explain that added waste causes SLR, while participant 7-F-7 explained SLR in terms of increased rain and wind. Though both categories of explanations indicating alternative conceptions represent non-normative scientific explanations, the first category is decidedly more normative than the latter. This observation suggests that even participants expressing alternative conceptions can be separated into qualitatively distinct levels or categories within a learning progression.

In the next section, I present a summary of the claims that participants made on the baseline written assessment based on the focused codes that I assigned to each participant's claim. These quantitative data provide a picture of the whole sample of written responses in the form of a summary (Silverman, 1996).

Summary of participant claims on baseline written assessment. As discussed in a previous section, I used an inductive process to develop codes for each claim to identify similarities among claims. After creating emergent codes for these claims, I applied one or more codes to categorize each claim, and this analysis allowed me to see patterns in participant claims. Codes for participant claims are presented in *Table 9* below.

Table 9

Inventory of Participants' Claims on Baseline Written Assessment

Final Code	Participant Names	Number of Participants
Melting ice on Earth's surface	7-M-1, 7-M-2, 7-F-2, 7-M-3, 7-F-3, 7-F-5, 7-F-8, 7-M-7, 7-M-8, 7-M-9, 7-M-11	11
Global warming or climate change	7-F-1, 7-M-4, 7-M-5, 7-M-12, 7-M-13, 7-F-10, 7-F-11, 7-F-12, 7-M-14	9
Alternative conception	7-M-3, 7-M-10, 7-F-6, 7-F-7, 7-F-14	5
More water in oceans	7-F-4	1
Confusion about topic of explanation	7-F-13	1

The majority of participants made claims coded as "melting ice on Earth's surface" (11) or "global warming or climate change" (9). None of the participants were assigned both of these codes, so 20 out of 26 participant responses were assigned one of these final codes. This finding provides support for the analytic concept *global warming and ice melt cause sea level rise*. By looking at the evidence and reasoning that participants used to support these claims, it is clear that participants tend to link together global warming or climate change with melting ice on Earth's surface.

Analysis of the claims participants made on the baseline written assessment also allows me to be more specific when describing the ideas that learners express at the lower and middle levels of the learning progression. In the next section, I explain changes that I made to the draft LP in response to these data.

Revisions to the draft learning progression. The lowest level of the learning progression should characterize the learner (7-F-13) who had significant confusion about the question she was asked to address when constructing her scientific explanation. Participant 7-F-13's baseline written assessment is presented below.

Write a scientific explanation that answers the question: What causes sea level rise?

Claim (Write a sentence that answers the question.)
The gummy bear is smaller and grows higher

Evidence (Provide data that support your claim.)
The molecules goes from higher concentration to lower concentration. lots of molecules go into and out of the gummy bear.

Reasoning (Connect evidence to claim.)
gummy bear is growing bigger by the molecules.

In her explanation, she referenced a gummy bear, which was completely unrelated to the written assessment prompt. I believed that this participant was accessing her memory of a previous lesson in which she was asked to construct a scientific explanation about the osmosis of water into a gummy bear.

In this lesson, students learned that molecules move from areas of higher concentration to areas of lower concentration, and this process is known as diffusion. As an example, a scented aerosol spray was released from one corner of the room, and students raised their hands when they were able to smell the scent. Over time, all students raised their hands, starting with students who are closest to the aerosol spray source and ending with students farthest from the source. In this way, students observed that the scent molecules spread out from where they were initially very concentrated to areas of the room where they were not concentrated. In a similar demonstration, students observed a gummy bear swelling with water after being placed in a dish full of water. Through a process known as osmosis, water molecules traveled into the gummy bear from an area where they had a high initial concentration (outside of the gummy bear) to an area where they had a low initial concentration (inside the gummy bear).

Participant 7-F-13's written response was tentative evidence that she has learned some complicated, abstract science in her science class. She stated a claim, provided evidence, and began to employ some level of scientific reasoning that addresses atomic-molecular theory. If the question were instead, "Write a scientific explanation that answers the question: How does a gummy bear change when placed in a dish filled with tap water," then her response may in fact be considered emerging and productive. If this were the question asked, then I would push her to provide more developed reasoning than "it grows bigger by the molecules." Yes, molecules were involved in the osmosis, but what kind of molecules, how are they moving, why are they moving, and why is that causing the gummy bear to grow in size? She began to address this in her evidence, explaining that molecules move from areas of higher concentration to lower concentration, but this concept needed to be more developed in the reasoning section of her explanation.

It is worth noting that osmosis and sea level rise share conceptual similarities. Both topics involve the movement of uncountable, invisible water molecules under changing conditions. The same thinking about water molecules that participant 7-F-13 used to explain the gummy bear demo could potentially be transferred to explain sea level rise. However, it is a relatively basic notion that a student must be aware of the topic of instruction to be able to learn in a meaningful way. Though participant 7-F-13 expressed some productive thinking in her explanation on the baseline written assessment, her lack of awareness about the sea level rise topic should represent the lowest category of the sea level rise learning progression.

Participant 7-F-13 expressed the sort of confusion that may potentially be present for a student who has not had any formal instruction on the sea level rise topic. When analyzing the explanation structure of her baseline written assessment response, I answered "no" to each question about the structure of her explanation. She did not supply a claim that took a stance on the question asked, she did not justify her claim with appropriate or sufficient evidence, and she did not include reasoning about scientific principles.

The first category or level of the LP involves "relatively unschooled or intuitive kinds of thinking and activity" (Lehrer & Schauble, 2015, p. 433). "Relatively unschooled" thinking can appear confused, disjointed, or inappropriate. An unschooled learner might also lack any awareness about a topic. The draft learning progression should be revised to include a new first level, which describes confusion or lack of awareness about sea level rise. This modification gives the learning progression a total of five different levels of performance. The following should be the description for the new lowest level of the learning progression:

> Learners express confusion or a lack of awareness about the sea level rise phenomenon when constructing scientific explanations about sea level rise. This confusion or lack of awareness prevents learners from drawing on appropriate evidence or scientific reasoning when attempting to explain the sea level rise phenomenon.

It follows that an awareness of the sea level rise phenomenon should characterize the second level of the learning progression. Additionally, incomplete explanations, explanations expressing certain alternative explanations, and less sophisticated scientific explanations should characterize the second and third levels of the learning progression.

The most basic yet logical conception expressed on the baseline written assessments was the idea that sea level is rising because humans have added waste to the sea. This claim aligns with a child's experiences with volume displacement in a bathtub. As additional objects are added to a tub, the level of water in the tub rises. Similarly, if humans add objects to the sea (e.g., plastic bottles, gunk), then the sea level will rise. A similar conception expressed on the baseline written assessment is that there is simply more water in the sea, which could be added through increased rainfall. Again, this idea aligns with a child's experiences, as empty containers will fill with rainwater during rainy weather. Additionally, increased wind can make it appear as if the sea level is higher—wind has a tendency to push matter upwards, which is a visible phenomenon. What all three of these ideas have in common—additional waste, additional water, additional wind—is that they are all visible and macroscopic. Also, these ideas are borne through a child's experience with the natural world, rather than what has been learned through the other forms that science education can take. Based on these data, the second level of the learning progression should be revised to the following (changes are in bold):

> **Learners are aware that sea level rise is occurring.** Learners sometimes use evidence and ideas to construct evidence-based accounts of sea level rise and sometimes they rely more heavily on scientific reasoning to support their claims about sea level rise. Due to learners' inconsistent and/or incomplete use of both evidence and reasoning, learners often fail to connect their claims and evidence using reasoning that adheres to scientific principles. Learners know that water is found in many types of places and in different forms on Earth. Learners also know that matter exists as different substances that have observable different properties. Different properties are suited to different purposes. Objects can be built up from smaller parts. **Learners rely on their experiences with macroscopic and visible phenomena to explain sea level**

rise. For example, learners may explain that sea level rise is caused when humans add waste (e.g., trash) to the sea, when increased rainfall enters the sea, and/or when additional wind raises the water to a greater height.

Other participants expressed claims on the baseline written assessment that involve less visible and more abstract phenomena, such as ice melting, the moon's gravity, and global warming/climate change. This appeared to be a qualitatively significant shift in conceptual understanding among participants—that the cause of sea level rise might be indirect, invisible, and somewhat complex. However, explanations at this next level still may involve important alternative conceptions, such as the idea that the moon's gravity causes sea level rise—a conflation of the cause of tides with the causes of sea level rise. Also, it is important to note that learners may appear to develop this alternative conception during the eighth grade year because this is when participants learn about the earth-moon system and lunar tides in their science classes. Therefore, the third level of the learning progression should be changed to the following (changes are in bold):

> Learners use evidence and/or scientific reasoning in constructing explanations that specify variables that describe and predict phenomena related to sea level rise. Learners know that most of Earth's water is in the ocean and much of the Earth's fresh water is in glaciers or underground. Learners also know that because matter exists as particles that are too small to see, matter is always conserved even if it seems to disappear. Additionally, learners know that moving objects contain energy. Energy can be converted from one form to another form. **When constructing scientific explanations about the causes of sea level rise, learners may express alternative conceptions that involve abstract concepts and/or invisible phenomena. For example, learners may explain that the moon's gravity causes sea level rise, conflating the cause of tides with the causes of sea level rise. Learners are aware**

of some connections between global warming/climate change and sea level rise, though they may misunderstand some of those connections. For example, learners might explain that the increased sunlight from global warming/climate change causes more ice to melt, which adds to the level of water in the sea. It is important to note that this alternative conception adheres to both the conservation of energy (the transformation of light into different forms of energy) and the conservation of matter (solid water becomes liquid water, which moves to a new location on Earth).

Finally, many participants correctly identified that global warming/climate change and ice melt on Earth's surface are causes of sea level rise. This correct understanding should characterize levels of the learning progression above level three. Thus, the fourth level of the learning progression should be modified to the following (changes are in bold):

> Learners construct explanations about sea level rise supported by multiple sources of evidence consistent with scientific ideas, principles, and theories. Learners apply scientific ideas, principles, and/or evidence to construct, revise, and/or use an explanation for sea level rise. **Learners know that sea level rise is caused by global warming/climate change, which causes increased ice melt on Earth's surface.** Learners know that water cycles among land, ocean, and atmosphere, and is propelled by sunlight and gravity. Density variations of seawater drive interconnected ocean currents. Water movement causes weathering and erosion, changing landscape features. Learners also know that the fact that matter is composed of atoms and molecules can be used to explain the properties of substances, diversity of materials, states of matter, phase changes, and conservation of matter. Additionally, learners know that kinetic energy can be distinguished from the various forms of potential energy. Energy changes to and from each type can be tracked through physical or

chemical interactions. The relationship between the temperature and the total energy of a system depends on the types, states, and amounts of matter.

Participant claims on the baseline written assessment were useful in making significant changes to the learning progression. These changes included adding a new lowest level to the LP and providing specific learner conceptions about SLR to clearly distinguish among levels two, three, and four. In the next section, I provide a summary of participant evidence on the baseline written assessment, followed by additional revisions to the learning progression based on these data.

Summary of participant evidence on baseline written assessment. I followed the same process to code and analyze participants' use of evidence on the baseline written assessment as I did for their claims. I used an inductive process to develop codes for each piece of evidence to identify similarities among evidences. After creating emergent codes for these evidences, I applied one or more codes to categorize each piece of evidence, and this analysis allowed me to see patterns in the ways in which participants used evidence. Codes for participant evidence on the baseline written assessment are presented in *Table 10* below.

Table 10

Inventory of Participants' Evidence on Baseline Written Assessment

Final Code	Participant Names	Number of Participants
Temperatures on Earth are rising; ice melt on Earth is increasing	7-M-1, 7-M-2, 7-F-3, 7-F-4, 7-M-4, 7-F-5, 7-M-5, 7-M-7, 7-M-10, 7-M-11, 7-M-14	11
Alternative conception	7-F-6, 7-F-7, 7-F-8, 7-M-9, 7-M-12, 7-F-10, 7-F-14	7
Polar ice on Earth is melting	7-F-1, 7-F-2, 7-F-10, 7-M-8, 7-M-12	5
Media sources say melting ice on Earth is causing sea level rise	7-M-9, 7-M-10, 7-M-13, 7-F-11	4
Increased fossil fuel use; increased average temperature	7-M-3	1
Television advertisement said pollution and global	7-F-12	1

warming cause sea level rise		
Confusion about topic of explanation	7-F-13	1

The inventory of participant evidence shows the specific ways in which participants are supporting their ideas about sea level rise, which aligned well with the revised draft learning progression. For example, participants who used evidence coded as “Temperatures on Earth are rising; ice melt on Earth is increasing” showed distinctly different understanding from participants characterized by level two. The description of level two states that learners “rely on their experiences with macroscopic and visible phenomena to explain sea level rise,” and both rising global average temperatures and increasing ice melt are not directly visible (though they are admittedly macroscopic). However, learners at level two of the LP can learn to incorporate authentic scientific data about temperatures and ice melt, such as the graphs found in the Intergovernmental Panel on Climate Change (IPCC, 2013) report, through targeted instruction.

Even before targeted instruction, many of the participants identified melting glaciers as a source of added seawater, which corresponded with the sentence in the level three description, “Learners know that most of Earth’s water is in the ocean and much of the Earth’s fresh water is in glaciers or underground.” Understanding that that glacial ice can be converted into seawater is an important conceptual steppingstone, which the learning progression should highlight.

Revisions to the draft learning progression. One participant (7-M-3) cited increased fossil fuel use as evidence of sea level rise. Participant 7-M-3’s baseline written assessment is presented below.

Write a scientific explanation that answers the question: What causes sea level rise? **Claim** (Write a sentence that answers the question.) *The increased sunlight from global warming melts the ice, putting more water in the oceans, so the sea level is rising.*

Evidence (Provide data that support your claim.)
The avg. temp. has risen about 1 degree at the past 20 years or something. Fossil fuels are being used more.

Reasoning (Connect evidence to claim.)
Since global warming is increasing more ice will melt, causing sea levels to rise.

Increased fossil fuel use is an important aspect of a complete explanation about the causes of sea level rise. Thus, an awareness of increased fossil fuel use as an indirect cause of sea level rise should characterize participants at levels three, four, and five of the learning progression, since these learners have moved beyond relying on macroscopic or immediately visible phenomena. However, some of these learners are not able to clearly explain the connection between fossil fuel use and sea level rise. For example, participant 7-F-14 wrote, "When the atmosphere rises the sea level rises because the atmospher causes it." I believed that participant 7-F-14 was speaking to the increased concentrations of greenhouse gases in the atmosphere due to fossil fuel use, though she could not yet articulate this idea. To account for explanations like this, I modified the description of level three to the following (changes in bold):

> Learners use evidence and/or scientific reasoning in constructing explanations that specify variables that describe and predict phenomena related to sea level rise. Learners know that most of Earth's water is in the ocean and much of the Earth's fresh water is in glaciers or underground. Learners also know that because matter exists as particles that are too small to see, matter is always conserved even if it seems to disappear. Additionally, learners know that moving objects contain energy. Energy can be converted from one form to another form. When constructing scientific explanations about the causes of sea level rise, learners may express alternative conceptions that involve abstract concepts and/or invisible phenomena. For example, learners may explain that the moon's gravity causes sea level rise, conflating the

cause of tides and the causes of sea level rise. Learners are aware of some connections between global warming/climate change and sea level rise, though they may misunderstand some of those connections. For example, learners might explain that the increased sunlight from global warming/climate change causes more ice to melt, which adds to the level of water in the sea. It is important to note that this alternative conception adheres to both the conservation of energy (the transformation of light into different forms of energy) and the conservation of matter (solid water becomes liquid water, which moves to a new location on Earth). **Though learners may hold alternative conceptions about global warming/climate change, they understand that human use of fossil fuels has contributed to global warming/climate change. They are aware of connections among fossil fuel use, the atmosphere, global warming, and sea level rise, though they are unable to clearly explain these connections in a scientifically normative way.**

Many participants expressed alternative conceptions when providing evidence for the causes of sea level rise, which was a part of my revised characterization of level two. A new example of an alternative conception about sea level rise is the idea that an iceberg would contribute to sea level rise, even though icebergs already occupy volume in the sea in solid form because they are already floating in the sea. Participant 7-M-12 used the melting of icebergs as evidence on his baseline written assessment, shown below.

Write a scientific explanation that answers the question: What causes sea level rise?

Claim (Write a sentence that answers the question.)
The raise of atmospheric tempature causes sea level rise.

Evidence (Provide data that support your claim.)
Anartica snow and icebergs are melting and causing heating of water and the water to rise.

Reasoning (Connect evidence to claim.)
Ice melts on water and pushes water up.

This alternative conception is common among learners and should be added to the descriptions of level two and three. Thus, I modified the description of level two to the following (changes are in bold):

> Learners are aware that global sea level rise is occurring. Learners sometimes use evidence and ideas to construct evidence-based accounts of sea level rise and sometimes they rely more heavily on scientific reasoning to support their claims about sea level rise. Due to learners' inconsistent and/or incomplete use of both evidence and reasoning, learners often fail to connect their claims and evidence using reasoning that adheres to scientific principles. Learners know that water is found in many types of places and in different forms on Earth**, such as icebergs and glaciers. However, learners may express the idea that icebergs contribute to sea level rise when they melt, rather than understanding that melting ice must originate from land in order to contribute to sea level rise**. Learners also know that matter exists as different substances that have observable different properties. Different properties are suited to different purposes. Objects can be built up from smaller parts. Learners rely on their experiences with macroscopic and visible phenomena to explain sea level rise. For example, learners may explain that sea level rise is caused when humans add waste (e.g., trash) to the sea, when increased rainfall enters the sea, and/or when additional wind raises the water to a greater height.

Also, I modified level three of the LP to the following (changes are in bold):

> Learners use evidence and/or scientific reasoning in constructing explanations that specify variables that describe and predict phenomena related to sea level rise. Learners know that most of Earth's water is in the ocean and much of the Earth's fresh water is in glaciers or underground. **However, learners may express the idea**

that icebergs contribute to sea level rise when they melt, rather than understanding that melting ice must originate from land in order to contribute to sea level rise. Learners also know that because matter exists as particles that are too small to see, matter is always conserved even if it seems to disappear. Additionally, learners know that moving objects contain energy. Energy can be converted from one form to another form. When constructing scientific explanations about the causes of sea level rise, learners may express alternative conceptions that involve abstract concepts and/or invisible phenomena. For example, learners may explain that the moon's gravity causes sea level rise, conflating the cause of tides and the causes of sea level rise. Learners are aware of some connections between global warming/climate change and sea level rise, though they may misunderstand some of those connections. For example, learners might explain that the increased sunlight from global warming/climate change causes more ice to melt, which adds to the level of water in the sea. It is important to note that this alternative conception adheres to both the conservation of energy (the transformation of light into different forms of energy) and the conservation of matter (solid water becomes liquid water, which moves to a new location on Earth). Though learners may hold alternative conceptions about global warming/climate change, they understand that human use of fossil fuels has contributed to global warming/climate change. They are aware of connections among fossil fuel use, the atmosphere, global warming, and sea level rise, though they are unable to clearly explain these connections in a scientifically normative way.

I added the alternative conception about melting icebergs contributing to sea level rise to levels two and three because the baseline written assessment data did not allow me to make a claim that this alternative conception should characterize one level and not the other. As I analyze and present my findings on the second written assessment, classroom observation, and interview data, I will further explore what does and does not allow me to distinguish among the different levels of the LP.

In the next section, I will present a summary of participant reasoning on the baseline written assessment, as I did with claims and evidence in the preceding sections. However, analysis of the reasoning on the baseline written assessment did not allow me to make any additional revisions to the draft LP. Thus, after presenting the summary of participant reasoning, I will then present my findings from the classroom observation.

Summary of participant reasoning on baseline written assessment. As with participant claims and evidence on the baseline written assessment, I used an inductive process to develop codes for each participant's reasoning on the baseline written assessment. After creating emergent codes for these reasonings, I applied one or more codes to categorize them. This analysis allowed me to see patterns in the ways in which participants used reasoning to support their claims. Codes for participant reasoning on the baseline written assessment are presented in *Table 11* below.

Table 11

Inventory of Participants' Reasoning on Baseline Written Assessment

Final Code	Participant Names	Number of Participants
Increased temperatures cause ice to melt, and melted water adds to the sea, raising the sea level	7-M-1, 7-F-2, 7-M-3, 7-F-3, 7-M-4, 7-F-5, 7-M-5, 7-F-8, 7-M-9, 7-M-10, 7-M-11, 7-F-11, 7-M-14	13
Alternative conception	7-F-1, 7-M-2, 7-F-6, 7-F-7, 7-M-10	5
Additional water occupies space	7-F-4, 7-M-12, 7-M-13	3
Increased fossil fuel use raises temperatures	7-F-10	1
Global warming causes sea level rise according to a television source	7-F-12	1
The atmosphere causes sea level to rise	7-F-14	1
Icebergs cause sea level rise	7-M-7	1

Polar bears are dying because the ice they need to live is melting	7-M-8	1
Confusion about topic of explanation	7-F-13	1

The data on participant reasoning align well with the changes I have made to the LP based on other data thus far. Participant 7-M-2 provided a particularly useful example of learners who are unclear about the relationships among fossil fuel use, the atmosphere, global warming, and sea level rise (described by level two). He wrote, "W*hen people use cars, buses, and planes which causes exost which is carbon dixid which melts the ice"*. There was evidence that this learner knew that carbon dioxide emissions lead to ice melting, but he misunderstood the complexities of the science and the indirect effect of carbon dioxide on ice melt (i.e., the greenhouse effect).

Based on the data in *Table 11*, half of participants used the scientific reasoning embodied by the analytic concept *global warming and ice melt cause sea level rise*. This analytic concept corresponds to the code "increased temperatures cause ice to melt, and melted water adds to the sea, raising the sea level," which I used to label 13 out of 26 participants. This finding reinforced the notion that the relationships among global warming, ice melt, and sea level rise should occupy a central position in the sea level rise LP.

In the next section, I provide a summary of my classroom observations of a sea level rise lesson that represents targeted instruction on the topic. In contrast to the static data from the baseline written assessment, the classroom observation provided more dynamic data. These data indicated the ways in which participants were actively learning about sea level rise through targeted instruction. In particular, the lesson was targeted towards student learning about the sea level rise construct known as thermal expansion, as well as improving students' capacities to incorporate authentic scientific data into their sea level rise explanations.

Classroom Observation Data

In this section, I introduce two new analytic concepts that emerged when analyzing the classroom observation data. The first analytic concept is *participants learned about thermal expansion as a fundamental aspect of sea level rise*. The second analytic concept is *participants learned to incorporate authentic scientific data*. After presenting these two new analytic concepts, I then provide examples from the classroom observations to demonstrate them.

Analytic concept: Participants learned about thermal expansion as a fundamental aspect of sea level rise. On the baseline written assessment, no participants identified the thermal expansion of water as a cause of sea level rise. Yet, the thermal expansion of ocean water is the largest single contributor to sea level rise (Boesch et al, 2013; IPCC, 2013). Thus, any targeted instruction on explaining the causes of sea level rise should involve the construct of thermal expansion as the primary cause of sea level rise. During classroom observations, I observed a seventh grade teacher explicitly teaching about thermal expansion and participants expanding their conceptions of sea level rise to include thermal expansion.

In order to understand the thermal expansion construct, participants must have a basic understanding of atomic-molecular theory. As liquid water increases in temperature, water molecules move faster and spread farther apart, decreasing the density of water and expanding the total volume that the liquid molecules occupy. The targeted instruction during the classroom observation involved participants visualizing this change among water molecules and relating this phenomenon to authentic scientific data on thermal expansion. After watching a video clip that helped students to visualize this change, participant 7-M-14 explained, "As the water heated up, the molecules started spreading out more, and they started moving faster because there was more energy." Participant 7-F-5 added, "Since

Earth's temperature is rising, um, the water in the oceans is expanding. It's only expanding a little bit, but it's so much water, that it causes sea level rise." After learning about thermal expansion through targeted instruction, participants should be expected to incorporate thermal expansion into their scientific explanations about sea level rise.

Analytic concept: Participants learned to incorporate authentic scientific data. The second analytic concept that emerged when analyzing the classroom observation data was *participants learned to incorporate authentic scientific data*. On the baseline written assessments, participant relied on background knowledge when identifying evidence for the causes of sea level rise. During the targeted instruction, the teacher explicitly worked to teach learners how to incorporate authentic scientific data into their explanations about sea level rise, such as graphs from the IPCC (2013) report.

During the observed lesson, participant 7-F-5 was at a table with three other students, and they worked together to summarize what different scientific graphs showed. At another table, participant 7-M-14 related the "Change in Global Average Upper Ocean Heat Content" graph to the video clip watched during the lesson.

> Participant 7-M-14: Because the video showed us how heat makes the water expand. [pointing to the graph] This shows…the content of the ocean is going up [pointing to the graph]. The interval is by 40.

During the observed lesson, participants were encouraged to make connections such as this in order to incorporate them into their explanations about sea level rise.

Description of the classroom observations. On February 2, 2015, I observed a full day of instruction of the participating seventh grade teacher's classes. She taught five sections of the same course, and all lessons were intended to follow the same agenda with the same activities. First period was 46 minutes long, while the other four periods were 45 minutes long. The 28 seventh grade participants were distributed among these five sections.

For the duration of each class period, students were seated in square tables with four seats per table. These squares were spaced evenly throughout the room. The teacher spent the majority of the class period at the front of the room, where the Promethean board was stationed. She used this Promethean board to post information, show video clips, and project graphs during whole class discussions.

The lesson began with "fun facts" related to Ground Hog's Day and Black History Month. Following a brief discussion about the fun facts, students were asked to write "no homework" in their assignment books. Then, standing at the front of the room, the teacher asked students to recall their responses to the baseline written assessment from December 2, 2015, exactly two months earlier. During period one, the following exchange occurred:

> Teacher: What did we do with claim, evidence, and reasoning last time with global warming. It was a while ago.
>
> Student 1: To explain how…I remember it being boxes and um we had to say why and a little bit to do it we had to turn it in.
>
> Participant 7-M-14: I think it was about sea level rise and we had to say how it…
>
> Student 2: We had to explain what happens to global warming. When ice melted it becomes water and it becomes global warming.
>
> Student 3: When the ice turns into water it absorbs more light and it happens faster.
>
> Teacher: What did you use as evidence last time?

After the teacher asked this question, the students were silent and did not respond.

Recently, students had been learning about the structures of atoms and molecules, the states of matter, and phase changes. However, they had not learned anything specifically about sea level rise, global warming, or climate change. After several seconds of wait time, the teacher explained, "I have two videos to go along with what you have learned about with atoms and molecules. Then, we will look at some graphs that you can use as evidence, so we can keep using claim, evidence, and reasoning." Scaffolding student explanations with a claim, evidence, and reasoning had been an instructional focus throughout the year, and students were now being asked to apply this explanation structure to the atomic-molecular basis of sea level rise.

The teacher showed a short YouTube video clip, which explained the thermal expansion of water—how water molecules spread farther apart as they increase in temperature and gain kinetic energy. The video clip also demonstrated an experiment in which a light bulb was used to heat water inside of a plastic two-liter bottle. As the water heated, it rose up through a straw, which was sticking out through the bottle cap (click here to watch the video clip). The video demonstration provided students with evidence that water expands as its temperature increases. After the video, the following exchange occurred during period one:

Teacher: Who can summarize what was said?

Student 4 described the set-up of the demonstration involving the straw, light bulb, and two-liter bottle.

Student 4: This experiment is supposed to show how water expands with heat.

Teacher: Who else can explain the video?

Participant 7-F-5: Since Earth's temperature is rising, um, the water in the oceans is expanding. It's only expanding a little bit, but it's so much water, that it causes sea level rise.

After showing and discussing the first video clip, the teacher showed a second video clip that simulated water molecules spreading farther apart as they are heated (click here to watch the video clip).

Teacher: That was quick, what did that show?

Participant 7-M-14: As the water heated up, the molecules started spreading out more, and they started moving faster because there was more energy.

After watching and discussing the second video clip, the teacher asked the students to analyze a set of graphs related to sea level rise (see Appendix D). The graphs were printed on 8” by 11” paper and organized into a manila folder for each group. Students were seated at square tables with four seats per table. Students worked in groups of three to four to discuss each graph, one by one.

Participant 7-F-5 was at a table with three other students, and they worked together to summarize what each graph showed. At another table, participant 7-M-14 related the “Change in Global Average Upper Ocean Heat Content” graph to the video clip. Participant 7-M-14 explained, “Because the video showed us how heat makes the water expand [pointing to the graph] this shows…the content of the ocean is going up [pointing to the graph]. The interval is by 40.”

After giving students approximately 7 minutes to discuss the six graphs at their tables, the teacher led a whole class discussion to explain each graph. As part of this discussion, students read aloud the summary given above each graph. Additionally, students had the opportunity to clarify what different aspects of the graphs were indicating, such as the use of different colors to indicate different data sets.

After discussing the six graphs, the teacher handed out a written assessment. Students were asked to complete the written assessments individually, using the graphs at their tables as evidence, when appropriate. Students had the remainder of class to complete the written assessment, and most students appeared to have sufficient time to record their thoughts on paper. Some students finished earlier than others and had time to complete an additional written assessment, which was printed on the back of the handout.

Each class period was given a specific question to respond to on their written assessment (see appendix A for all of the written assessment prompts). The question assigned to each class period is given in the *Table 12* below. For each question, participants were prompted to include a claim, evidence, and reasoning, as they were on the baseline written assessment.

Table 12

Questions Asked to Each Class Period on the Second Written Assessment

Class Period	Question on Written Assessment Prompt
1	How will the global average sea level change over the next 50 years?
3	How has the global average sea level changed over the past 50 years?
4	How has the sea level around the Chesapeake Bay changed over the past 50 years?
6	How has the global average sea level changed over the past 50 years?
7	How will sea level around the Chesapeake Bay change over the next 50 years?

After watching the video and while discussing the graphs, participants asked questions and made connections when making sense of the data. Quotes from participants during the observed sea level rise lesson constituted evidence of learning tied to targeted instruction about the topic. It was possible to relate this evidence to participant responses on the baseline written assessment, the second written assessment, and individual interviews. *Table 13* below presents cogent participant quotes from the lesson, indicating the class period and context for each quote.

Table 13

Student Quotes from the Observed Lesson on Sea Level Rise

Class Period	Participant	Context	Quote
1	7-F-5	Explaining the first video clip	*Since Earth's temperature is rising, um, the water in the oceans is*

			expanding. It's only expanding a little bit, but it's so much water, that it causes sea level rise.
1	7-M-14	Explaining the second video clip	*As the water heated up the molecules started spreading out more and they started moving faster because there was more energy.*
1	7-M-14	Explaining graph four	*Because the video showed us how heat makes the water expand [pointed to graph] this shows…The content of the ocean is going up [pointing to the heat content of the ocean graph] The interval is by 40.*
3	7-M-1	Summarizing the first video clip	*How water expands.*
3	7-M-1	Asking the teacher a question about Graph One	7-M-1: *Why are some of them shorter?* Teacher: *Because they started taking data later.* Student: *But it's showing similar results.*
3	7-F-12	Explaining Graph Two to her table during small group discussion	*This map shows the sea level around the globe…you can see around Manila, where it's red, the sea level is higher and where it's blue, it's lower…*
3	7-M-7	While discussing the graphs in small groups	Student: *I know because of the, if the temperature were to rise, wouldn't that cause a decrease though, because there would be more evaporation?* 7-M-7: *Because some of the water would evaporate.*
6	7-M-13	Summarizing the first video clip	Student: *Water rises when it's heated.* 7-M-13: *Water EXPANDS when it's heated.*
6	7-F-1	Discussing Graph Two as a whole class	*This is the satellite image of different water body places and it shows that most of them are increasing or neutral.*

Revisions to the draft learning progression. Based on the two analytic concepts that emerged from the classroom observation data, I decided to make revisions to the draft learning progression. Specifically, I added language about using thermal expansion to explain sea level rise at levels 4 and 5 of the LP. Also, I added language about incorporating authentic scientific data to levels 2, 3, 4, and 5 of the LP. I chose to incorporate language about using authentic scientific data at lower levels of the LP (levels 2 and 3) rather than language about thermal expansion because this scientific practice seemed more accessible to participants than the abstract concept of thermal expansion, based on my classroom observations and experiences as a middle school science and high school chemistry teacher. Grasping thermal expansion requires some level of understanding of the underlying atomic-molecular and kinetic molecular theories, which I had already expected learners to grasp only at higher levels of the LP (levels 4 and 5). Consequently, I made the following revision to levels 2, 3, 4, and 5 of the LP, found in *Table 14*, below (changes are in bold).

Table 14

Revised Draft Learning Progression, Levels 2 to 5

	Description of Learning Performance
Level 2	Learners are aware that global sea level rise is occurring. Learners sometimes use evidence and ideas to construct evidence-based accounts of sea level rise and sometimes they rely more heavily on scientific reasoning to support their claims about sea level rise. Due to learners' inconsistent and/or incomplete use of both evidence and reasoning, learners often fail to connect their claims and evidence using reasoning that adheres to scientific principles. **Through targeted instruction, learners can begin to use authentic scientific data as evidence when explaining sea level rise.** Learners know that water is found in many types of places and in different forms on Earth, such as icebergs and glaciers. However, learners may express the idea that icebergs contribute to sea level rise when they melt, rather than understanding that melting ice must originate from land in order to contribute to sea level rise. Learners also know that matter exists as different substances that have observable different properties. Different properties are suited to different purposes. Objects can be built up from smaller parts. Learners rely on their experiences with macroscopic and visible phenomena to explain sea level rise. For example, learners may explain that sea level rise is caused when humans add waste (e.g., trash) to the sea, when increased rainfall enters the sea, and/or when additional

	wind raises the water to a greater height.
Level 3	Learners use evidence and/or scientific reasoning in constructing explanations that specify variables that describe and predict phenomena related to sea level rise. **Through targeted instruction, learners can use authentic scientific data as evidence in a consistent way when explaining sea level rise and are able to connect these data to their claims using scientific reasoning.** Learners know that most of Earth's water is in the ocean and much of the Earth's fresh water is in glaciers or underground. However, learners may express the idea that icebergs contribute to sea level rise when they melt, rather than understanding that melting ice must originate from land in order to contribute to sea level rise. Learners also know that because matter exists as particles that are too small to see, matter is always conserved even if it seems to disappear. Additionally, learners know that moving objects contain energy. Energy can be converted from one form to another form. When constructing scientific explanations about the causes of sea level rise, learners may express alternative conceptions that involve abstract concepts and/or invisible phenomena. For example, learners may explain that the moon's gravity causes sea level rise, conflating the cause of tides and the causes of sea level rise. Learners are aware of some connections between global warming/climate change and sea level rise, though they may misunderstand some of those connections. For example, learners might explain that the increased sunlight from global warming/climate change causes more ice to melt, which adds to the level of water in the sea. It is important to note that this alternative conception adheres to both the conservation of energy (the transformation of light into different forms of energy) and the conservation of matter (solid water becomes liquid water, which moves to a new location on Earth). Though learners may hold alternative conceptions about global warming/climate change, they understand that human use of fossil fuels has contributed to global warming/climate change. They are aware of connections among fossil fuel use, the atmosphere, global warming, and sea level rise, though they are unable to clearly explain these connections in a scientifically normative way.
Level 4	Learners construct explanations about sea level rise supported by multiple sources of evidence consistent with scientific ideas, principles, and theories. **Learners consistently use authentic scientific data as evidence.** Learners apply scientific ideas, principles, and/or evidence to construct, revise, and/or use an explanation for sea level rise. Learners know that sea level rise is caused by global warming/climate change, which causes increased ice melt on Earth's surface. Learners know that water cycles among land, ocean, and atmosphere, and is propelled by sunlight and gravity. Density variations of seawater drive interconnected ocean currents. Water movement causes weathering and erosion, changing landscape features. Learners also know that the fact that matter is composed of atoms and molecules can be used to explain the properties of substances, diversity of materials, states of matter, phase changes, and conservation of matter. Additionally, learners know that kinetic energy can be distinguished from the various forms of potential energy. Energy changes to and from each type can be tracked through physical or

	chemical interactions. The relationship between the temperature and the total energy of a system depends on the types, states, and amounts of matter**. Learners also know that thermal expansion is a significant cause of sea level rise and can explain how thermal expansion causes sea level rise using principles of atomic-molecular theory.**
Level 5	Learners construct explanations about sea level rise supported by multiple and independent student-generated sources of evidence consistent with scientific ideas, principles, and theories. **Learners consistently use authentic scientific data as evidence.** Learners apply scientific reasoning, theory, and/or models to link evidence to the claims to assess the extent to which the reasoning and data support the explanation or conclusion. Learners know that the planet's dynamics are greatly influenced by water's unique chemical and physical properties. Learners also know that the sub-atomic structural model and interactions between electric charges at the atomic scale can be used to explain the structure and interactions of matter. Additionally, learners know that the total energy within a system is conserved. Energy transfer within and between systems can be described and predicted in terms of energy associated with the motion or configuration of particles (objects). **Consequently, learners are able to explain sea level rise using the constructs glacial ice melt and thermal expansion.**

In the next section, I present my findings from analysis of the second written assessment. This assessment was administered at the conclusion of the classroom observation and was identical to the baseline written assessment in format, though content was slightly different. I begin the section by revisiting themes that emerged during analyses of the baseline written assessment and classroom observation data, such as *participant explanation structures varied widely*.

Second Written Assessment Data

Similar to my findings from the baseline written assessment, the second written assessment data supported the analytic concept: *participant explanation structures varied widely*. As with the baseline assessments, participant explanations varied widely with respect to the inclusion and coordination of claims, evidence, and reasoning. Nearly all students were able to make an appropriate claim, taking a stance in response to the question asked in the explanation prompt. However, the differences among participant explanations became more extreme, as some participants learned to incorporate multiple and relevant pieces of evidence and reasoning involving more than one scientific principle, while other participants failed to support their claims with evidence and reasoning. For example, participant 7-F-3 wrote:

> Write a scientific explanation that answers the question: How has the global average sea level changed over the past 50 years?
>
> **Claim** (Write a sentence that answers the question.)
> *The average sea level has risen over the past 50 years because of the temperature rising from global warming.*
>
> **Evidence** (Provide data that support your claim.)
> *Global warming causes water molecules to spread out, so the water would expand more causing sea levels to go up. Also the sea level in the Chesapeake Bay has risen about a foot over the past 50 years and the amount of ice has decreased. So this shows that the high temperatures have melted the glaciers.*
>
> **Reasoning** (Connect evidence to claim.)
> *The high temperatures from global warming makes water molecules to spread out and make water expand leading to sea level rise. Also having les ice would show that temperatures would make sea level to rise. Global warming is making the global average sea level to change over the past 50 years.*

Participant 7-F-3 wrote a sophisticated explanation not seen on any baseline written assessment that incorporates sea level rise data on the Chesapeake Bay, as well as data on the amount of ice present. Not only did she present relevant data, but she carefully explained what the data mean—the extra heat from global warming has melted glaciers, which is why there were lower ice measurements and why sea levels around the Chesapeake Bay were rising. After learning about thermal expansion, she was able to take her explanation a step further, reasoning that higher temperatures from global warming have caused the water molecules to spread out, leading to sea level rise. At the end, she tied her reasoning and evidence about global warming back to her claim about how average sea levels have increased over the past 50 years. Participant 7-F-3 provided a high level explanation in terms of both structure and content.

In contrast, participant 7-F-9 did not present a claim that directly addressed the explanation prompt. She also failed to present relevant and appropriate evidence and scientific reasoning to support her claim. Participant 7-F-9 wrote:

Write a scientific explanation that answers the question: How has the global average sea level changed over the past 50 years? **Claim** (Write a sentence that answers the question.) *In 50 years it means that the sea level relative to the 1900-1905 mean that of the longest running data set, and with all data sets aligned to have the same value in 1993.* **Evidence** (Provide data that support your claim.) *The Evidence is that when* **Reasoning** (Connect evidence to claim.)

Both participants 7-F-9 and 7-F-3 participated in the same lesson within the same classroom. However, at the end of the lesson, these two participants were able to produce dramatically different products. In terms of the sea level rise LP, participant 7-F-3 should be associated with an upper level of the LP, while participant 7-F-9 should be associated with a lower level of the LP.

Participant 7-F-11 provided an explanation on the second written assessment that fell somewhere between participants 7-F-3 and 7-F-9 in terms of the structure of coordinating claim, evidence, and reasoning. Participant 7-F-11 wrote:

Write a scientific explanation that answers the question: How has the sea level around the Chesapeake Bay changed over the past 50 years? **Claim** (Write a sentence that answers the question.) *the bay water level increased* **Evidence** (Provide data that support your claim.) *Sience 1900 the water level increased from -0.25 ft to 0.82 ft. that is more than a foot.* **Reasoning** (Connect evidence to claim.) *the evidence shows that the water level increased by more than a foot during a time period of 100 years.*

Participant 7-F-11 directly addressed the explanation prompt with her claim. She also provided relevant and appropriate data, citing the specific change in water level since 1900, which she determined from one of the graphs that her teacher provided. However, her explanation lacked reasoning using scientific principles. To improve the structure of her explanation, she needed to incorporate some of the concepts that she learned during class to explain why the water level has increased more than a foot. Just before writing her explanation, she learned about thermal expansion and glacial ice melt. Thus, her teacher expected her to incorporate that learning into the written assessment, much like participant 7-F-3 did on her written assessment.

Summary of explanation structures on second written assessment. As a group, the seventh grade participants showed wide variation in terms of the structures of their scientific explanations on the second written assessment. *Table 15* below summarizes the structure of each participant's response. As I did for the baseline written assessment, I analyzed each response to determine whether or not the participant made a successful claim, used appropriate and sufficient evidence, included scientific reasoning, and connected the claim and evidence using that scientific reasoning.

Table 15

Structures of Scientific Explanations on Second Written Assessments

Learner Name	Is a claim present that takes a stance on the question asked?	Does the learner justify his or her claim using appropriate evidence?	Does the learner justify his or her claim using sufficient evidence?	Does the learner include reasoning about scientific principles to explain the claim?	Does the learner connect the claim and evidence using scientific principles?
7-M-1	Yes	Yes	Yes	Yes	Yes
7-F-1	Yes	Yes	Yes	No	No
7-M-2	Yes	No	Yes	No	No
7-F-2	Yes	Yes	Yes	No	No
7-M-3	Yes	Yes	Yes	No	No

7-F-3	Yes	Yes	Yes	Yes	Yes
7-F-4	Yes	Yes	Yes	Yes	Yes
7-M-4	Yes	Yes	Yes	No	No
7-F-5	Yes	Yes	Yes	No	No
7-F-6	Yes	Yes	Yes	No	No
7-M-5	n/a	n/a	n/a	n/a	n/a
7-F-7	Yes	Yes	Yes	No	No
7-M-6	Yes	No	Yes	No	No
7-F-8	Yes	Yes	Yes	Yes	Yes
7-M-7	n/a	n/a	n/a	n/a	n/a
7-F-9	No	No	No	No	No
7-M-8	Yes	Yes	Yes	Yes	Yes
7-M-9	Yes	No	Yes	No	No
7-M-10	n/a	n/a	n/a	n/a	n/a
7-M-11	No	No	No	Yes	No
7-M-12	n/a	n/a	n/a	n/a	n/a
7-M-13	Yes	Yes	Yes	Yes	Yes
7-F-10	Yes	No	Yes	Yes	Yes
7-F-11	Yes	Yes	Yes	No	No
7-F-12	Yes	Yes	Yes	No	No
7-F-13	n/a	n/a	n/a	n/a	n/a
7-F-14	Yes	Yes	Yes	No	No
7-M-14	Yes	Yes	Yes	Yes	Yes
Total “Yes”	21/23 = 91%	17/23 = 74%	21/23 = 91%	9/23 = 39%	8/23 = 35%

The data indicated that 91% of learners stated a claim that takes a stance on the question asked, 74% of learners provided appropriate evidence to support the claim, 91% of learners provided sufficient evidence to support the claim, and 39% of learners included reasoning about scientific principles to explain the claim. Finally, 35% of learners connected the claim and evidence using scientific principles.

These data were surprising because they were dramatically different from the first written assessment data. On the first written assessment, fewer participants included sufficient evidence (54%) than on the second written assessment (91%). Alternatively, fewer participants provided reasoning on the second written assessment (39%) than participants did on the first written assessment (88%). Moreover, fewer participants connected their claim and evidence using scientific principles (reasoning) on the second written assessment (35%) than the first written assessment (65%). Though the data were surprising, they did support some of the statements in the draft learning progression. Specifically, these data supported the line on level two of the LP that says,

> Learners sometimes use evidence and ideas to construct evidence-based accounts of sea level rise and sometimes they rely more heavily on scientific reasoning to support their claims about sea level rise. Due to learners' inconsistent and/or incomplete use of both evidence and reasoning, learners often fail to connect their claims and evidence using reasoning that adheres to scientific principles.

Based on the entirety of the data presented thus far, learners did not necessarily follow linear trajectories of learning how to construct explanations about sea level rise. Learners seemed to take steps back or to the side before they were able to advance their understandings. In the context of the targeted intervention, some learners were less capable of constructing a complete and coherent scientific explanation about sea level rise after learning additional concepts about sea level rise and after analyzing authentic sea level rise data.

Many learners changed the structures of their explanations from the first to the second written assessment. After the targeted instruction, participants appeared to pay more attention in their explanations to the scientific evidence that was now accessible to them than to the scientific reasoning associated with this evidence. In contrast, before studying data related to sea level rise, participants were better able to tie what they already knew about sea level rise into a cohesive explanation that incorporated scientific reasoning. For example, on the first written assessment, participant 7-F-1 wrote:

Write a scientific explanation that answers the question: What causes sea level rise? **Claim** (Write a sentence that answers the question.) *Sea level rise is caused by change in the climate.* **Evidence** (Provide data that support your claim.) *If there is a lot of rain at the sea and little amount of sun, then the water from the rain wont evaporize very fast. The sea level can rise also when there are large glaciers melting which*

increases the amount of water in the sea.

Reasoning (Connect evidence to claim.)
The less sun there is to evaporate the water the more water is left and the more huge glaciers melt the more the water in the sea which can also mean global warming is causing glaciers to melt at the sea.

On this baseline written assessment, participant 7-F-1 relied heavily on scientific reasoning, but did not provide any evidence or data to support her claim. In contrast, on her second written assessment, she focused almost exclusively on using evidence to support her claim, citing data from two different graphs that her teacher provided. She wrote:

Write a scientific explanation that answers the question: How has the global average sea level changed over the past 50 years?

Claim (Write a sentence that answers the question.)
Over the past 50 years the average sea level rise has changed significantly and has rosen.

Evidence (Provide data that support your claim.)
In the satellite graph, it shows the change of various areas in the world. Almost all of the areas provided sea level data over 50 years has risen. Example: Manila + 250mm

Also, in the graph of the bodies of water's level rose. The Baltimore data has risen almost 100ft!

Reasoning (Connect evidence to claim.)
In conclusion, the global average sea level rise has rosen over the past 50 years in emmense amounts.

Participant 7-F-1's second written assessment provided support for the analytic concept *participants learned to incorporate authentic scientific data*. However, her explanation on the second written assessment lacked scientific reasoning, which was the strength of her explanation on the baseline written assessment.

The interview with participant 7-F-1 occurred on March 12, more than a month after she wrote the second written assessment (on February 2). During that interview, participant

7-F-1 continued to demonstrate a focus on using authentic scientific data to explain sea level rise. The following transcript is from that interview:

> Researcher: Alright, so, remember in Ms. [Teacher]'s class, you've been working on claim, evidence, and reasoning?
>
> 7-F-1: Yeah.
>
> Researcher: So, just keeping that in mind, what would be your scientific explanation for what causes sea level rise?
>
> 7-F-1: Uh, that could be many things. It could be natural or, like, man caused. And, um, man-caused can be, like, um, the air being polluted and having more rain. And, like, natural could be just more ice, or glaciers, melting in ocean and stuff.

During this interview, participant 7-F-1 was asked the same question that she was asked on the baseline written assessment. Yet, her explanation was significantly different during the interview. Rather than relying solely on scientific reasoning (e.g., *If there is a lot of rain at the sea and little amount of sun, then the water from the rain wont evaporize very fast. The sea level can rise also when there are large glaciers melting which increases the amount of water in the sea.*), she presented evidence. She explained that the air is being polluted, there is more rain, and more ice/glaciers are melting. Participant 7-F-1's greater reliance on evidence, data, and facts to construct her explanation during the interview is consistent with the shift seen in her explanation structure between the first and second written assessments. The next interview question was similar to the prompt of the second written assessment, as seen in the interview transcript below.

> Researcher: So, how about around the Chesapeake Bay? How does sea level…how has sea level changed around the Chesapeake Bay over the past 50 years or so?
>
> 7-F-1: It has risen more than it was before 50 years, and that it's like not a small change, but also it's like a significant kind of change, according to the graph.

Just as she did on the second written assessment following the observed lesson on sea level rise, participant 7-F-1 incorporated authentic scientific data into her explanation. Specifically, she cited the graph titled “Trends in relative sea level at tide gauges around the Chesapeake Bay” (Boesch et al., 2013, p. 1).

Later in the interview, I asked her the same question that she was asked on the second written assessment. Then, I asked her to make a prediction about the future. The transcript is below:

> Researcher: How about how has global average sea level changed over the past 50 years? So, around the whole world on average, how has sea level changed?
>
> 7-F-1: It has mostly risen over 50 years, like on that graph. And, um, yeah, it’s not too much but it is pretty significant for, like, 50 years, which is a short time for that much, that amount of rise.
>
> Researcher: How about it over the next 50 years--the whole global average sea level, the whole world?
>
> 7-F-1: I think it’s going to be more, like, faster because of global warming and the glaciers will probably be melting more and there’s more technology that affects the air, it might pollute more.

Participant 7-F-1 was able to answer the first question directly using the graphs that were in front of her during the interview. Consequently, she simply cited the graph to support her claim that the sea level had mostly risen over the past 50 years. However, participant 7-F-1 did not appear to be aware that she could have used the graph showing various sea level rise projections in a similar way to directly answer the question about predicting sea level change over the next 50 years. Or, it is possible that she instead chose to rely on her own ability to reason about the future instead of citing someone else’s projections as evidence (e.g., global warming will melt more glaciers and new technology will cause even more air pollution). In any case, these data demonstrate that participant 7-F-1 uses evidence and/or reasoning inconsistently when constructing scientific explanations about sea level rise.

Generally, the data from the second written assessment supported the notion that participants with less sophisticated understandings use evidence and reasoning inconsistently, aligning well with the current language of the LP. However, the LP does not currently describe how learners may respond to targeted instruction focusing on authentic scientific data. Thus, I modified level two of the draft LP to the following (changes are in bold):

> Learners are aware that global sea level rise is occurring. Learners sometimes use evidence and ideas to construct evidence-based accounts of sea level rise and sometimes they rely more heavily on scientific reasoning to support their claims about sea level rise. Due to learners' inconsistent and/or incomplete use of both evidence and reasoning, learners often fail to connect their claims and evidence using reasoning that adheres to scientific principles. Through targeted instruction, learners can begin to use authentic scientific data as evidence when explaining sea level rise, **though this may cause them to use less scientific reasoning.**

Participant 7-M-2 also used evidence and reasoning inconsistently when constructing scientific explanations. Similar to participant 7-F-1, participant 7-M-2 relied on reasoning to support his claim on the baseline written assessment, but he relied on evidence to support his claim on the second written assessment. On the first written assessment, participant 7-M-2 wrote:

Write a scientific explanation that answers the question: What causes sea level rise? **Claim** (Write a sentence that answers the question.) *Sea level rises because poler ice caps melt wich makes the sea level rise* **Evidence** (Provide data that support your claim.) *because of Global Warming is causing the ice to melt and make the sea rise* **Reasoning** (Connect evidence to claim.) *when people use cars, buses, and planes which causes exost which is carbon dixid which*

melts the ice

On the baseline written assessment, participant 7-M-2's "evidence" is actually reasoning. He reasoned that increased temperatures cause the ice to melt, and that ice melting causes the sea levels to rise. In the reasoning section, he added that the ice also melts because people pollute the air with carbon dioxide when they use transportation. In contrast, he presented strong evidence and authentic scientific data on the second written assessment but little reasoning. On the second written assessment, participant 7-M-2 wrote:

Write a scientific explanation that answers the question: How has the global average sea level changed over the past 50 years?

Claim (Write a sentence that answers the question.)
The global average sea level has rised

Evidence (Provide data that support your claim.)
One example that the sea level has rised is that more Artic glashers are melting casing the water to rise. Another example is in Manila the sea level has risen largly and that in San Francisco the sea level has risen little or has gone down because it is hotter some where else and colder there

Reasoning (Connect evidence to claim.)
Because of the glashers melting and it getting hotter some where else and colder in some places which will change the global sea level.

Though I could imagine how participant 7-M-2 could add a few more phrases to turn his "reasoning" into a clear discussion of scientific principles, they read more like a chain of facts: glaciers are melting, it is getting hotter, and it is getting colder. I considered these facts as evidence, rather than scientific reasoning.

Unlike participant 7-F-1, participant 7-M-2 provided a significant amount of reasoning during his interview with me. This was evident in his response to my first question:

Researcher: So, the first question is, what does sea level rise mean to you?

7-M-2: Um, it just means…to me, it means that humans are using a lot more inefficient not healthy ways to the environment, like using more cars, more buses, that pollute more…um…and that they're making more factories to build cars that pollute. Just factories, in general, are really not helping, and it means the factories and cars that pollute warm the atmosphere here right on the earth, which melts glaciers, which causes the water to rise, which sometimes…which can and has destroyed land from getting so high.

Later in the interview, I asked participant 7-M-2 the question that was asked on the baseline written assessment about the cause of sea level rise. As he did on the written assessments, participant 7-M-2 displayed inconsistency in terms of the structure of his explanation, even though he held relatively sophisticated ideas about the causes of sea level rise. Consequently, he only provided evidence and reasoning when I specifically prompted him to do so.

Researcher: So, what causes sea level rise? Try to do a scientific explanation with the claim, the evidence, and reasoning. Just like those written assessments you did at the very beginning.

7-M-2: What causes sea rise? Humans.

Researcher: How?

7-M-2: Everything we do in life. We're not really…I don't think most humans are thinking about the earth. I think they're thinking about themselves. But, more companies that make cars, buses, they work on more efficient things so it doesn't cause so much pollution to air.

Researcher: So, the *pollution* causes sea level rise.

7-M-2: Yes.

Researcher: So, what's your evidence that the pollution causes sea level rise?

7-M-2: Pretty much, anywhere you go, you're going to see exhaust from cars, trucks, factories—you drive by a factory, you can see a ton of pollution coming out of factories. Oil…stuff like that.

Researcher: So when stuff comes out of factories, how does that end up making the water level go up?

7-M-2: Um, it warms the water, which will end up in Antarctica or the North Pole, melts that ice, and then, it also rises to the atmosphere, which will end up in Antarctica, North Pole.

Researcher: What rises up into the atmosphere?

7-M-2: What?

Researcher: What rises up into the atmosphere?

7-M-2: The fumes, pollution.

Researcher: Pollution, okay. And so, the main thing I've heard you say causes the sea level rise is when the pollution causes the ice to melt, but I wasn't quite sure what you meant by the pollution rising up to the atmosphere causing the sea level to rise.

7-M-2: Um, I remember seeing a picture—it was not here—but, the ozone layer of Earth…of Earth. And, as the pollution goes into the air, it then tries to leave the earth, but it can't because the ozone layer is holding it in. So, when it gets stuck there, and there's a lot of it, it will warm the earth, which warms the oceans, which warms the ice.

Researcher: And, how does that get transferred around to the different things? When this warms this, warms that, warms that, how does it flow?

7-M-2: Um, humans and pollution. Then, the ozone layer, and then the ozone layer warms the ocean, and the ocean melts the ice, which causes sea level rise.

In participant 7-M-2's responses during the interview, there was evidence of three different analytic concepts discussed previously. First, there was variation in the structures of his scientific explanations. Second, he frequently expressed the idea that global warming and ice melt cause sea level rise. Finally, he expressed an alternative conception when describing the mechanism for global warming and sea level rise when he said that the ozone layer traps the gases that warm the earth.

Participant 7-M-2 used evidence or reasoning (or occasionally both evidence and reasoning) to specify the effect that temperature (a variable) will have on the amount of ice melt (a variable) or the effect that the amount of ice melt will have on the sea levels (a variable). To make level three more specific to how participants actually explained sea level rise, I will add participant 7-M-2's examples to the description of level three of the LP.

Participant 7-M-2 also expressed the idea that most of Earth's water is in the ocean and much of the Earth's fresh water is in glaciers. At one point, he explained,

> With all the glaciers melting which is holding years of ice in the water, with that melting it causes [the ocean] to rise more. And, then the ocean will eventually reach to the lakes, which will cause the lakes to rise more…

Participant 7-M-2 also knew that matter exists as particles that are too small to see and that matter is always conserved even if it seems to disappear. He described the visible pollution that he has seen come from automobiles, and then he traced the pollution particles into the atmosphere, as these are the particles that he said warmed the earth and interacted with both ice and the ozone layer.

When participant 7-M-2 described how the invisible particles interacted with the ozone layer to warm the earth, he demonstrated that he was aware of some connections between global warming/climate change and sea level rise, though he misunderstood some of those connections, which is consistent with level three of the LP. He also demonstrated that he was aware of connections among fossil fuel use, the atmosphere, global warming, and sea level rise, though he did not clearly explain these connections in a scientifically normative way. Rather than explaining that greenhouse gas emissions from human fossil fuel use warms the earth through the greenhouse effect, he described an alternative conception involving the ozone layer acting as a barrier that prevents the hot pollution particles from leaving the earth. To improve the clarity and usefulness of level three of the LP, I will add participant 7-M-2's alternative conception as an example of how learners at level three might explain the connections among fossil fuel use, global warming, and sea level rise. In response to both the written and interview data from participant 7-M-2, I will revise level three of the LP to the following (changes are in bold):

> Learners use evidence and/or scientific reasoning in constructing explanations that specify variables that describe and predict phenomena related to sea level rise. **For example, a learner might specify the effect that the variable "temperature" will have on the variable "amount of ice melt" or the effect that the variable "amount of ice melt" will have on the variable "sea levels".** Through targeted instruction, learners can use authentic scientific data as evidence in a consistent way when explaining sea level rise and are able to connect these data to their claims using scientific reasoning. Learners know that most of Earth's water is in the ocean and much of the Earth's fresh water is in glaciers or underground. However, learners may express the idea that icebergs contribute to sea level rise when they melt, rather than understanding that melting ice must originate from land in order to contribute to sea level rise. Learners also know that because matter exists as particles that are too small to see, matter is always conserved even if it seems to disappear. Additionally, learners know that moving objects contain energy. Energy can be converted from one form to another form. When constructing scientific explanations about the causes of sea level rise, learners may express alternative conceptions that involve abstract concepts and/or invisible phenomena. For example, learners may explain that the moon's gravity causes sea level rise, conflating the cause of tides and the causes of sea level rise. Learners are aware of some connections between global warming/climate change

and sea level rise, though they may misunderstand some of those connections. For example, participants might explain that the increased sunlight from global warming/climate change causes more ice to melt, which adds to the level of water in the sea. It is important to note that this alternative conception adheres to both the conservation of energy (the transformation of light into different forms of energy) and the conservation of matter (solid water becomes liquid water, which moves to a new location on Earth). Though learners may hold alternative conceptions about global warming/climate change, they understand that human use of fossil fuels has contributed to global warming/climate change. They are aware of connections among fossil fuel use, the atmosphere, global warming, and sea level rise, though they are unable to clearly explain these connections in a scientifically normative way. **Instead, learners may express alternative conceptions about these connections. For example, a learner might explain that fossil fuel use results in the emission of air pollution particles, which causes global warming as the ozone layer works to trap these warming particles.**

While participants 7-M-2 and 7-F-1 showed inconsistency with the structure of their explanations, participant 7-F-3 consistently demonstrated a strong integration of evidence (i.e., authentic scientific data) and scientific reasoning (i.e., scientific principles learned in her science class) on both the second written assessment and on her interview responses. As discussed previously, participant 7-F-3 provided an explanation on the second written assessment that incorporated multiple relevant pieces of evidence and reasoning involving multiple and relevant scientific principles. On her baseline written assessment, she also wrote a coherent explanation that supported her claim with evidence and connected that evidence to the claim using scientific reasoning. Participant 7-F-3's baseline written assessment is presented below.

Write a scientific explanation that answers the question: What causes sea level rise?

Claim (Write a sentence that answers the question.)
Through global warming glaciers and ice melts, going into the ocean, causing the sea level to rise.

Evidence (Provide data that support your claim.)
Before global warming the sea level was normal and wasn't rising, but after global warming the sea level rose by many inches each day, because of ice melting.

Reasoning (Connect evidence to claim.)
When global warming melts ice and glaciers melt causing the ocean level to rise above the level it was before.

While participant 7-F-3's explanation for the cause of sea level rise is coherent, logical, and scientifically normative, it is incomplete in that she does not discuss thermal expansion. However, after the observed classroom lesson on thermal expansion, she learned to incorporate this concept into her explanations, demonstrating her growth in response to the targeted instruction. Her second written response is presented below.

Write a scientific explanation that answers the question: How has the global average sea level changed over the past 50 years?

Claim (Write a sentence that answers the question.)
The average sea level has risen over the past 50 years because of the temperature rising from global warming.

Evidence (Provide data that support your claim.)
Global warming causes water molecules to spread out, so the water would expand more causing sea levels to go up. Also the sea level in the Chesapeake Bay has risen about a foot over the past 50 years and the amount of ice has decreased. So this shows that the high temperatures have melted the glaciers.

Reasoning (Connect evidence to claim.)
The high temperatures from global warming makes water molecules to spread out and make water expand leading to sea level rise. Also having les ice would show that temperatures would make sea level to rise. Global warming is making the global average sea level to change over the past 50 years.

In this response, participant 7-F-3 included multiple pieces of evidence (increase in sea level around the Chesapeake Bay and decrease in the amount of ice) and multiple scientific principles (thermal expansion and glacial ice melt in response to global warming). During her interview, participant 7-F-3 continued to incorporate thermal expansion into her explanation, which further supports the analytic concept *participants learned about thermal expansion as a fundamental aspect of sea level rise.*

During participant 7-F-3's interview, I asked her the same question that she answered on the baseline written assessment, though her answer changed. The transcript is below.

> Researcher: Alright, so, the next question is a lot like the first paper you did in class. So, if you think about a claim, evidence, and reasoning, um, what causes sea level rise?
>
> 7-F-3: Well, I think the glaciers in like the Arctic is starting to melt with global warming, so it would go into the water and melt, so it causes sea level rise. And, also, when there's high temperature, the water molecules…um…expand more, which causes more volume and causing the sea level to rise.

Though she did not remember the term thermal expansion during the interview (on February 19), she understood the concept and was able to incorporate it into her explanation for the cause of sea level rise more than two weeks after the observed classroom lesson (on February 2). Participant 7-F-3 also remained committed to using authentic scientific data during the interview and in the transcript below.

> Researcher: So, how about around the Chesapeake Bay? So, that's like the bodies of water around Maryland. How have those changed over the last 50 years?
>
> 7-F-3: Can I use these? [indicating the graphs on the table in front of her]
>
> Researcher: And yeah, you can look at any of those. Take your time. There's no rush.
>
> [7-F-3 takes time to look over the graphs]
>
> 7-F-3: So, the different parts of the Chesapeake Bay started to have different sea levels, and they're getting higher each year.

In this interview transcript, participant 7-F-3 explicitly communicated her desire to incorporate authentic scientific data into her explanation. She viewed the graphs as tools that she could use to construct a better scientific explanation. With minimal prompting from me in the following transcript, she was able to connect that evidence back to her claim using scientific reasoning.

> Researcher: So, you said, uh, different parts have different sea level changes. So, why do you think they could be different at different parts?
>
> 7-F-3: So, if the place was warmer, it could have more sea level rise than somewhere colder, and that could show how it changes in the area.

The reasoning that participant 7-F-3 provided in this interview response is consistent with reasoning from her prior interview responses. As she explained earlier, increased temperatures cause increased ice melt and thermal expansion, both of which cause sea levels to rise. Because of her consistent use of evidence and reasoning, as well as her consistent application of atomic-molecular theory and thermal expansion, participant 7-F-3 aligned well with the description of level four on the LP.

Participant 7-F-3 seemed to have a particularly strong grasp on the relationship between temperature and the kinetic energy of water molecules (when she discussed the movement of the particles during thermal expansion). Participant 7-F-3 also explained how water's movement changes features of the land at the beginning of our interview:

> Researcher: The first question is, what does sea level rise mean to you?...When you think of sea level rise.
>
> 7-F-3: Well, to me, when I hear sea level rise, I think of, like, floods and…and the geography of the land changing.
>
> Researcher: Can you talk more about the geography of the land changing? So, what are some examples of what you mean?

7-F-3: Like…like, coasts and stuff.

Researcher: Coasts will change?

7-F-3: Yeah.

Though participant 7-F-3's responses aligned with most of the description in level four of the draft LP, I did not find any evidence of her understanding of how density variations of seawater drive interconnected ocean currents. Moreover, based on my experiences as both a middle and high school teacher, I would not expect participant 7-F-3 to have a strong understanding of ocean currents, especially since Earth Science is not taught until grade 8. Consequently, I decided to pay particularly close attention to whether any of my written assessment or interview data supported a statement about ocean currents on the LP. In the next section, I present a summary of the claims that participants provided on the second written assessment.

Summary of claims, evidence, and reasoning on second written assessment. In this section, I present summaries of the claims, evidence, and reasoning that participants used on the second written assessment. I begin by first presenting two matrices (*Tables 16* & *17*) showing how frequently I was able to apply a particular code to a participant's claim.

Table 16

Inventory of Claims for the Questions About How Sea Levels Have Changed Over the Past 50 Years (Globally or Around the Chesapeake Bay)

Code	Participant Names	Number of Participants
Sea levels have increased	7-M-1, 7-F-1, 7-M-2, 7-F-2, 7-M-3, 7-F-3, 7-F-6, 7-M-6, 7-M-8, 7-M-9, 7-M-13, 7-F-12, 7-M-4, 7-F-10, 7-F-11	15
Water expansion causes sea level rise	7-M-11, 7-F-8	2
Sea level is measured over time on a relative basis	7-F-9	1

Table 17

Inventory of Claims for the Questions About How Sea Levels Will Change Over the Next 50 Years (Globally or Around the Chesapeake Bay)

Code	Participant Names	Number of Participants
Sea level will rise	7-F-5, 7-F-4, 7-F-8, 7-F-14, 7-F-7, 7-M-14	6

The claims inventoried in *Tables 16* and *17* demonstrate that all participants were aware of sea level rise following the targeted instruction. Thus, no participants demonstrated the confusion or lack of awareness that characterize level one of the learning progression. However, only two participants incorporated thermal expansion into their claims (7-M-11, 7-F-8), even though this was a significant focus of the targeted instruction. On the other hand, thermal expansion should be present in participant reasoning, rather than participant claims. Thus, I paid particularly close attention to the ways in which participants incorporated new understandings about thermal expansion into the reasoning portions of their scientific explanations. In the matrices below (*Tables 18* & *19*), I show how frequently I was able to apply a particular code to a participant's use of evidence.

Table 18

Inventory of Evidence for the Questions About How Sea Levels Have Changed Over the Past 50 Years (Globally or Around the Chesapeake Bay)

Code	Participant Names	Number of Participants
Graph(s) show sea level rise	7-M-1, 7-F-1, 7-F-2 7-M-13, 7-M-4, 7-F-8, 7-M-10, 7-F-1, 7-F-2, 7-M-6, 7-M-1, 7-M-3, 7-F-3, 7-M-6, 7-F-1, 7-M-2, 7-M-9, 7-F-11	18
Ice levels have decreased	7-M-2, 7-F-3, 7-F-6, 7-M-8, 7-M-10, 7-M-1	6
Graph(s) shows ocean warming	7-M-1, 7-M-13, 7-F-12, 7-M-13	4
Thermal expansion	7-F-3, 7-M-11	2
San Francisco sea level has risen little or decreased	7-M-2	1
Global warming has occurred over recent years	7-M-11	1

Sea levels will increase by 1 meter by 2100	7-M-13	1
Polar bear populations are shrinking	7-M-8	1

Table 19

Inventory of Evidence for the Questions About How Sea Levels Will Change Over the Next 50 Years (Globally or Around the Chesapeake Bay)

Code	Participant Names	Number of Participants
Graph(s) shows sea level rise	7-F-5, 7-F-7, 7-M-14, 7-F-4, 7-F-8, 7-F-14	6
Projections predict sea level increase	7-F-5, 7-F-7	2
Manila is on an island and has increased way more than the global average	7-F-5	1
Graph(s) shows ocean warming	7-M-14	1
Videos showed thermal expansion of water	7-F-14	1

The inventories of the evidence on the second written assessment provide support for the analytic concept *participants learned to incorporate authentic scientific data*. For example, 25 out of 26 participants cited evidence from one of the graphs provided in class showing increased sea levels or ocean warming. The one participant who did not incorporate authentic scientific data (participant 7-F-9) did not provide any evidence—she left that section blank.

Similar to my findings from the inventory of claims on the second written assessment, only three participants incorporated thermal expansion into their evidence section (7-M-11, 7-F-3, 7-F-14), even though this was a significant focus of the targeted instruction. Again, thermal expansion should be present in participant reasoning, rather than participant claims or evidence. So, I looked to see the ways in which participants incorporated new understandings about thermal expansion into the reasoning portions of their scientific explanations. As with the claims and evidence, in the matrices below (*Tables 20* & *21*), I show how frequently I was able to apply a particular code to a participant's reasoning.

Table 20

Inventory of Reasoning for the Questions About How Sea Levels Have Changed Over the Past 50 years (Globally or Around the Chesapeake Bay)

Code	Participant Names	Number of Participants
Higher temperatures cause ice to melt, which raises sea levels	7-M-1, 7-M-2, 7-F-3, 7-M-13, 7-F-8, 7-M-8	6
The data show sea level rise	7-F-2, 7-M-3, 7-M-6, 7-M-4, 7-F-10, 7-F-11	6
Pollution and global warming	7-F-12, 7-M-11, 7-F-10	3
The sea level rise trend could continue	7-M-6, 7-M-9	2
Graph shows ice melt	7-F-6	1
Thermal expansion	7-F-3	1

Table 21

Inventory of Reasoning for the Questions About How Sea Levels Will Change Over the Next 50 Years (Globally or Around the Chesapeake Bay)

Code	Participant Names	Number of Participants
Thermal expansion	7-M-14, 7-F-4, 7-F-14	3
Continued fossil fuel use and greenhouse gas emission will heat the Earth's surface	7-F-4, 7-F-8	2
The data show sea level rise	7-F-5	1
Projections predict sea level increase	7-F-7	1

As expected, more participants incorporated thermal expansion into the reasoning section of their explanation (7-M-14, 7-F-4, 7-F-14, 7-F-3) than in the claim or evidence sections, though not by a wide margin. Importantly, only five out of 26 participants addressed thermal expansion in some way on the second written assessment (7-M-14, 7-F-4, 7-F-14, 7-F-3, 7-M-11). Thus, an overwhelming majority of participants (21/26) were not able to incorporate thermal expansion into their explanations about sea level rise, even though this was a primary goal of the targeted instruction. This has important implications for the analytic concept that I presented earlier *participants learned about thermal expansion as a fundamental aspect of* *sea level rise*. Though I observed participants learning about thermal expansion and discussing thermal expansion during class that does not mean that students have learned about thermal expansion's contribution to sea level rise in any sort of deep way. Rather, they had only begun to learn about thermal expansion and required more substantial experiences in order to incorporate the construct into their mental models of sea level rise.

A next step in the targeted instruction would be for the students to conduct an inquiry investigation to study the thermal expansion of water. While teaching a 10th grade Chemistry course this year, I had my students conduct such an investigation. My students worked in teams to construct a set-up similar to the one in the video shown during the classroom observation. The set up included a plastic water bottle filled with water, a cap that has a straw coming through its center, and a heat lamp. My students investigated questions such as:

- How does the thermal expansion of fresh water compare to salt water?
- How does the rate of thermal expansion of salt-water change as the concentration of salt increases?
- How does the rate of thermal expansion change with distance from the heat source?

After conducting these inquiry investigations, I found that my students were better able to incorporate thermal expansion into their mental models of sea level rise.

Based on my teaching experiences, all learners can gain a deep understanding of thermal expansion with sufficient and well-designed instruction, such as the inquiry investigations I have described. However, in terms of the sea level rise learning progression, incorporation of thermal expansion into explanations about sea level rise should only be a feature of the upper levels of the LP (levels four and five). This finding corresponded well with my personal experiences in speaking with many different people of different ages, levels of education, and experiences. Many more people are aware of the contribution of increased ice melt to sea level rise than are aware of the contribution of thermal expansion to sea level rise. Moreover, understanding thermal expansion requires a more sophisticated understanding of atomic-molecular theory than does the melting of ice. Therefore, I believed I was justified in adding thermal expansion to levels four and five of the learning progression, but not lower levels of the LP.

Interview Data

In this section, I present my findings from individual interviews with sixth, seventh, and eighth grade participants. First, I present the entire draft learning progression with all changes that I have made in response to the written assessment and observation data. Next, I present three new analytic concepts that emerged while analyzing the interview data. After exploring these concepts with examples from the interviews, I use the following process for further developing the draft LP:

1. First, I use the interview data to show how the data disconfirmed or contested portions of the draft learning progression, providing cogent student examples that support my claims (i.e., strike some pieces or rearrange them by level).
2. Second, I show how my analysis of the student interviews confirmed portions of the draft learning progression, again providing cogent student responses for each of the portions that are confirmed.
3. Finally, I use interview data to add new (and therefore unexpected) material to the learning progression, providing cogent student examples to support my claims.

After explaining my revisions to the draft learning progression based on the interview data, I present one of the major products of my dissertation study: an empirical learning progression based on and partially validated using collected data. In chapter five, I will discuss the process I used to develop and begin validating this empirical LP product and explore the new theory I have generated through this process.

Revised draft learning progression. In *Table 22* below, I present the five levels of the draft learning progression with all changes that I have made in response to the written assessment and observation data.

Table 22

Revised Draft Learning Progression

	Description of Learning Performance
Level 1	Learners express confusion or a lack of awareness about the sea level rise phenomenon when constructing scientific explanations about sea level rise. This confusion or lack of awareness prevents learners from drawing on appropriate evidence or scientific reasoning when attempting to explain the sea level rise phenomenon.
Level 2	Learners are aware that global sea level rise is occurring. Learners sometimes use evidence and ideas to construct evidence-based accounts of sea level rise and sometimes they rely more heavily on scientific reasoning to support their claims about sea level rise. Due to learners' inconsistent and/or incomplete use of both evidence and reasoning, learners often fail to connect their claims and evidence using reasoning that adheres to scientific principles. Through targeted instruction, learners can begin to use authentic scientific data as evidence when explaining sea level rise, though this may cause them to use less scientific reasoning. Learners know that water is found in many types of places and in different forms on Earth, such as icebergs and glaciers. However, learners may express the idea that icebergs contribute to sea level rise when they melt, rather than understanding that melting ice must originate from land in order to contribute to sea level rise. Learners also know that matter exists as different substances that have observable different properties. Different properties are suited to different purposes. Objects can be built up from smaller parts. Learners rely on their experiences with macroscopic and visible phenomena to explain sea level rise. For example, learners may explain that sea level rise is caused when humans add waste (e.g., trash) to the sea, when increased rainfall enters the sea, and/or when additional wind raises the water to a greater height.
Level 3	Learners use evidence and/or scientific reasoning in constructing explanations that specify variables that describe and predict phenomena related to sea level rise. For example, a learner might specify the effect that the variable "temperature" will have on the variable "amount of ice melt" or the effect that the variable "amount of ice melt" will have on the variable "sea levels". Through targeted instruction, learners can use authentic scientific data as evidence in a consistent way when explaining sea level rise and are able to connect these data to their claims using scientific reasoning. Learners know that most of Earth's water is in the ocean and much of the Earth's fresh water is in glaciers or underground. However, learners may express the idea that icebergs contribute to sea level rise when they melt, rather than understanding that melting ice must

	originate from land in order to contribute to sea level rise. Learners also know that because matter exists as particles that are too small to see, matter is always conserved even if it seems to disappear. Additionally, learners know that moving objects contain energy. Energy can be converted from one form to another form. When constructing scientific explanations about the causes of sea level rise, learners may express alternative conceptions that involve abstract concepts and/or invisible phenomena. For example, learners may explain that the moon's gravity causes sea level rise, conflating the cause of tides and the causes of sea level rise. Learners are aware of some connections between global warming/climate change and sea level rise, though they may misunderstand some of those connections. For example, participants might explain that the increased sunlight from global warming/climate change causes more ice to melt, which adds to the level of water in the sea. It is important to note that this alternative conception adheres to both the conservation of energy (the transformation of light into different forms of energy) and the conservation of matter (solid water becomes liquid water, which moves to a new location on Earth). Though learners may hold alternative conceptions about global warming/climate change, they understand that human use of fossil fuels has contributed to global warming/climate change. They are aware of connections among fossil fuel use, the atmosphere, global warming, and sea level rise, though they are unable to clearly explain these connections in a scientifically normative way. Instead, learners may express alternative conceptions about these connections. For example, a learner might explain that fossil fuel use results in the emission of air pollution particles, which causes global warming as the ozone layer works to trap these warming particles.
Level 4	Learners construct explanations about sea level rise supported by multiple sources of evidence consistent with scientific ideas, principles, and theories. Learners consistently use authentic scientific data as evidence. Learners apply scientific ideas, principles, and/or evidence to construct, revise, and/or use an explanation for sea level rise. Learners know that sea level rise is caused by global warming/climate change, which causes increased ice melt on Earth's surface. Learners know that water cycles among land, ocean, and atmosphere, and is propelled by sunlight and gravity. Density variations of seawater drive interconnected ocean currents. Water movement causes weathering and erosion, changing landscape features. Learners also know that the fact that matter is composed of atoms and molecules can be used to explain the properties of substances, diversity of materials, states of matter, phase changes, and conservation of matter. Additionally, learners know that kinetic energy can be distinguished from the various forms of potential energy. Energy changes to and from each type can be tracked through physical or chemical interactions. The relationship between the temperature and the total energy of a system depends on the types, states, and amounts of matter. Learners also know that thermal expansion is a significant cause of sea level rise, and can explain how thermal expansion causes sea level rise using principles of atomic-molecular theory.
Level 5	Learners construct explanations about sea level rise supported by multiple and independent student-generated sources of evidence consistent with

	scientific ideas, principles, and theories. Learners consistently use authentic scientific data as evidence. Learners apply scientific reasoning, theory, and/or models to link evidence to the claims to assess the extent to which the reasoning and data support the explanation or conclusion. Learners know that the planet's dynamics are greatly influenced by water's unique chemical and physical properties. Learners also know that the sub-atomic structural model and interactions between electric charges at the atomic scale can be used to explain the structure and interactions of matter. Additionally, learners know that the total energy within a system is conserved. Energy transfer within and between systems can be described and predicted in terms of energy associated with the motion or configuration of particles (objects). Consequently, learners are able to explain sea level rise using the constructs glacial ice melt and thermal expansion.

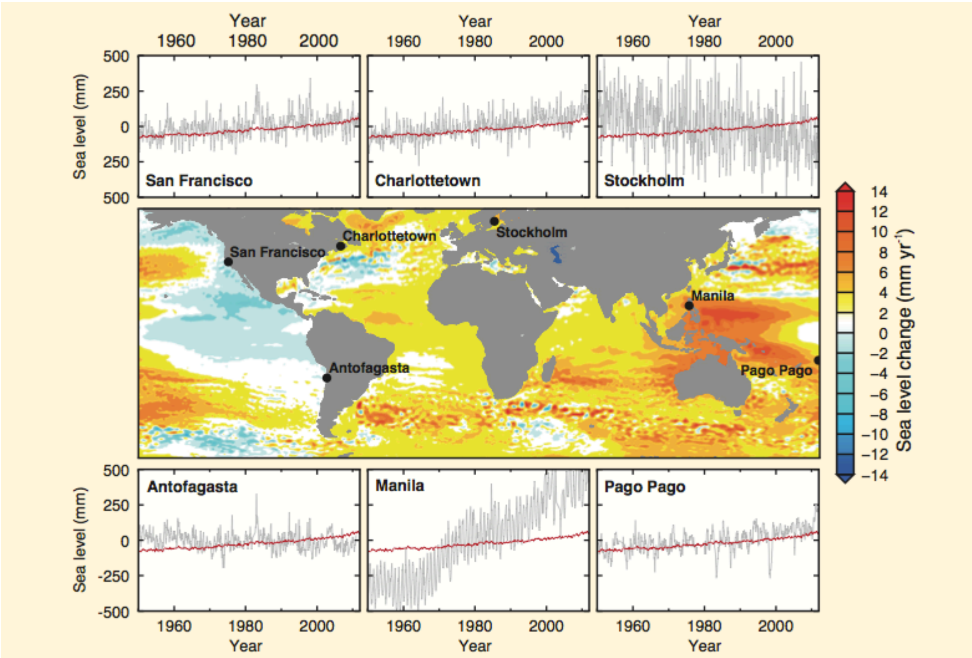
Throughout the rest of this chapter, I will relate my analysis of the interview data to this draft learning progression, modifying the draft LP when needed. In the next section, I will present the first analytic concept that emerged when analyzing the interview data, which addresses participants' mental models of the oceans.

Analytic concept: Participants' mental models of the ocean varied widely. The first analytic concept that emerged from the interview data was *participants' mental models of the ocean varied widely.* The surface of the ocean, like the surface of the earth's land, is not flat, and the sea surface is not changing at the same rate at different locations around the globe (NOAA, 2013). Though many people think of the ocean as a flat, unchanging surface that is the same all around the world, local sea level is subject to factors such as the gravity of nearby ice mass, ocean currents, local changes in temperature, and vertical land movement (Don Boesch, personal communication, July 2013).

During the interviews, I had the opportunity to probe participant thinking to learn about their mental models of the ocean as they related to sea level rise. These mental models manifested themselves when I asked participants to explain the map of sea level change around the world (see *Figure 1*, below), as well as when I asked participants to explain local verses global sea level change.

Figure 1

Map of Rates of Change in Sea Surface Height (IPCC, 2013, p. 1148)



FAQ13.1, Figure 1 | Map of rates of change in sea surface height (geocentric sea level) for the period 1993–2012 from satellite altimetry. Also shown are relative sea level changes (grey lines) from selected tide gauge stations for the period 1950–2012. For comparison, an estimate of global mean sea level change is also shown (red lines) with each tide gauge time series. The relatively large, short-term oscillations in local sea level (grey lines) are due to the natural climate variability described in the main text. For example, the large, regular deviations at Pago Pago are associated with the El Niño-Southern Oscillation.

In the interview transcript below, participant 6-F-4 explained how the proximity of the sea to melting ice caps affects local sea level:

> 6-F-4: Well, like, bodies of water that are closer to things…ice caps, I guess, rise more because they're closer, and it would be easier for the extra water to pile up in them.

Later in the interview, she gave specific examples of bodies of water near and far from ice caps:

> 6-F-4: Um, I've been to the Mediterranean, I've been to, um, Lake Michigan, um, I've been to the Atlantic Ocean. So, those, like, aren't that close to, like, ice caps, so I guess they wouldn't be as much as…they wouldn't rise as much, but oceans, um, closer to, like, the North Pole and the South, I guess, would rise more.

However, participant 6-F-4 did acknowledge the interconnectedness of bodies of water.

> 6-F-4: Um, I think I would [directly observe sea level rise at the beach], like, a little bit because they kind of connect to other oceans that are close. So, they would eventually, they would, rise a little bit but not like dramatically.

Later, she explained that when glaciers melt, "the extra water will, like, flow through, like, Arctic oceans, too. And then, it will just spread through." Though she did acknowledge that the oceans and other bodies of water are interconnected, participant 6-F-4 did not think of the water as flowing and evening out in a fast or "dramatic" way. Rather, she imagined sea level evening as a slow process, which allowed her to explain why sea level changes differently in different locations around the globe.

In contrast to participant 6-F-4, participant 6-F-3 held strikingly different views of local verses global water systems. She explained about a local water system like the Chesapeake Bay:

> 6-F-3: Um, well I really don't expect it to change because, I mean, the water cycle will always happen, so, I mean, there will always be sort of the same amount of water…like, half year round, so, I mean...
>
> Researcher: So, if you were to follow this graph into the future, it would level out, and it would stay the same?
>
> 6-F-3: Um, I feel like it would stay the same, because the water cycle just continues.

Alternatively, she believed that global sea level worked differently, and I probed her thinking about this difference:

> Researcher: So, something, um, that I'm interested in is, with the, around the Chesapeake Bay, you said it would level off, and not increase. You explained it using the water cycle. But, for the global average, you said it would continue to increase.

So, what causes the difference between around the Chesapeake Bay verses the whole world?

6-F-3: Well, I mean, the whole world, I mean, there is a lot more water than land. So, I mean, of course, yeah, the water cycle will like, have this…do the same thing in the same places. But, um…having it for like, global average, it would have increase, but just for the Chesapeake Bay, it would most likely stay the same since it's only that body of water.

Unlike participant 6-F-4, participant 6-F-3 believed that locations that were warmer would have greater sea level rise, as opposed to locations that were closer to melting glaciers (i.e., polar regions). Consequently, she predicted that the Arctic regions (which are generally cold) would be more likely to have a sea level decrease than an increase due to a lack of ice melt.

Participant 6-F-3 came up with the concept of an "off stream" to reconcile her ideas about local water systems, the water cycle, and sea level rise. She explained, "When the water cycle happens, the same amount of water stays, or maybe an off stream will have more…have more water to the body." Her reasoning seemed relatively complex, yet she fell back on the simplicity of global warming and ice melt when I asked her about local variation in sea level across the globe:

Researcher: Okay, so what might cause the differences in the different parts around the world?

6-F-3: Global warming, maybe? Like, maybe there's, like, less ice that has melted here [pointing to the graph] but a lot more…

R: In Pago?

6-F-3: Yeah, or here [pointing to the graph], or where there's less lines on the graph. But, like, where there's more lines, it's probably meaning that a lot of ice has melted, so it's getting a lot warmer.

Alternatively, participant 6-F-2's conception of local variation in the ocean was framed in terms of underwater events.

Researcher: So, what would you think would cause it to be a different change in sea level around the different parts of the world?

6-F-2: Maybe because there are different, like, things, going on under water that aren't happening in every place…Like…like, maybe if there was some sort of eruption under water, it would cause some places to go higher.

Researcher: And, what would cause an eruption under the water?

6-F-2: I actually don't know.

Researcher: Alright…so, you're being creative, here.

6-F-2: Kinda.

In addition to these mysterious underwater events, participant 6-F-2 also explained local variations in sea level in terms of the more familiar ice melt.

6-F-2: So, maybe the ice from…the ice was melting and it would come down to the places it was closer to, and the level of the water would rise in those places, I think. And so, some places weren't as high as the others.

In this response, participant 6-F-2's mental model of the ocean did appear similar to 6-F-4. Both participants believed that proximity to melting ice is an important factor in determining local sea level rise. The closer the sea is to melting ice, the higher the sea will rise.

Participant 7-F-2 appeared to have a more sophisticated, complex model of how the ocean works, and she struggled to reconcile this model with her explanation for the causes of sea level rise. Participant 7-F-2 explained that both melting ice caps and thermal expansion cause sea level rise. She also expressed the idea that sea level rise should happen everywhere around the globe because it is all water. However, she did explain that the Chesapeake Bay water was especially polluted, and that pollution could spread as the Bay water mixes with other bodies of water.

After viewing a map showing local sea level change across the globe, participant 7-F-2 suggested that sea level rise should be greater in warmer areas, since thermal expansion will happen to a greater extent. Yet, she was conflicted, as she also predicted that sea level rise should be greater in colder areas because that is where the ice is melting. Although participant 7-F-2 was not able to reconcile her conflicting explanations for local sea level rise during our brief interview, she did seem to be on a pathway towards tackling the complexities of the hydrosphere.

Participant 7-F-2's ability to recognize the contradictions in her model of the ocean and struggle to reconcile those with her explanation about the causes of sea level rise represented an important steppingstone in being able to "tell the whole story" about sea level rise. The next step for this participant was to start learning about the complexities of global and local sea level change, which depends on many factors, including the two that she identified. Specifically, participant 7-F-2 should be taught about the effects of gravity, ocean currents, and vertical land movement on local sea level change.

Participants' mental models of the ocean were important because they were an important factor in participants' abilities to construct explanations about sea level rise. Their models affected their ideas about how sea levels can be rising in some areas while falling in others, and their models also affected the ways in which learners predicted sea level change in the future (both locally and globally).

Analytic concept: Sea ice melt contributes to sea level rise. The second analytic concept that emerged from the interview data was *sea ice melt contributes to sea level rise.*

Several interview participants identified glacial ice melt as a contributor to climate change, but they defined glaciers as ice floating around in the ocean (like an iceberg).

For example, participant 6-F-3 explained that glacial ice melt causes sea level rise, yet her alternative conception of glaciers is evident in the following transcript:

Researcher: So where are these glaciers? Are they on land? Are they in water? The ones that would contribute and add onto the water level, raising the water level.

6-F-3: Um, I would have to say in the water. Because, I mean, glaciers are just…big pieces of water, just frozen.

Researcher: So the ones that are already in the water are the ones that would add to the water level.

6-F-3: Yes.

Researcher: But not the ones that are on land.

6-F-3: [Nods in agreement]

Interestingly, participant 6-F-3 specifically identified land-based ice as not contributing to sea level rise. She was unaware that the opposite is true. Land-based ice melt does contribute to sea level rise, while sea ice melt does not.

Participant 6-M-1, on the other hand, did not distinguish between land-based ice melt and sea ice melt. To him, both types of ice would contribute to sea level rise when melted.

Researcher: So, where are these glaciers that would melt?

6-M-1: Like, in Antarctica.

Researcher: Antarctica. And, how do they add to the water? Like, how does the water travel?

6-M-1: Like, in the ocean.

Researcher: It travels in the ocean?

6-M-1: Yeah.

Researcher: Okay, and where does the water come from in Antarctica? Where are the glaciers?

6-M-1: They're like, frozen in the ocean or on parts of land.

Researcher: So it's both of them—it's frozen in the ocean and frozen on the land?

6-M-1: Yeah.

Similar to participant 6-M-1, participant 6-F-1 explained that it did not matter if ice melted on land or in the ocean—both would contribute to sea level rise.

Researcher: You were talking about the ice. So, where is the ice that would be melting. Can it be in the water? On the land? Does it matter?

6-F-1: I don't think it matters because I think if the ice is melting on the land, it's gonna add more water eventually to the sea because it will probably get there through, like, erosion or whatever. And then, I think even if it's in the water, it's still gonna end up in the sea. So, I think no matter where the ice is, it's gonna end up in the water.

Researcher: And so, it will still contribute to sea level rise?

6-F-1: Yeah.

Like participant 6-F-1, participant 7-F-2 also held the alternative conception that both sea ice and land-based ice contribute to sea level rise. In the interview transcript below, she stated this conception explicitly, indicating that she still needed instruction on this aspect of sea level rise.

Researcher: So, where are the glaciers?

7-F-2: Um, in Antarctica and Alaska, and places that are cold.

Researcher: Are they on the land or are they in the water?

7-F-2: Um, I think they're in the water. Or…near the land…Wait, I think they're like on mountains.

Participant 7-F-2 expressed uncertainty about the location of glaciers on Earth. However, she seemed to believe that sea ice could plausibly cause an increase in sea levels.

The draft learning progression explicitly states that participants in levels two and three might think that sea ice or icebergs contribute to sea level rise. However, this alternative conception is not present in the descriptions of levels four or five of the learning progression. Thus, the learning progression states that an important shift in learner thinking between levels three and four is the realization that the melting of only certain kinds of ice has the potential to contribute to sea level rise.

However, participant 7-F-2 represented an important problem with the learning progression. This participant held sophisticated, though imperfect, ideas about sea level rise. Participant 7-F-2 was able to construct an explanation that incorporated authentic scientific data as evidence and used reasoning about both thermal expansion and ice melt to connect the data to her claims. Additionally, she did not express any of the alternative conceptions that seemed to confuse other learners, such as the conflation of sea level rise with lunar tides. Yet, she would be characterized as a level three learner due to her alternative conceptions about ice melt.

My experiences as an educator tell me that participant 7-F-2 exceeded the performance described by level three of the LP, even if she was not quite aligned with the description of level four. This contradiction between the interview data and the LP suggested that the LP needed to be revised to better capture what was going on with this participants' explanations. Before discussing further revisions to the LP, however, I will present the final analytic concept that emerged from the interview data regarding how pollution works.

Analytic concept: Participants held vague and alternative conceptions about how pollution impacts the ocean. The third and final analytic concept that emerged from the interview data analysis was *participants held vague and alternative conceptions about how* *pollution impacts the ocean*. Some participants spoke about humans polluting the water and directly causing sea level rise. They conceived of the pollution as trash or "gunk," which displaces the water and raises sea levels. Other participants described a mechanism where hot pollution gases are emitted from cars or factories, and these hot pollution gases directly melt the ice.

Participant 6-F-4 expressed ideas that indicated a relatively complex, yet alternative conception for how pollution leads to sea level rise:

> 6-F-4: Well, it looks like it's going lower, like, near bigger cities. So, maybe since there's…and, like, I've never heard of these places where it's, like, getting higher, so, um, maybe it's going lower in bigger cities because there's more pollution, and then the pollution's, like, it could be like, global warming I guess. And then, over here, it's not…it's increasing because, um, not as much is, like, evaporating, or, going.

Participant 6-F-4 used the reasoning that pollution causes global warming, which causes increased evaporation and declining sea levels. Her mechanism for how pollution causes global warming represented a significant yet common alternative conception about the ozone layer:

> 6-F-4: Well, like, factories, and like, cars, when they give off exhaust and chemicals…I'm pretty sure, like…um…It like thins, or something, the ozone layer, so like, more heat's like, getting through, as before. And then, the extra heat, and like pollution, causes the ice caps, and like, glaciers to melt, and then that will…the extra water will, like, flow through, like, Arctic oceans, too. And then, it will just spread through.

Here, she conflated ozone depletion with global warming, confusing two distinct environmental issues that are both related to air pollution.

In contrast to participant 6-F-4, participant 6-M-1 discussed a relatively simple and direct relationship between pollution and sea level rise. Rather than relating sea level rise to air pollution, he was thinking only in terms of water pollution:

> Researcher: So, how do you explain why sea level rise happens? So, what causes sea level rise?
>
> 6-M-1: Maybe because of the tide…and something…that has to do with, like, pollution.
>
> Researcher: Pollution…what kind of pollution?
>
> 6-M-1: Like, water pollution.
>
> Researcher: Water pollution…have you, in science class, have you talked about a claim, evidence, and reasoning?
>
> 6-M-1: Yeah.
>
> Researcher: So, what would be your claim for what causes sea level rise?
>
> 6-M-1: Um…that it probably has to do with something that people do.
>
> Researcher: Uh huh…and what would be your evidence for that?
>
> 6-M-1: Um, like, a long time ago, the sea level rise was, like, lower, and we didn't do as much, like, pollution, and stuff. But now we do it a lot more and the sea level rise got, like, bigger.
>
> Researcher: Uh huh. So, you talked about the pollution being in the water, so is it people polluting the water and that, over time, has caused the sea level to rise?
>
> 6-M-1: Yeah.
>
> Researcher: And any other kind of pollution?
>
> 6-M-1: Uh…I don't think so…

Participant 6-M-1's ideas about water pollution were consistent with other participants who explained sea level rise in terms of water displacement. As humans add waste to the sea, the sea rises. However, participant 6-M-1 did not explicitly make that connection.

Participant 6-F-1 appeared to express a similar conception about water pollution, though she did make her ideas about water displacement explicit:

> Researcher: The first question is what does sea level rise mean to you?
>
> 6-F-1: Well, I don't know if this really connects, but last year our science teacher spent a little while talking about, like, how the tide sort of affects, like, the sea level. But, um…and then, I also think it probably has something to do with pollution. Like, I mean, like, whatever is on the bottom is gonna obviously make the water rise up more. So, if there is more, like, gunk in the water, it will probably rise, I'm assuming.

Later in the interview, I asked her to construct a complete explanation about what causes sea level rise, and she returned to the topic of pollution:

> 6-F-1: Um…well, I'd assume that pollution would cause it, and the evidence would be…that…there's…I mean I already know there's a lot of pollution in the world. Or that like when jellyfish are dying because of unnatural causes and finding, like, random bits of like glass and bottles washing, go, like…wash up on the shore. Reasoning would be…um…that like, I know that because when stuff is put in water it rises so the more bottles people throw into the water, the more animals they take out of the water, the sea level would change, I guess.

The vague and alternative conceptions about pollution that the interview participants discussed would align them with lower levels of the learning progression—levels two and three. In order for participants to advance to higher levels of the learning progression, they must have more normative conceptions about the connections between pollution and sea level rise, including the indirect mechanism of the greenhouse effect, which would allow them to construct stronger explanations about what causes sea level rise and about how sea levels will change in the future.

Interview data that disconfirmed portions of the LP. Participant 6-F-2's responses to my interview questions appeared to disconfirm certain elements of the first two levels of the draft learning progression. Specifically, level one of the LP describes learners who express confusion or lack of awareness about the sea level rise phenomenon, while level two describes learners who are aware that sea level rise is occurring. Moreover, level two learners are able to inconsistently use evidence and/or reasoning to construct explanations about sea level rise. However, participant 6-F-2 did not match either description. She was aware that sea level rise is occurring, yet she did not offer any evidence or reasoning to explain this phenomenon.

> Researcher: So, trying to think of the claim, the evidence, and the reasoning for your explanation, can you please give me a scientific explanation for what causes sea level rise?
>
> 6-F-2: I actually don't know what causes sea level to rise.
>
> Researcher: So, the water level's getting higher, what makes it higher? Where does the water come from? [4-second pause] Not sure?
>
> 6-F-2: I'm not sure.

To account for participant 6-F-2's inability to provide evidence or reasoning for the cause of sea level rise, I expanded level one of the learning progression to the following (changes are in bold):

> **Some** learners express confusion or a lack of awareness about the sea level rise phenomenon when constructing scientific explanations about sea level rise. This confusion or lack of awareness prevents learners from drawing on appropriate evidence or scientific reasoning when attempting to explain the sea level rise

phenomenon. **Other learners may be aware that sea level rise is occurring, yet they are not able to use evidence or reasoning to explain what causes sea level rise. Consequently, they are not able to construct basic explanations about sea level rise.**

As mentioned in a previous section, participant 7-F-2's interview responses surfaced a problem with levels three and four of the draft LP. While participant 7-F-2's ideas about the causes of sea level rise were more sophisticated than the ideas in the level three description of learner thinking, she held two important alternative conceptions. First, when she identified melting icecaps as one of the two major causes of sea level rise, she did not distinguish between sea ice melt and land ice melt. Rather, she believed that both contribute to sea level rise. Second, while participant 7-F-2 identified thermal expansion as the other major cause of sea level rise, she expressed the alternative conception that water molecules grow in size when heated. In general, participant 7-F-2's thinking aligned well with level four of the LP, as she was able to identify multiple causes of sea level rise, she used a relatively sophisticated mental model of how the ocean works, and she did not express any of the more problematic alternative conceptions about sea level rise or global warming, such as the conflation of lunar tides and sea level rise or the conflation of ozone layer depletion with global warming.

Though level four of the LP does not quite capture participant 7-F-2's thinking, neither does level three adequately represent it. This problem led me to consider two possibilities. First, it was possible that this was simply an instance of a learning progression's failure to describe a coherent set of ideas that a learner is presumed to hold at a particular level. In other words, these levels do not really exist. Rather, the levels of an LP are imperfect models of learner thinking, and these models are not a good fit to describe participant 7-F-2's thinking.

The second possibility to consider was that the LP needed to be revised to better fit the data. Specifically, I needed to add a new level between levels three and four to account for learners like participant 7-F-2. Though I continued to consider the possibility that my LP could not adequately describe learner thinking with coherent levels of achievement, I continued to strive to make my model of learner thinking (i.e., the learning progression) fit the data as well as possible. Thus, I created a new level four of the LP, which changed the current levels four and five into levels five and six. The description of the new level four is given below:

> Learners construct explanations about sea level rise supported by multiple sources of evidence that are generally consistent with scientific ideas, principles, and theories, though learners still hold important alternative conceptions about sea level rise. Learners consistently use authentic scientific data as evidence. Learners apply scientific ideas, principles, and/or evidence to construct, revise, and/or use an explanation for sea level rise. Learners know that sea level rise is caused by global warming/climate change, which causes increased ice melt on Earth's surface. Learners know that water cycles among land, ocean, and atmosphere because the Earth's spheres are interconnected. Water movement causes weathering and erosion, changing landscape features. Learners also know that the fact that matter is composed of atoms and molecules can be used to explain the properties of substances, diversity of materials, states of matter, phase changes, and conservation of matter. However, learners may hold alternative conceptions about constructs related to atomic-molecular theory. Though learners know that thermal expansion is a significant cause of sea level rise, learners may express the idea that water molecules grow larger in size as temperature increases, which allows them to explain how thermal expansion works. Additionally, learners may hold the alternative conception that both sea ice

melt and land ice melt cause sea level rise, since both types of melted water can add to the total volume of liquid water in the ocean. In order to advance beyond level four of the learning progression, learners must gain a stronger grasp on the nature and interaction among energy and the particles involved in the sea level rise phenomenon.

The new description of level four of the learning progression is very similar to level five. However, level four of the LP now describes participant 7-F-2's thinking very well. As I was writing the description for level four, I realized what was absent in participant 7-F-2's thinking. She had not yet studied chemistry as it is usually taught at the high school level. In particular, her ideas about matter, atomic-molecular theory, and kinetic molecular theory were underdeveloped, so she was not able to explain that thermal expansion occurs as water molecules move more quickly and spread farther apart as their temperature increases. Similarly, she was not thinking about how sea ice and liquid seawater were both taking up volume in the ocean and both contributing to sea level.

As with the levels of all learning progressions, a learners' progression from level four to level five is not inevitable. Even after participant 7-F-2 takes high school chemistry, she may still hold alternative conceptions about matter. Or, what participant 7-F-2 learns about matter in high school chemistry may never be transferred to the context of sea level rise. If a learner like participant 7-F-2 is to advance to higher levels of the sea level rise LP, she must experience targeted instruction that explicitly connects the atomic-molecular and kinetic molecular theories to glacial ice melt, thermal expansion, and sea level rise.

Interview data that confirmed portions of the LP. Other interview responses appeared to confirm portions of the draft LP, aligning with descriptions of LP levels, as well as analytic concepts discussed in previous sections. The most prominent sea level rise concept on the LP is related to the analytic concept *global warming and ice melt cause sea level rise*, and that analytic concept fit the data well. In this section, I report examples of how participants used global warming and ice melt to explain sea level rise in a way that aligned well with the level two description. I also report examples of alternative conceptions these participants held that aligned with the level two description. Finally, I report how these participants structured their explanations, using evidence and reasoning in ways that supported the level two description. After showing how those interview data confirmed portions of level two, I follow a similar process to report confirmation of higher levels of the LP.

***Interview data that confirmed portions of level two of the* LP.** My interview data showed that many of the participants were aware that sea level rise was related to an increase in the amount of melting ice on Earth. However, participants whose thinking helped to confirm level two of the LP were less able to coordinate reasoning about this ice melt with authentic scientific data to support their claims. Additionally, they held specific alternative conceptions that characterized level two thinking.

For example, Participant 6-F-4 explained that she associated sea level rise with glacial ice melt. A portion of her interview transcript is presented below:

> 6-F-4: Um, sea level rise just means, like, um, when like glaciers melt, and, or, like, anything really, and the sea level rises to higher than before it was, like, before the average, I guess.

Participant 6-F-3 explained the cause of sea level rise in a similar way:

> 6-F-3: Um…Well I think like, what causes sea level to rise is like, glaciers, say, like, usually like, like in the wind and storms, they usually build up snow…and then, and like, warmer conditions, there they'll like melt and go into the water, and the water will rise and rise from the position where they were last time.

Though interview participants identified glacial ice melt as a cause of sea level rise, they failed to distinguish between the melting of sea ice verses land-based ice.

Participants' discussions of melting ice supported the following description on level two of the learning progression:

> Learners know that water is found in many types of places and in different forms on Earth, such as icebergs and glaciers. However, learners may express the idea that icebergs contribute to sea level rise when they melt, rather than understanding that melting ice must originate from land in order to contribute to sea level rise.

Participants did not have a strong conception about the definition of glaciers. In general, they defined glaciers as ice on Earth's surface, whether on land or in water.

Interview participants' use of evidence and reasoning to construct explanations about sea level rise also supported level two of the draft LP. For example, participant 6-M-1 was able to use a graph of sea level rise data as evidence to explain how sea level changed around the Chesapeake Bay, though he was not able to incorporate scientific reasoning to explain what the data meant:

> Researcher: Alright, great. Um, so you talked about the Chesapeake Bay. And, so, here's a graph showing how the Chesapeake changed in different spots over the years. So, um, how has sea level changed around the Chesapeake Bay?
>
> 6-M-1: It's gotten a lot higher over the past hundred years.
>
> Researcher: And, so, what's your evidence for that?
>
> 6-M-1: Like, the graph shows, like, it starts from, like, really low, and it rises up as the years go by.
>
> Researcher: Okay, and how about your reasoning? So, your claim is that the sea level has risen, and the evidence is that the graph shows that it goes up. So, how do you connect those two together?
>
> 6-M-1: Uh… [12-second pause]
>
> Researcher: Not sure? Okay, fair enough.

This inability to consistently integrate evidence and reasoning is captured in the following description of level two of the LP:

> Learners sometimes use evidence and ideas to construct evidence-based accounts of sea level rise and sometimes they rely more heavily on scientific reasoning to support their claims about sea level rise. Due to learners' inconsistent and/or incomplete use of both evidence and reasoning, learners often fail to connect their claims and evidence using reasoning that adheres to scientific principles. Through targeted instruction, learners can begin to use authentic scientific data as evidence when explaining sea level rise, though this may cause them to use less scientific reasoning.

Throughout my study, I found that as learners began to use authentic sea level rise data, their use of scientific reasoning declined, and participant 6-M-1's interview was a good example of that phenomenon.

In general, I found that the thinking of the sixth grade interview participants was accurately captured by level two of the draft LP. This thinking tended to focus on visible and familiar phenomena, such as melting ice, trash, and rain. For example, participant 6-F-1 explained sea level rise in terms of gunk in the water:

> Researcher: What does sea level rise mean to you?
>
> 6-F-1: Well, I don't know if this really connects, but last year our science teacher spent a little while talking about, like, how the tide sort of affects, like, the sea level. But, um…and then, I also think it probably has something to do with pollution. Like, I mean, like, whatever is on the bottom is gonna obviously make the water rise up more. So, if there is more, like, gunk in the water, it will probably rise, I'm assuming.

Participant 6-F-1's interview was not the original evidence that prompted the following language on the level two description of the LP, though it matched well:

> For example, learners may explain that sea level rise is caused when humans add waste (e.g., trash) to the sea, when increased rainfall enters the sea, and/or when additional wind raises the water to a greater height.

Since participant 6-F-1's interview was not the evidence used to create this description, yet the description fit these data well, the data helped to confirm this portion of the LP.

Data from my interview with participant 8-F-1, an eighth grade learner, also helped to confirm the portion of the level two description in the preceding paragraph. Participant 8-F-1 consistently explained that sea levels increase as it rains more. Below is a portion of the interview transcript that captured her thinking well:

> 8-F-1: Okay, sea level rise occurs when there's more rain, and when there's more rain then the ocean, like, fills up and there's more water, and then it kind of makes the beach less big—well, smaller. And then, um, and then when there's more water things overflow and, well, they get dirtier because there's more rain.
>
> Researcher: So, here is a graph of the sea level measurements around the Chesapeake Bay. So, different colors are different points. So, please explain how sea level has changed around the Chesapeake Bay around the last one hundred years or so.
>
> 8-F-1: Over the last one hundred years? Um, it's increasing at a steady rate. So, it probably means that we're getting, like, every year more and more rain, and then it keeps increasing.
>
> Researcher: How do you expect it to change over the next one hundred years?
>
> 8-F-1: Well, probably it's probably going to keep on rising because we're going to keep getting more rain and snow and things like that. Then again, we could use more water, and it could get lower. It all depends, I guess.
>
> Researcher: Why are we getting more rain?

8-F-1: Um, maybe because…and like, the polar ice caps and things are melting. And then, because of the water cycle it becomes more precipitation, and then we get more rain.

Researcher: So, the glaciers melting causes the sea level to rise because that water…

8-F-1: That water gets reused into rain, and then when it rains it fills up the oceans.

Participant 8-F-1's model for how sea level rise works was coherent in that she explained everything in terms of the amount of rainfall, a highly visible phenomenon with which she had experience. She explained that global warming causes polar ice caps to melt, and this melted ice turns into precipitation, which fills the ocean to higher levels. When I asked her to explain the map showing regional sea level change, she explained that warmer areas will have more sea level rise because these areas will experience more ice melt and more precipitation.

What participants 6-F-4, 6-F-3, 6-M-1, and 8-F-1 have in common is that they are aware that sea level rise is occurring, though they used evidence and reasoning inconsistently when explaining sea level rise using visible and familiar phenomena. These phenomena included ice melt, rainfall, wind, dumping of trash, and volume/weight displacement. In contrast, interview participants whose responses supported level three of the LP coordinated evidence and reasoning more consistently and used reasoning that was more abstract and less immediately visible.

Interview data that confirmed portions of level three of the LP. Interview data from participant 8-M-1 helped to confirm level three of the LP. Like participants 6-F-3 and 6-F-4, participant 8-M-1 also explained that sea ice melt can contribute to sea level rise, though his explanations were more sophisticated than those of these sixth grade learners. During his interview, participant 8-M-1 explained the transition of solid ice to liquid water, predicted that he would notice retreating sands at the beach as sea level rise continued, correctly interpreted a graph of sea levels around the Chesapeake Bay (Boesch et al., 2013, p. 1), and he related these data to his ideas about Arctic ice melt. Participant 8-M-1's coordination of evidence and reasoning was shown in the following interview transcript:

> Researcher: Okay, so the ice that melts in the water, when it melts in the water, it raises the sea level because it becomes…
>
> 8-M-1: Water.
>
> Researcher: Becomes liquid water. Okay. So, this first question with the graph is, this is showing sea level rise around the Chesapeake Bay. So, how has sea level changed around the Chesapeake Bay over the past hundred years?
>
> 8-M-1: It's dramatically increased from .16 to .66.
>
> Researcher: So, why has it changed?
>
> 8-M-1: Um, from the more water coming into the ocean.
>
> Researcher: And, what's your explanation for how it will change over the next hundred years?
>
> 8-M-1: Even more water coming into the ocean from the ice caps melting.

Unlike the sixth grade participants, participant 8-M-1 was able to integrate evidence with his reasoning to support his claim in a consistent way. Rather than inhibit his ability to use scientific reasoning, learning to use authentic sea level rise data only enhanced his ability to support his claims.

In general, participant 8-M-1's interview responses supported the level three description of the draft LP, presented below:

> Learners use evidence and/or scientific reasoning in constructing explanations that specify variables that describe and predict phenomena related to sea level rise. For example, a learner might specify the effect that the variable "temperature" will have on the variable "amount of ice melt" or the effect that the variable "amount of ice

melt" will have on the variable "sea levels". Through targeted instruction, learners can use authentic scientific data as evidence in a consistent way when explaining sea level rise and are able to connect these data to their claims using scientific reasoning. Learners know that most of Earth's water is in the ocean and much of the Earth's fresh water is in glaciers or underground. However, learners may express the idea that icebergs contribute to sea level rise when they melt, rather than understanding that melting ice must originate from land in order to contribute to sea level rise.

Participant 8-M-1 used both evidence and reasoning to support his claim that sea level rise will continue, and he was learning how to incorporate authentic scientific data into his explanations about sea level rise. Yet, he still held important alternative conceptions consistent with level three of the LP, such as the idea that sea ice melt contributes to sea level rise.

Later in the interview, participant 8-M-1 further showed that he was learning to use and understand authentic scientific data on sea level rise. It seemed that he had begun the interview with the alternative conception that sea levels have been rising everywhere on Earth. However, after studying the map and graphs of sea levels around the world (IPCC, 2013, p. 1148), he began to rework his model of how the ocean works:

8-M-1: Where it's decreasing? [takes time to study the graph/map] Wait, so is the blue where it's decreasing?

Researcher: Yes.

8-M-1: But then why does the chart say it's increasing?

Researcher: Um…so, an area that's blue is…like San Francisco is sort of in the blue area, and then this one that starts with an A is in the blue area. And, so this one for San Francisco doesn't really increase.

8-M-1: Like very little.

Later in the interview, participant 8-M-1's reworked model of the ocean manifested itself:

> Researcher: The last [question] is, how do you expect sea level to change…or how do you explain how sea level will change over the next hundred years for the whole world?
>
> 8-M-1: I think it will mostly increase. I don't think that this trend will change very much because that'd be not likely because the past hundred years hasn't gone down much at all.
>
> Researcher: Uh huh.
>
> 8-M-1: And, maybe some spots will change. Maybe this won't stay decreasing, this will start to increase and this will start to decrease.
>
> Researcher: And, so, what would cause that?
>
> 8-M-1: Um, just the flow of the ocean where the most water is going to. So, if there's tons of water going over here, the water level will increase. If there's very little over here, it will decrease.
>
> Researcher: So, um, what you're pointing to is the blue area, and you're saying that area over time could increase if the water is flowing towards it, and the red area could start to decrease if water is flowing away from it.
>
> 8-M-1: Yeah.

Participant 8-M-1's interview responses demonstrated that level two of the LP was not a good fit to describe his thinking. Rather, the level three description was a good fit for these data because participant 8-M-1 was able to support his claims with evidence and reasoning in a consistent way.

Also aligned with the level three description of the LP, participant 8-M-1 demonstrated that he was able to reason about sea level rise in terms of invisible phenomena. For example, he emphasized the role of evaporation of water in sea level rise, explaining that evaporation occurred to a greater extent near the equator, where it is warm. He further explained that the evaporated water would simply rain back down as part of the water cycle, and so sea levels should increase more near the equator. Participant 8-M-1 was able to reason using concepts that were not immediately visible, and he demonstrated a commitment to the law of conservation of matter. Yet, he still held important alternative conceptions about sea level rise (e.g., sea levels will increase more near the equator because there is greater evaporation and precipitation), which is a key aspect of level three of the LP.

The interview data from participant 8-M-2 also confirmed portions of the level three description of the LP. In particular, he talked about how much of the Earth's fresh water is in glaciers:

> 8-M-2: One of the things that's causing [sea level rise] is, well, the glaciers melting, because they hold a lot of the world's water, and the melting would definitely raise the sea level by a lot…Because since they hold water, if they melt, it will release it into the oceans, or wherever it actually ends up from there. And, that would lead to the sea level rise because it will go into the ocean, and a majority of the world's water is actually frozen. I was pretty sure.

Not only does participant 8-M-2 explicitly state his knowledge about the location of the world's water on Earth, he also related this knowledge to his reasoning about the causes of sea level rise. This integration of evidence and reasoning to support a claim is a distinguishing feature between levels two and three of the LP.

Participant 8-M-2's interview responses also aligned with the portion of level three of the LP that describes how learners hold the alternative conception that sea ice melt contributes to sea level rise. He explained his ideas on this topic in the transcript below:

> Researcher: So, you talked about glacial ice melt, you talked about what that means. Where are the glaciers?

8-M-2: At the North and South Poles and a few other locations around the Arctic Circle.

Researcher: Are they on land or are they in water if they're contributing to sea level rise?

8-M-2: In water. Or, it can be on land, but then it would kind of have to evaporate into it.

Not only did he identify sea ice melt as contributing to sea level rise, but he showed fairly sophisticated reasoning about why it is more difficult for land-based ice to contribute to sea level rise—that water would have to evaporate and enter the atmosphere in order to reach the ocean.

While participant 8-M-2 demonstrated some fairly sophisticated scientific reasoning, he did not know about thermal expansion or incorporate this construct into his explanations about sea level rise. Moreover, he expressed the same sorts of alternative conceptions that characterize level three:

Researcher: And, what does thermal expansion mean to you, if anything? Have you heard that term?

8-M-2: I think, but I think I forgot what it meant.

Researcher: Okay, is there anything else that you wanted to share about sea level rise?

8-M-2: Well, also, the glacial ice melting is…part of the reason that's causing it to melt is the ozone layer because it's missing a big area, and also, the greenhouse effect.

As I have shown with data from other participants, learners at level three frequently conflate global warming (and its consequences, such as sea level rise) with ozone layer depletion.

Interview data that confirmed portions of upper levels of the LP. Participant 8-M-4's interview responses helped to confirm portions of the level five description of the LP. In particular, he demonstrated the ability to incorporate multiple sources of authentic scientific data and used reasoning to connect these data to his claim. In particular, he used the concept of ocean currents to explain regional variations in sea level change, citing evidence from the map of sea level change around the world (IPCC, 2013, p. 1148). A portion of his interview transcript is given below:

> 8-M-4: For example, if there was a strong current over here in San Francisco... [indicating a blue area on the map where sea level has decreased]
>
> Researcher: Where it's a blue area.
>
> 8-M-4: Yeah.
>
> Researcher: Okay.
>
> 8-M-4: And let's say that it pulled a lot of water towards an area that was red.
>
> Researcher: Okay.
>
> 8-M-4: Like, that's just, like, the way that current went was from blue area…just, the way it happened to go was from an area that was in a darker blue to an area that was red.

In this transcript, participant 8-M-4 was explaining how ocean currents work with the atmosphere to transfer water around the earth as water moves through the water cycle.

Participant 8-M-4's interview provided the only data where a participant directly discussed ocean currents. Thus, his responses provided the only support for the following portion of the level five description of the LP:

> Learners know that water cycles among land, ocean, and atmosphere, and is propelled by sunlight and gravity. Density variations of seawater drive interconnected ocean currents.

Participant 8-M-4 discussed how the ocean currents are interconnected, though he did not mention that density variations of seawater drive these currents. However, he did explain the role of wind in moving water across Earth's surface:

8-M-4: So, I imagine specific areas where it's decreasing, um, when the water is being evaporated, the winds, like, I guess the jet stream, maybe, I don't know if that could affect it, but could take it to places that are where the jet stream's weaker. So, for example, over here in Manila, it's a lot more, it's rised a lot more than near San Francisco. And, in that area it might be that the jet stream's higher and can bring it to areas like Manila where it kind of like dies off. So then, all of the rain doesn't move as the…the rain and the cloud doesn't move as much, and it can fall more in those areas.

Researcher: So, what's being moved by the jet stream? I might have missed this. Is the water?

8-M-4: The water and the clouds.

Researcher: The water and the clouds. Thank you.

8-M-4: And, um, ocean currents.

Though his mechanism for how ocean currents relate to sea level rise did not completely align with the level five description, the concept is the same—he reasoned that water cycles among land, ocean, and atmosphere through evaporation, precipitation, and ocean currents to support his claims about sea level rise.

The interview data from participant 8-M-3 helped to confirm other portions of the level five description. In addition to explaining sea level rise in terms of glacial ice melt, participant 8-M-3 also explained that thermal expansion causes sea level rise, demonstrating a strong understanding of atomic-molecular theory. He articulated his complex reasoning in the following interview transcript:

Researcher: Um, so you said [melting ice] was the main cause. Is there another cause, or is that it? Is that the only important one?

8-M-3: I think another main cause might be like, um, you know, when stuff gets hotter, uh, the molecules start expanding more, and the oceans are getting hotter, so the molecules are probably expanding, the ocean, the water in the ocean is expanding. Yeah.

Researcher: So, can you clarify what you mean by the molecules expanding? What does that mean?

8-M-3: Like, when, when the water gets hot. Okay, when any sort of object gets…the hotter it gets, the more molecules expand apart and start, you know, going apart, and, um. Because, you know, with the sun, uh, coming down on the ocean all day, plus the heat we get from, you know, greenhouse gases, you know, trapping the heat in. That's heating up the ocean, making molecules, um, expand, get more jumpy, um, and basically causing the sea in turn to expand.

Researcher: So, the molecules get farther apart or the size of the molecules changes?

8-M-3: The molecules get farther apart.

In this transcript, participant 8-M-3 demonstrated the sort of strong understanding of atomic-molecular theory that distinguishes level four of the LP from level five. Unlike learners at level four, participant 8-M-3 clearly understands that water molecules spread farther apart and occupy a greater volume as their kinetic energy increases—as they get "more jumpy."

Participant 8-M-3's interview data helped to confirm the portion of level five of the LP that describes learners' conceptions about atoms in molecules. Specifically, these data supported the following portion of level five:

> Learners also know that the fact that matter is composed of atoms and molecules can be used to explain the properties of substances, diversity of materials, states of matter, phase changes, and conservation of matter. Additionally, learners know that kinetic energy can be distinguished from the various forms of potential energy. Energy

> changes to and from each type can be tracked through physical or chemical interactions. The relationship between the temperature and the total energy of a system depends on the types, states, and amounts of matter. Learners also know that thermal expansion is a significant cause of sea level rise, and can explain how thermal expansion causes sea level rise using principles of atomic-molecular theory.

Participants 8-M-3 and 8-M-4 both demonstrate sophisticated understandings about concepts related to sea level rise, and they are able to coordinate authentic scientific evidence with reasoning about these concepts. For participant 8-M-3, these concepts relate to the molecular basis for sea level rise, while for participant 8-M-4, these concepts relate to Earth's systems.

While both of these participants gave interview responses that aligned well with the level five description of the LP, their responses fell short of the level six description. Specifically, neither participant provided responses that align with the following portion of level six of the LP:

> Learners apply scientific reasoning, theory, and/or models to link evidence to the claims to assess the extent to which the reasoning and data support the explanation or conclusion.

Neither participant 8-M-3 nor 8-M-4 explicitly used models in their explanations, and neither attempted to assess the extent to which the reasoning and data supported their explanations and conclusions. Moreover, both participants only applied reasoning about one concept to explain the data on the map of sea level change around the world. For participant 8-M-3, he explained local sea level change in terms of thermal expansion. In contrast, participant 8-M-4 explained local sea level change in terms of ocean currents. Neither participant was able to include reasoning about other concepts they had mentioned, such as glacial ice melt, to explain these data.

New and unexpected additions to the LP. In this section, I present new and unexpected findings from the interview data. Correspondingly, I present and explain additions to the draft LP that I have made in response to these unexpected findings. I begin this section by describing interview data addressing ideas about how tectonic activity affects local sea levels.

The effect of tectonic activity on local sea levels. One unexpected finding from the interview data was that two of the participants (8-M-2 and 7-M-4) were able to reason that sea level might be higher or lower in certain areas because of the interaction of tectonic plates. Participant 8-M-2 was taking an eighth grade Earth Science class at the time of his interview, so he had recently learned about tectonic activity. The following transcript is from the portion of our interview when he was explaining regional variation in sea level change:

> 8-M-2: I honestly don't know why it's decreasing in some areas. I'm guessing it has to do with location, the elevation of the sea floor in that area.
>
> Researcher: So, what's causing the elevation of the sea floor to be different?
>
> 8-M-2: Tectonic activity, such as plates subducting over each other, which creates trenches, which causes probably a bit of a difference in sea level or sea floor level.
>
> Researcher: So, if there were those trenches, how would that change the sea level? Would it increase or decrease?
>
> 8-M-2: In the area that has a trench in it, or the trench at least, it would decrease.
>
> Researcher: Decrease? And, um, so, if it's doing that, then it would be a decrease. Is there anything that could cause a more dramatic increase with the tectonic plates?
>
> 8-M-2: Also, with convergent plates at boundaries, they can create mountains when it's different weights, so that would definitely raise the sea level, or sea floor level. I don't know why I keep calling them the same thing because they're very different.

While participant 8-M-2 had recently learned about tectonic activity, it was surprising that he was able to transfer this learning to the context of sea level rise. When learning about tectonic plate movement in his science class, the instruction did not address sea level rise. Additionally, the concept of regional variation in sea level was new to participant 8-M-2 during the interview. Thus, he had to pull all of his new understanding together on his own, and he did so in a coherent and sophisticated manner.

In contrast to participant 8-M-2, participant 7-M-4 had not learned about tectonic activity in school, and he would was not scheduled to learn about this until the following year. Still, participant 7-M-4 was able to accurately explain the process of tectonic plate subduction, which causes the sea floor to fall in some areas, lowering local sea level. His interview transcript is provided below:

> 7-M-4: Um, so it could be, I guess, this is just a wild guess. It's probably wrong, but, tectonic plates, I guess.
>
> Researcher: And what are those tectonic plates doing?
>
> 7-M-4: Um, well, some are constantly pushing down. Others are pushing up, which could—if it was pushing downward…that wouldn't work, would it? I guess, if a plate was pushing downward, um, on the coastline, and it was pushing another coastline upward, it wouldn't be going…if it was—that still wouldn't work. I'm not sure.

What is both surprising and impressive about participant 7-M-4's interview responses was his willingness and ability to reason using scientific principles about unfamiliar and sometimes puzzling scientific data.

In response to these surprising findings, I decided to add ideas about tectonic activity into the draft LP. However, I did not have enough data to associate these ideas with a particular level of the LP. Should these ideas be associated with levels four, five, or six? It was also important to consider that an understanding of how tectonic activity can affect local sea levels is not achievable without first learning about tectonic plates. I made the inference that participant 7-M-4 learned about tectonic plates outside of school (e.g., from a family member, a book, a video), while participant 8-M-2 learned about tectonic plates as part of the eighth grade science curriculum.

Since most participants were not able to reason about how tectonic activity and vertical land movement can affect local sea levels, and because this is a rather sophisticated concept, I felt strongly that these ideas should not characterize the lower levels of the LP (levels one, two, or three). Since I did not have data to restrict these ideas to specific levels of the LP, I decided to conditionally add them to levels four, five, and six. Changes to the draft LP are presented in the table below (changes are in bold):

Table 23

Revised Levels Four, Five, and Six of the Draft LP

Level 4	Learners construct explanations about sea level rise supported by multiple sources of evidence that are generally consistent with scientific ideas, principles, and theories, though learners still hold important alternative conceptions about sea level rise. Learners consistently use authentic scientific data as evidence. Learners apply scientific ideas, principles, and/or evidence to construct, revise, and/or use an explanation for sea level rise. Learners know that sea level rise is caused by global warming/climate change, which causes increased ice melt on Earth's surface. Learners know that water cycles among land, ocean, and atmosphere because the Earth's spheres are interconnected. Water movement causes weathering and erosion, changing landscape features. **Additionally, learners who have received instruction on tectonic plates and tectonic activity may be able to explain regional variations in sea level change in terms of vertical land movement, using concepts such as tectonic plate subduction.** Learners also know that the fact that matter is composed of atoms and molecules can be used to explain the properties of substances, diversity of materials, states of matter, phase changes, and conservation of matter. However, learners may hold alternative conceptions about constructs related to atomic-molecular theory. Though learners know that thermal expansion is a significant cause of sea level rise, learners may express the idea that water molecules grow larger in size as temperature increases, which allows them to explain how thermal expansion works. Additionally, learners may hold the alternative conception that both sea ice melt and land ice melt cause sea level rise, since both types of melted water can add to the total volume of liquid water in the ocean. In order to advance beyond level four of the learning progression, learners must gain

	a stronger grasp on the nature and interaction among energy and the particles involved in the sea level rise phenomenon.
Level 5	Learners construct explanations about sea level rise supported by multiple sources of evidence consistent with scientific ideas, principles, and theories. Learners consistently use authentic scientific data as evidence. Learners apply scientific ideas, principles, and/or evidence to construct, revise, and/or use an explanation for sea level rise. Learners know that sea level rise is caused by global warming/climate change, which causes increased ice melt on Earth's surface. Learners know that water cycles among land, ocean, and atmosphere, and is propelled by sunlight and gravity. Density variations of seawater drive interconnected ocean currents. Water movement causes weathering and erosion, changing landscape features. **Additionally, learners who have received instruction on tectonic plates and tectonic activity are able to explain regional variations in sea level change in terms of vertical land movement, using concepts such as tectonic plate subduction.** Learners also know that the fact that matter is composed of atoms and molecules can be used to explain the properties of substances, diversity of materials, states of matter, phase changes, and conservation of matter. Additionally, learners know that kinetic energy can be distinguished from the various forms of potential energy. Energy changes to and from each type can be tracked through physical or chemical interactions. The relationship between the temperature and the total energy of a system depends on the types, states, and amounts of matter. Learners also know that thermal expansion is a significant cause of sea level rise, and can explain how thermal expansion causes sea level rise using principles of atomic-molecular theory.
Level 6	Learners construct explanations about sea level rise supported by multiple and independent student-generated sources of evidence consistent with scientific ideas, principles, and theories. Learners consistently use authentic scientific data as evidence. Learners apply scientific reasoning, theory, and/or models to link evidence to the claims to assess the extent to which the reasoning and data support the explanation or conclusion. Learners know that the planet's dynamics are greatly influenced by water's unique chemical and physical properties. Learners also know that the sub-atomic structural model and interactions between electric charges at the atomic scale can be used to explain the structure and interactions of matter. Additionally, learners know that the total energy within a system is conserved. Energy transfer within and between systems can be described and predicted in terms of energy associated with the motion or configuration of particles (objects). Consequently, learners are able to explain sea level rise using the constructs glacial ice melt and thermal expansion. **Additionally, learners are able to explain regional variations in sea level change in terms of vertical land movement, using concepts such as tectonic plate subduction. Moreover, learners explain sea level changes in terms of vertical land movement in a consistent way, always recognizing that sea level change varies due to multiple factors.**

The changes to the draft LP above indicate some assumptions that I have made, all of which need to be further explored through research. First, the description of level four indicates that inclusion of tectonic activity is tentative. Not only did I include the disclaimer that participants need to experience instruction on tectonic activity for the description to apply, but I also acknowledged that learners at level four may still not incorporate these ideas into their explanations.

For level five, I again included the disclaimer that learners need to experience instruction on tectonic activity for the description to apply. However, I also stipulated that learners who have experienced this instruction *can* explain regional variations in sea level change in terms of tectonic activity. This distinction aligned with the overall pattern of the learning progression—as the level of the LP increases, the consistency of explanations increases, too. The language changes from "may be able to explain" at level four to "are able to explain" at level five.

Finally, I removed the disclaimer about experiencing instruction on tectonic plates for level six—the highest level of the LP. This distinction between level five and six emphasizes the point that learners at level five still require instruction, while learners at level six have already experienced the instruction. Not only have learners at level six experienced significant instruction about sea level rise, including concepts relating to vertical land movement, but they also incorporate these ideas in a consistent, predictable way. Learners at level six do not consider sea level change without acknowledging factors such as vertical land movement.

Forgetting thermal expansion. Another surprising finding from the interview data was that many students forgot what they had learned about thermal expansion. In a previous section, I presented the analytic concept *participants learned about thermal expansion as a fundamental aspect of sea level rise*. I had observed the seventh grade participants learning about thermal expansion during a classroom lesson. During the observation, I witnessed students explaining thermal expansion in relation to two YouTube video clips, which were intended to help them visualize the phenomenon. I also heard students relating the concept of thermal expansion to the authentic scientific data that the teacher and I made available to them (i.e., the graphs related to sea level rise). For example, in small groups, students were discussing the connections between the graph showing increasing heat content in the upper oceans and the graph showing increasing global average sea level. Moreover, some participants used thermal expansion when constructing their explanations about sea level rise on the second written assessment, which followed the targeted instruction on thermal expansion.

Surprisingly, some participants struggled to use the term thermal expansion during the interview, even when they were able to clearly employ this concept to explain sea level rise. Other participants acknowledged that they had learned about a sea level rise cause other than glacial ice melt, though they were unable to remember what they had learned. For example, when I asked participant 7-F-4 for her scientific explanation for what causes sea level rise, she stated,

> I think there are a lot of explanations because there's, some of the water in the world is in the form of ice, and global warming can make the ice melt. And, also there's…I'm sorry, I've forgotten the…I forgot the explanation from the classroom. I'm sorry.

After learning about thermal expansion through targeted instruction, I expected participants to incorporate thermal expansion into their scientific explanations about sea level rise. As noted in a previous section, only five out of 26 participants addressed thermal expansion on the second written assessment following the targeted instruction. Interestingly, participant 7-F-4 was one of the five participants who had successfully employed the thermal expansion concept to explain sea level rise. Later in the interview, the thermal expansion concept resurfaced:

> 7-F-4: And, as it gets warmer, the water also expands. So, if it…so, if it were suddenly getting…So, I guess the places with the most sea level rise would be the m—, would be where it was getting, it was heating up more rapidly. Like, right here, it's probably, it probably used to be cold and now it's getting a lot, and now it's warmer than it was, let's, ah, a few years ago.

Even though participant 7-F-4 originally claimed to have forgotten what she learned during the targeted instruction on sea level rise, she was still able to employ the concept of thermal expansion when explaining sea level rise.

Based on the interview data (e.g., the transcript from the participant 7-F-4's interview), most participants did not remember the concept of thermal expansion very well. Moreover, participants were not able to clearly explain the connections among global warming, thermal expansion, and global sea level rise. Surprisingly, even participants who understood the concept of thermal expansion did not recognize the term thermal expansion.

As I suggested previously in this chapter, the next step in the targeted instruction would be for the students to conduct an inquiry investigation to study the thermal expansion of water. Such instruction would allow students to construct their own personal meanings about the nature of thermal expansion and how it relates to sea level rise. During the targeted instruction in my study, many participants were exposed to the thermal expansion construct for the first time, which is an important first step. However, the instruction represented just another science classroom narrative that had been imposed upon them, and I asked them to reproduce this narrative that an adult teacher had presented. So, while I was surprised to find that most participants had forgotten what they had learned about thermal expansion during science class, I should not have been so naive. As I have learned many times in my teaching career, experience matters, and the participants in my study lacked sufficient experience to own the thermal expansion concept in any sort of deep way.

I do not think that this surprising finding warrants a change to the learning progression because the LP already addresses the way that learners at different levels do and do not explain sea level rise using thermal expansion. However, the learning progression should not be considered separately from the research study that produced it. Level three of the LP does not mention thermal expansion, while level four indicates that learners may have alternative conceptions about thermal expansion. What the level descriptions do not say is that these learners may forget about thermal expansion after instruction, even if they are able to explain sea level rise using thermal expansion during instruction. This finding is important and should be taken into account when readers are thinking about how the targeted instruction interacted with student thinking, resulting in the six level descriptions of the empirical LP.

Chapter Summary

In this chapter, I described my findings from the analysis of written assessment, classroom observation, and interview data. During these analyses, I employed analytic induction to develop several analytic concepts, which guided my modification of the draft learning progression. In total, I developed eight different analytic concepts:

1. Participant explanation structures varied widely
2. Global warming and ice melt cause sea level rise
3. Participants held alternative conceptions about sea level rise
4. Participants learned about thermal expansion as a fundamental aspect of sea level rise
5. Participants learned to incorporate authentic scientific data
6. Participants' mental models of the ocean varied widely
7. Sea ice melt contributes to sea level rise

8. Participants held vague and alternative conceptions about how pollution impacts the ocean

These analytic concepts informed me about what ideas should be represented in the learning progression and helped me to answer my research question: What is a process by which a hypothetical learning progression on sea level rise is developed into an empirical learning progression using learners' explanations?

During this chapter, I explained my reasoning for making each modification to the learning progression. After revising the learning progression to fit the collected data, the learning progression comprised six levels. The first level of the LP described learners who are confused or unaware about sea level rise, while level two described learners who are aware about sea level rise but use evidence and reasoning inconsistently. Additionally, they hold alternative conceptions about sea level rise that are based on immediately visible phenomena and/or everyday experiences. On the other hand, level three described learners who use evidence and reasoning more consistently and hold alternative conceptions based on more abstract and less visible phenomena.

At the upper levels of the learning progression, learners incorporate constructs such as thermal expansion into their explanations about sea level rise. While level four described participants who are aware of thermal expansion, level five described learners who have a stronger understanding of chemistry concepts, such as atomic-molecular theory. Level six learners have a strong understanding of atomic molecular theory, too, but they also use models to link evidence to claims to assess the extent to which the reasoning and data support an explanation or conclusion.

In the next chapter, I discuss my findings and generate new theory about a process for developing a learning progression. After discussing my process, I relate my findings to the research literature on learning progressions. Finally, I discuss implications for my findings in terms of science education research, curriculum, instruction, assessment, and policy.

Chapter Five: Discussion

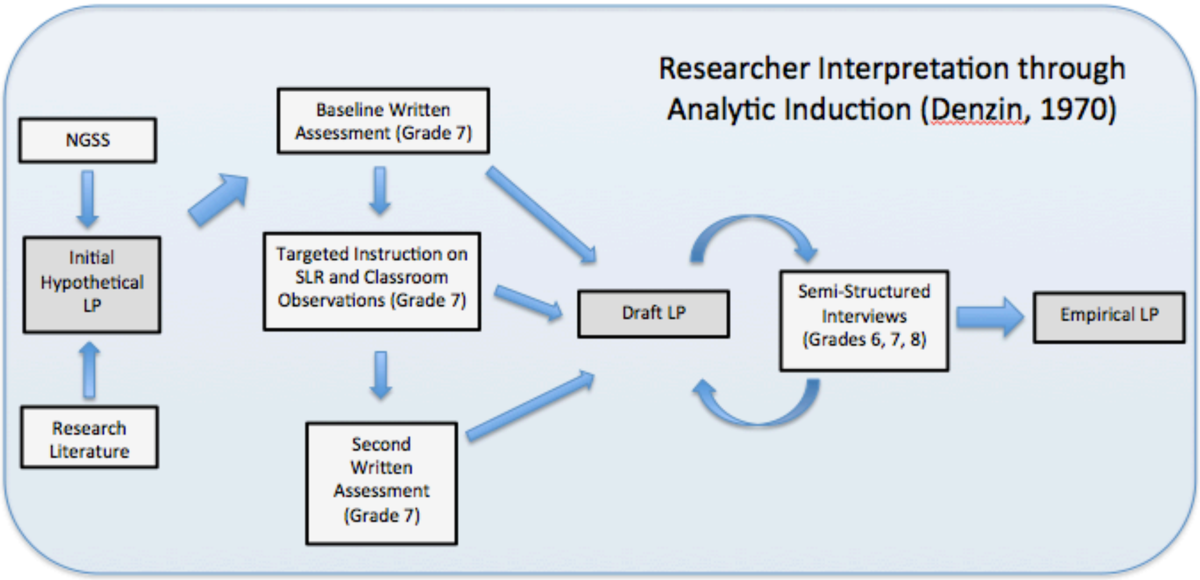
In this chapter, I engage in theory generation about how researchers can use learners' explanations about a scientific construct to inform the development of a valid learning progression. The example construct in my single case study is sea level rise, a major consequence of climate change. I focused on explicitly describing my decision-making process when responding to empirical data on learner thinking, filling a recognized gap in the LP research literature (Shea & Duncan, 2013). My research question was: What is a process by which a hypothetical learning progression on sea level rise is developed into an empirical learning progression using learners' explanations? I will discuss the process I engaged in, which informed the development and validation of an empirical learning progression based on analysis of data collected from middle school learners. I will also relate my findings to the research literature as I generate new theory on science learning. I end this chapter by discussing potential implications of my study for future LP research. Additionally, I discuss implications for science curriculum, instruction, and assessment, as well as education policy.

LP Development and Validation Process

I developed a process to inform the development and validation of an empirical LP based on analysis of empirical data collected from middle school learners. To start, I used an initial hypothetical LP on sea level rise that was not based on any empirical data. Rather, it was constructed by examination of both the NGSS and the research literature. Through the collection of data from a variety of sources including written assessments, classroom observations, and semi-structured interviews, I was able to modify the initial LP and base it on empirical data collected from middle school learners. *Figure 2*, below, describes my development process visually. The diagram shows how versions of the LP interacted with the NGSS, research literature, classroom events, and data sources, such as written assessments.

Figure 2

Visual Depiction of LP Development Process



Throughout the LP development process, my "researcher interpretation" of standards documents, research literature, and data shaped the learning progression and how it was modified.

The first step in my LP development process was to review the research literature on learners' conceptions about phenomena related to sea level rise (e.g., Boyes & Stanisstreet, 1998; Gunckel et al., 2012; Shepardson, Niyogi, Choi, & Charusombat, 2009), as well as the constructing explanations practice (e.g., Gotwals & Songer, 2013; McNeill et al, 2006; Sandoval & Millwood, 2005). Prior to the release of the NGSS, I worked with a research team to construct a more comprehensive hypothetical LP on sea level rise that was based on prior science education research. During that process, we had the opportunity to interact and share ideas with prominent ocean and climate scientists, such as Don Boesch (President of the University of Maryland Center for Environmental Science) and Nancy Targett (Dean of the College of Earth, Ocean, and Environment at the University of Delaware), and their thinking about sea level rise influenced our thinking about the LP, especially the more sophisticated upper levels. After developing the initial hypothetical LP, we created assessment items, and the research team worked to develop and validate the LP based on empirical data until the LP reached “conditional LP” status. This work was ultimately reported in Breslyn et al. (2016).

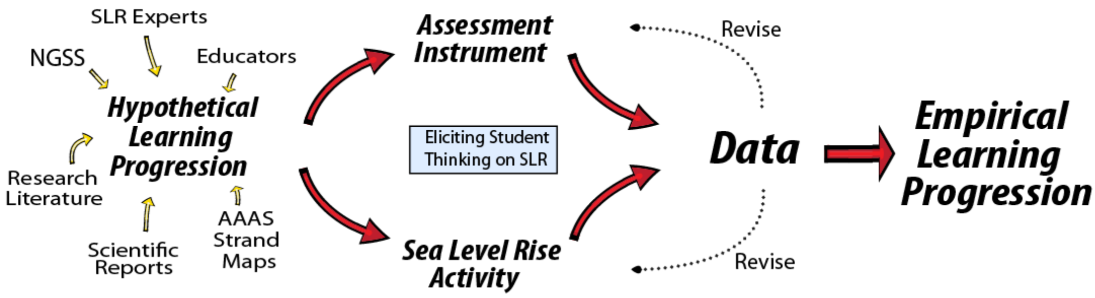
For my dissertation study, because I had participated in developing a conditional LP for sea level rise (Breslyn et al., 2016), I chose to develop an LP on constructing explanations about sea level rise. I wanted to incorporate sea level rise content knowledge with the constructing explanations practice because the LP research community has identified the integration of a science practice with disciplinary core ideas as an essential component of LP research (Duncan & Hmelo-Silver, 2009; Duschl et al, 2011; Duschl et al, 2007; Jin & Anderson, 2012; Smith & Wiser, 2015). I also believed that sea level rise was an important area and urgently needed area of research in science education because it is a major consequence of climate change.

Additionally, by developing a second learning progression on sea level rise, I was able to compare my LP with the LP I helped develop from Breslyn et al. (2016). This comparison allowed me to find similarities and differences, including different possible pathways that learners might take when progressing through the middle levels of a sea level rise learning progression. Generally, past LP research studies have worked to develop a single learning progression on a topic, rather than working to develop two different but parallel LPs. Consequently, prior LP research has not identified multiple pathways that learners can take to advance towards the upper anchor of an LP, even though this has been identified as a primary goal of the LP research movement (Duschl et al., 2007).

Figure 3, below, is reproduced from Breslyn et al. (2016). This figure depicts the process of developing an empirical learning progression for sea level rise from this study.

Figure 3

Research Design Reproduced from Breslyn et al. (2016, p. 8)



The LP development process depicted in *Figure 3* is very similar to my LP development process depicted in *Figure 2*. As seen on the left of both diagrams, the processes began with the creation of initial hypothetical LPs. Next, the hypothetical LPs were used to guide the development of assessments and the design of instructional activities, which were used to elicit and advance learner thinking, and which allowed us to collect empirical data on learner thinking. These data were used to make revisions to the learning progression, ultimately resulting in an empirical learning progression. As *Figure 3* shows, the process is iterative, as collected data are used to modify the learning progression, assessments, and instructional activities through cycles of inquiry.

For the development of the sea level rise LP for this study, I applied what I had learned about learners' conceptions related to sea level rise to the new NGSS performance expectations. In many cases, I had to interpret how a specific performance expectation could be reasonably related to sea level rise, as sea level rise is not explicitly mentioned. In my initial hypothetical LP based on the NGSS, I arranged portions of NGSS performance expectations into four levels based on increasing sophistication. I chose to use four levels because this was a common number of levels in prior LP research (e.g., Breslyn et al., 2016; Mohan et al., 2009), though LPs vary in terms of the number of levels. The initial number of levels was not critically important because I knew that the number of LP levels could be modified in response to empirical data analyses. For the descriptions of each LP level, I used quotes to indicate words taken directly from the NGSS, and I added my own words and punctuation to do the following:

1. Relate the NGSS language more directly to the sea level rise construct
2. Make the description of the LP level clear and easy to read
3. Align the LP descriptions with descriptions in prior LP research (e.g., Alonzo & Steedle, 2008)

An example of aligning the LP descriptions with prior research is adding the words "students know" at the beginning of a sentence, as the NGSS would never use this language. Rather, each NGSS performance expectation combines content knowledge with a science and engineering practice.

In addition to using the NGSS to develop my initial hypothetical LP, I made the decision to integrate the sea level rise topic with a particular science and engineering practice—constructing scientific explanations. The integration of content knowledge with the scientific practices is a key component of LP research (Duschl et al, 2011; Duschl et al., 2007; Gotwals & Songer, 2013). For my learning progression, I chose to integrate the sea level rise topic with the constructing explanations practice because I felt this practice was an important area of research. Research on constructing explanations is prominent in the literature (e.g., Gotwals & Songer, 2013; McNeill et al, 2006; McNeill & Knight, 2013; Ryoo & Linn, 2014; Sandoval & Millwood, 2005; Songer et al., 2009; Swanson, Bianchini, & Lee, 2014; Zangori, Forbes, & Biggers, 2013), but up-to-date, I have not found evidence of it applied to the sea level rise topic.

As with NGSS performance expectations that addressed topics related to sea level rise, I used language directly from the NGSS regarding scientific explanations, indicating language from the NGSS in quotes. Since the NGSS do not specifically mention constructing explanations about sea level rise, I had to make this connection myself. For example, I created the following description for level one of the initial hypothetical LP:

> Learners use "evidence and ideas to construct evidence-based accounts" of sea level rise. Learners know that "water is found in many types of places and in different forms on Earth." Learners also know that "matter exists as different substances that have observable different properties. Different properties are suited to different purposes. Objects can be built up from smaller parts."

I knew that the first task in modifying this description would be to use empirical data to make the description more specific to sea level rise. For instance, I imagined that the line, "Objects can be built up from smaller parts," might transform into, "Water is a substance that is made up of smaller parts, which can be divided and transferred across Earth's surface."

After developing the initial hypothetical LP, I collected empirical data on learner thinking in the order indicated in *Figure 2*. First, I collected a baseline written assessment from seventh grade participants. Approximately two months later, I observed targeted instruction on sea level rise during a classroom observation, which involved the administration of a second written assessment. Finally, approximately one month after the classroom observation and second written assessment, I conducted individual interviews with sixth, seventh, and eighth grade participants, though only seventh grade participants were observed during the classroom observation.

While I conducted continuous data analysis throughout data collection, I did not make modifications to the draft LP until after all data were collected. Those data analyses informed future data collection and my thinking while in the field, but I waited to modify the LP until all data were collected to ensure that LP modification occurred in an organized and systematic manner.

Figure 2 indicates how the LP was modified in four different stages. Each stage of the modification process was based on a different data source. The stages of LP modification are presented in *Table 24*, below.

Table 24

Stages of LP Modification

Stage of LP Modification	Data Source	Description of Modifications
One	Baseline Written Assessment (Grade 7)	Data were used to make the initial hypothetical LP more specific to sea level rise. Data were also used to make the LP based on empirical data.
Two	Classroom Observations of Targeted Instruction (Grade 7)	Data were used to make further modifications to the draft LP. In particular, changes were made regarding how participants learned about sea level rise in the context of an instructional intervention.
Three	Second Written Assessment and Semi-Structured Interviews (Grade 7)	Data were used to make further modifications to the draft LP. In particular, participant responses on the second written assessment were compared to the baseline assessment following the instructional intervention. When needed, interview data were used to track participant responses over time and in different formats (data triangulation).
Four	Semi-Structured Interviews (Grades 6, 7, and 8)	Interview data from participants at all three grade levels were used to start evaluating the validity of the LP using qualitative methods. Specifically, interview data were used to disconfirm, confirm, and make revisions to the LP.

In the next section, I discuss the first stage of the LP modification process, which used the baseline written assessment from grade 7 participants to modify the initial hypothetical LP.

Stage one: Use baseline written assessment data to make the LP more specific and empirically-based. In the first stage of LP modification I used baseline written assessment data from seventh grade participants to make my first round of revisions to the initial hypothetical LP. I used these data to make the LP more specific to sea level rise and to more accurately reflect participant explanations.

Before making decisions about how to respond to the baseline written assessment data, I employed analytic induction (Denzin, 1970), engaging in a process of coding and memoing to find patterns in the data and to develop analytic concepts. Three major analytic concepts emerged during this process:

1. Participant explanation structures varied widely
2. Global warming and ice melt cause sea level rise
3. Participants held alternative conceptions about sea level rise

The emergence of these analytic concepts alerted me to various features of participant explanations about sea level rise. I felt that all of these features of participant explanations should be represented in the learning progression. Thus, I knew where to focus my attention when revising the initial hypothetical LP.

The first analytic concept, *participant explanation structures varied widely*, helped me understand that participant use and coordination of claims, evidence, and reasoning were distinguishing features of their scientific explanations about sea level rise. Consequently, I decided to modify the initial hypothetical LP to reflect the different levels of sophistication in terms of explanation structure present in the data. An example of a modification I made was based on the fact that learners were more likely to incorporate scientific reasoning (88%) than sufficient evidence (54%) or appropriate evidence (74%) on the baseline written assessment, indicating the inconsistency with which learners employed evidence and/or reasoning when constructing less sophisticated explanations. To reflect this phenomenon, I changed level one of the draft LP to the following (changes are in bold):

> Learners **sometimes** use evidence and ideas to construct evidence-based accounts of sea level rise **and sometimes they rely more heavily on scientific reasoning to support their claims about sea level rise**. **Due to learners' inconsistent and/or incomplete use of both evidence and reasoning, learners often fail to connect their claims and evidence using reasoning that adheres to scientific principles.** Learners know that water is found in many types of places and in different forms on

> Earth. Learners also know that matter exists as different substances that have observable different properties. Different properties are suited to different purposes. Objects can be built up from smaller parts.

I began the LP modification process by modifying the lowest level of the LP, since it was easiest to identify the least sophisticated explanations.

Next, I tried to identify examples of explanations that appeared noticeably more sophisticated in terms of coordination of claim, evidence, and reasoning, though still characterized by inconsistency. As I wrote in Chapter Four, "Level two could also be revised to describe inconsistency in using evidence and reasoning, though it is unclear how this inconsistency relates to a clear distinction between levels one and two, the two lowest levels of the learning progression." Since I was unsure exactly what made an explanation "noticeably more sophisticated," my modifications to level two of the LP were especially tentative. However, making tentative decisions about how to change the wording of the LP descriptions allowed me to move forward with data analysis and LP modification. Though I was not completely confident with my modifications to levels one and two of the LP, I also needed to acknowledge that the initial hypothetical LP did not fit the baseline written assessment data very well. Thus, I felt that my modifications were an improvement.

Throughout the LP modification process, I found the following heuristic useful: *modify the descriptions of LP levels when the modifications allow the descriptions to better fit the data*. In the preceding example, the initial hypothetical LP assumed that learners at lower levels use evidence consistently, but do not necessarily include reasoning. Yet, my data indicated this was not always true. Many participants included reasoning using scientific principles but failed to use evidence to support their claims. Thus, the modifications I made allowed the level one and two descriptions to better fit the data.

Another analytic concept that emerged while analyzing the baseline written assessment data was *global warming and ice melt cause sea level rise*, as most participants explained sea level rise in terms of these phenomena. Yet, the initial hypothetical LP did not explicitly mention either construct. Thus, I knew that I needed to use the empirical data to make the draft LP actually reflect the way that learners explained sea level rise.

The third analytic concept that emerged from analyzing the baseline written assessments, *participants held alternative conceptions about sea level rise*, also made me aware that the initial hypothetical LP did not accurately reflect the way that participants explained sea level rise. This is because the hypothetical LP did not identify alternative conceptions that learners may hold about the topic.

During stage one of LP modification, the identification of important alternative conceptions about the LP topic can begin if these alternative conceptions are not already incorporated into the initial hypothetical LP. While a researcher could justifiably include alternative conceptions in the initial draft based on prior learning research, my initial draft was based on the NGSS, which did not identify alternative conceptions that learners may hold.

After identifying specific alternative conceptions that participants expressed on the baseline written assessment, I looked for patterns in their thinking. I determined that some of these alternative conceptions involved more concrete thinking and were based on immediately visible phenomena. For example, some participants explained that increased precipitation caused sea level rise, just as an empty cup fills with water as it rains. Other alternative conceptions involved more abstract thinking and were based on invisible phenomena and/or more complex scientific reasoning. For example, some participants explained that the increased light from global warming caused more ice to melt on Earth, increasing sea level rise. While both of these examples involved alternative conceptions, the latter was a decidedly more abstract alternative conception, and this level of abstractness could be used to distinguish among learners at different levels of performance.

In stage one of LP modification, I identified alternative conceptions found in the baseline data. Then, I asked the question, does the level of abstract thinking involved in the alternative conception allow me to distinguish among learners. The principle behind this question is that the more abstract the alternative conception, the more productive it will be to build upon as a learner's thinking becomes more sophisticated. Thus more abstract alternative conceptions should be written into higher levels of the draft LP, while more concrete alternative conceptions should be written into lower levels of the draft LP.

Through analytic induction, I was able to identify analytic concepts that shaped my thinking about how the initial hypothetical LP should be modified. Based on these analytic concepts, I changed the hypothetical LP into a draft that better reflected data on participants' explanations, that included important alternative conceptions, and that included language that was more specific to the sea level rise topic.

During analysis of the baseline written assessment, I also made a different type of modification—I added a new level to the LP that did not exist before. Specifically, I added a new lowest level of the LP, giving the LP a total of five levels, rather than four. The reason why I made this modification is that I encountered a participant response that did not align with any of the existing levels of the LP, and it appeared to be lower in terms of sophistication and learner understanding.

On her baseline written assessment, participant 7-F-13 provided an explanation that indicated she was not aware of the sea level rise topic. In general, the lowest level of an LP describes the knowledge that children bring to school with them—the entry point to learning about a topic (Duschl et al., 2011; Duschl et al, 2007; Lehrer & Schauble, 2015). However, a participant in my sample was not able to apply her preexisting ideas to explain sea level rise in a meaningful way due to confusion and/or lack of awareness. Thus, I found that my learning progression needed a lower anchor that described this learner, followed by a second level that describes the ideas that learners bring to school after becoming aware of the sea level rise phenomenon. For my LP, the new level two describes learners who are aware that sea level rise is occurring, though their explanations involve alternative conceptions that are based on learners' everyday experiences and intuitions.

In the next section, I report my process for stage two of LP modification. In stage two, I used classroom observation data to modify the LP in terms of what is possible to learn about sea level rise in the context of a targeted instructional intervention. This allowed me to expand upon my work in stage one of LP modification to include participants' ideas that were not present in the baseline data (prior to instruction).

Stage two: Use classroom observation data to modify the draft LP after a targeted instructional intervention. In the second stage of LP modification, I used classroom observation data from a targeted instructional intervention to modify portions of the LP. For stage two of the LP modification to occur, there must be a targeted instructional intervention. This instructional intervention should aim to advance participants to more sophisticated forms of scientific practices and understandings of content knowledge. Additionally, the instructional intervention should be designed in collaboration with participating teachers with the formation of a teacher-researcher team.

In my study, I worked with the three participating sixth, seventh, and eighth grade teachers to design the targeted instructional intervention. Ultimately, however, I worked most closely with the seventh grade teacher, who was the most willing and able to modify her instructional plans to incorporate both data collection and instructional intervention according to a well-defined schedule.

Together, the participating teachers and I decided when data collection would occur and which data would be collected from specific students. We also worked as a team to determine the flow, materials, activities, and format of the targeted instruction. The teachers were crucial in determining what would work best for their students in terms of what had already been taught and how the instructional intervention could be seamlessly weaved into the curriculum to advance student learning.

Duschl et al. (2011), Shavelson (2009), and Lehrer and Schauble (2009) all emphasized the importance of coordinating the development of a learning progression with instruction. Shavelson stated that the validity of an LP depends on the context of teaching and learning, while Duschl et al. emphasized that instruction-assisted LPs allow researchers to explore what sort of learning is possible under the right conditions. Similarly, Lehrer and Schauble explained that LPs should be descriptions of learning under defined instructional conditions, which should work to inspire improvement in science education.

After working with the participating teachers to design the targeted instruction, I observed all five seventh grade classes experiencing the intervention. The teachers and I had worked together to design instruction that sought to enhance students' abilities to analyze authentic data on sea level rise, reason about what these data mean through peer-to-peer discussion, and incorporate these data into their scientific explanations about sea level rise. Additionally, we wanted to introduce the concept of thermal expansion and help students understand its contribution to sea level rise. After analyzing the baseline written assessment data, I knew that both of these components of the instructional intervention would help participants to address two areas of weakness in their explanations about sea level rise. On the baseline written assessment, most participants did not draw on authentic scientific data to explain sea level rise, and not a single participant explained the contribution of thermal expansion to sea level rise. By analyzing the baseline written assessments before designing and implementing the instructional intervention, the participating seventh grade teacher and I were able to explore what students can learn under specific instructional conditions.

Following the same process of analytic induction used to analyze the baseline data, two additional analytic concepts emerged from the classroom observation data:

1. Participants learned about thermal expansion as a fundamental aspect of sea level rise
2. Participants learned to incorporate authentic scientific data

Not surprisingly, the analytic concepts that emerged from the data matched the areas of growth that our teacher-researcher team targeted for the instructional intervention. The next step in modifying the LP was to incorporate ideas related to these analytic concepts into the LP.

Based on my analysis of the classroom observations, I decided to modify levels 4 and 5 of the LP to include language about using thermal expansion to explain sea level rise. I also decided to modify levels 2, 3, 4, and 5 of the LP to add language about incorporating authentic scientific data into learners' explanations about sea level rise. The reason why I only included language about using thermal expansion to explain sea level rise at higher levels of the LP is because thermal expansion is a more abstract concept. Understanding thermal expansion involves understanding abstract chemistry ideas, such as the atomic and kinetic molecular theories. Following my general principle of associating level of sophistication with level of abstractness, I made the decision that the ability to use thermal expansion to explain sea level rise was a distinguishing feature between levels 3 and 4 of the LP.

Because the validity of my LP is related to the context of instruction, I used the language "through targeted instruction" to make this connection explicit. For example, I modified level 2 of the LP to read "Through targeted instruction, learners can begin to use authentic scientific data as evidence when explaining sea level rise." Since stage two of LP modification involves analyzing data from observing a targeted instructional intervention, this is the stage when this sort of modification should be made to the LP.

In the next section, I explain changes I made to the LP during stage three of the LP modification process. During stage three, I used data from a second written assessment to modify the LP. Specifically, I analyzed what participants had learned from the targeted instruction by exploring how their explanations had changed. When needed, I used interview data to better understand whether participants' explanations about sea level rise had actually changed, or whether the format and content of the second written assessment had changed their responses.

Stage three: Use second written assessment data to further modify the draft LP after targeted instruction. In the third stage of LP modification I used data from a second written assessment to modify the LP to incorporate what participants had learned from the targeted instruction. Specifically, I analyzed the data to determine how their explanations had changed in comparison to the baseline written assessments. In terms of the structures of their explanations, I wanted to know if participants had learned to incorporate authentic scientific data about sea level rise. In terms of content knowledge, I wanted to know if they had learned to incorporate the thermal expansion construct into their explanations.

Surprisingly, while participants used more evidence to support their claims, their use of reasoning declined in comparison to the baseline written assessment. Thus, as they learned to incorporate authentic scientific data into their explanations, they stopped using as much reasoning to link evidence to their claims. This was the sort of finding that was able to surface in stage three of LP modification because the data were collected after the targeted instructional intervention.

In response to this unexpected finding, I decided to modify the LP to indicate that the targeted instruction can have this unanticipated consequence. Specifically, I modified level two of the LP to read (changes are in bold), "Through targeted instruction, learners can begin to use authentic scientific data as evidence when explaining sea level rise, **though this may cause them to use less scientific reasoning**."

To support this finding about how participants responded to the targeted instructional intervention, I found it necessary to triangulate data from the written assessment, classroom observations, and semi-structured interviews. After coordinating participant responses among data sources, I found support for my finding that participants' explanations had actually changed structure after experiencing the instruction. In other words, they did not simply use more evidence than reasoning on the second written assessment because of the question asked or the proximity of the targeted instruction. More than a month later during the semi-structured interviews, participants continued to favor evidence over reasoning when constructing explanations about sea level rise, even when they were asked the same question asked on the baseline written assessment.

In the next section, I explain stage four of the LP modification process. During stage four, I used interview data from participants in grades six, seven, and eight in order to begin validating the LP.

Stage four: Use interview data to disconfirm, confirm, and modify portions of the draft LP. In the fourth and final stage of LP modification, I analyzed semi-structured interview data from sixth, seventh, and eighth grade participants to disconfirm portions of the LP. When portions of the draft LP were disconfirmed, I moved to strike some of those portions or to rearrange components of the LP by level to better match the data. By starting this validation process with a search for disconfirming evidence, I helped to establish the trustworthiness of my research findings.

After searching for disconfirming evidence, I then analyzed the interview data to confirm portions of the draft LP. The premise of this activity is that if the LP is a valid description of how learners' explanations about sea level rise can progress over time, then their explanations during an interview should align with a particular level of the LP. Moreover, during that interview, learners should consistently demonstrate the same level of performance. In chapter three, I identified this premise as one of two theoretical propositions of my case study (the other being the initial hypothetical LP).

Finally, I used the interview data to find new and surprising participant responses that were not represented in the LP. When I found such responses, I modified the LP by adding new language to reflect participants' ideas. This last step in stage four of my LP modification process underscores an important point. Even though my LP had gone through the first three stages of the LP modification process, and even though I had thoroughly analyzed interview data for both disconfirming and confirming evidence, my LP was still tentative and subject to future modification.

Through the same analytic induction process I engaged in when analyzing other data sources (Denzin, 1970), I developed three new analytic concepts:

1. Participants' mental models of the ocean varied widely
2. Sea ice melt contributes to sea level rise
3. Participants held vague and alternative conceptions about how pollution impacts the ocean

These analytic concepts represented patterns in the interview data, and they directed my attention to key aspects of the draft LP that should be disconfirmed, confirmed, or were missing. For example, if the draft LP implied that learners' mental models of the oceans were similar, then that aspect of the LP should be disconfirmed. On the other hand, if the LP addresses the notion that learners' models of the oceans are variable, even within a particular LP level, then that aspect of the LP should be confirmed. However, if participants have expressed important ideas about their models of the ocean that are not represented on the LP, then new additions should be made.

In chapter four, one example of disconfirming evidence I found in the interview data involved participant 7-F-2. In the draft LP, I had associated an understanding of thermal expansion with level four. After the targeted instruction, it appeared that participant 7-F-2 had begun to learn about how thermal expansion contributes to sea level rise. However, her interview responses indicated that she did not yet grasp the atomic-molecular basis of thermal expansion, and her responses were not quite consistent with the other portions of the level four description, which do require an understanding of basic chemistry concepts.

Since participant 7-F-2's responses did not consistently align with a particular level of the LP, I modified the LP to fit the data. Specifically, I modified my LP to include a new level between levels three and four—a new level four, which included the following text:

> Learners also know that the fact that matter is composed of atoms and molecules can be used to explain the properties of substances, diversity of materials, states of matter, phase changes, and conservation of matter. However, learners may hold alternative conceptions about constructs related to atomic-molecular theory. Though learners know that thermal expansion is a significant cause of sea level rise, learners may express the idea that water molecules grow larger in size as temperature increases, which allows them to explain how thermal expansion works. Additionally, learners may hold the alternative conception that both sea ice melt and land ice melt cause sea level rise, since both types of melted water can add to the total volume of liquid water in the ocean. In order to advance beyond level four of the learning progression, learners must gain a stronger grasp on the nature and interaction among energy and the particles involved in the sea level rise phenomenon.

If participant 7-F-2 had not participated in the targeted instructional intervention, she would not have attempted to explain sea level rise using thermal expansion, and there would not have been a need to create a new LP level to capture her thinking. I also would not have been able to detect what was missing in her thinking—a need to study chemistry before progressing in understanding. The validity of this learning progression is dependent upon instruction, and the instruction was necessary to explore possible pathways for learning.

When using interview data to confirm portions of the LP, I was forced to start at level two. This is due to the fact that my interview sample did not comprise any learners who demonstrated a level one understanding, apart from the learner whose responses were used to revise level one (participant 6-F-2). Interview data confirmed many aspects of the level two description as participants consistently explained sea level rise in terms of immediately visible phenomena, expressed specific alternative conceptions, and struggled to coordinate both authentic scientific data and reasoning to explain sea level rise. Since many of the interview participants' explanations aligned with level two of the LP, I was able to provide many examples of confirming evidence.

Similarly, many participants provided explanations that aligned well with level three of the draft LP. Consequently, I was able to provide many examples of confirming evidence for level three, as participants consistently explained sea level rise in terms of more abstract and less visible phenomena, expressed specific alternative conceptions, and consistently coordinated both authentic scientific data and reasoning to explain sea level rise.

Finally, I found evidence to confirm higher levels of the LP. Confirming evidence for higher levels of the LP included participants explaining sea level rise by coordinating authentic scientific data with reasoning involving thermal expansion, ocean currents, and land-based ice melt. Participants whose interview responses were represented by these upper levels had a strong grasp of atomic-molecular theory and Earth's systems, and they were able to reason through new scientific data and ideas with what appeared to be a coherent model of how nature works.

Surprisingly, some participants aligning with higher levels of the LP explained local variation in sea level rise using concepts that were not addressed during instruction. Specifically, participants reasoned that tectonic activity and vertical land movement could cause sea level to change differently at different locations on Earth. Since the draft LP did not address this idea, this called for an unexpected new addition. However, I was forced to modify the LP with little basis for distinguishing among learners at different levels of the LP.

As I explained in chapter four, I decided to tentatively add text to the LP addressing tectonic activity and its relation to instruction to levels four, five, and six. I reasoned that because most participants did not include tectonic activity and vertical land movement in their explanations and because this is a challenging concept, these ideas should not characterize the lower levels of the LP (levels one, two, or three). So, I added the text to level four that reads, "Additionally, learners who have received instruction on tectonic plates and tectonic activity may be able to explain regional variations in sea level change in terms of vertical land movement, using concepts such as tectonic plate subduction." A limitation of my study is that my targeted instructional intervention did not include these concepts.

In future studies of this sea level rise LP, targeted instruction should include explicit instruction on how tectonic activity and vertical land movement contribute to local variation in sea level rise. This is in addition to participants learning about thermal expansion and using authentic scientific data to support claims. By studying how this expanded instructional intervention affects participants' explanations about sea level rise, researchers can investigate what learning pathways are possible under specific instructional conditions. Moreover, researchers can collect more empirical data on how understandings about this aspect of sea level rise can distinguish among levels of the LP. These are the data that would have allowed me to revise levels four, five and six of the LP with more certainty.

Empirical LP on Constructing Explanations about Sea Level Rise

After modifying the draft LP over four stages of development, the LP was then considered an empirical LP. In this empirical LP, there were specific features that distinguished the six levels from one another. In *Table 25* below, I present these distinguishing features by level.

Table 25

Distinguishing Features of LP Levels of the Empirical LP

	Distinguishing Features of LP Level of Performance
Level 1	Learners are confused or unaware about sea level rise and cannot yet use evidence or reasoning to construct a scientific explanation.
Level 2	Learners use evidence and reasoning inconsistently to construct explanations about sea level rise that focus on immediately visible phenomena, aligning with their everyday experiences with matter.
Level 3	Learners consistently use evidence and reasoning to construct explanations about sea level rise using concepts that are less visible and more abstract.
Level 4	Learners construct explanations about sea level rise supported by multiple sources of evidence that are generally consistent with scientific ideas, principles, and theories, though learners must gain a stronger grasp on the nature and interaction among energy and particles to gain a stronger understanding of sea level rise constructs, such as thermal expansion.
Level 5	Learners construct explanations about sea level rise supported by multiple sources of evidence consistent with scientific ideas, principles, and theories, including an understanding of global warming/climate change, different types of ice melt, thermal expansion, the movement of water across Earth's surface, and local variation in sea level change.
Level 6	Learners construct explanations about sea level rise supported by multiple and independent student-generated sources of evidence consistent with scientific ideas, principles, and theories, consistently using authentic scientific data as evidence and applying scientific reasoning, theory, and/or models to link evidence to the claims to assess the extent to which the reasoning and data support the explanation or conclusion.

While the descriptions in *Table 25* give a clear overview about what distinguishes one LP level from another, the LP levels need to be unpacked to fully describe how learners explain sea level rise with increasing levels of sophistication.

However, when I shared the full learning progression in narrative form (similar to the draft LP presented in *Table 22*) with members of my dissertation committee, they found the narratives difficult to interpret, as it was hard to track changes in learner performance through a large amount of continuous text. Consequently, I decided to redesign the presentation of each level of the LP. Complete descriptions of each level of my empirical LP on sea level rise are presented below in *Tables 26-31*, below. In agreement with Duschl et al. (2011), I decided not to separate the practice of constructing scientific explanations from sea level rise content knowledge. In my empirical LP, these components of constructing explanations about sea level rise depend upon one another and could not be logically be separated into separate dimensions or components. However, to aide readers in interpreting the learning progression, I have explicitly organized the LP levels into categories labeled explanation structure, content knowledge, and alternative conceptions.

Table 26

Level One of the Empirical LP

Level 1 Overview	Learners are confused or unaware about sea level rise and cannot yet use evidence or reasoning to construct a scientific explanation.
Explanation Structure	• Confusion or lack of awareness prevents learners from drawing on appropriate evidence or scientific reasoning when attempting to explain the sea level rise phenomenon. • Some learners may be aware that sea level rise is occurring, yet they are not able to use evidence or reasoning to explain what causes sea level rise. • Learners are not able to construct basic explanations about sea level rise.

In *Table 26* above, level one of the empirical LP describes learners who are unaware or confused about sea level rise, so they are unable to construct basic explanations about the topic. At level two, described in *Table 27* below, learners have become aware of sea level rise and are able to use evidence and reasoning inconsistently when constructing explanations about sea level rise.

Table 27

Level Two of the Empirical LP

Level 2 Overview	Learners use evidence and reasoning inconsistently to construct explanations about sea level rise that focus on immediately visible phenomena, aligning with their everyday experiences with matter.
Explanation Structure	• Learners sometimes use evidence and ideas to construct evidence-based accounts of sea level rise and sometimes they rely more heavily on scientific reasoning to support their claims about sea level rise. • Learners' inconsistent and/or incomplete use of both evidence and reasoning prevents learners from connecting their claims and evidence using reasoning that adheres to scientific principles. • Through targeted instruction, learners can begin to use authentic scientific data as evidence when explaining sea level rise, though this may cause them to use less scientific reasoning.
SLR Content Knowledge	• Learners know that water is found in many types of places and in different forms on Earth, such as icebergs and glaciers. • Learners know that matter exists as different substances that have observable different properties and that different properties are suited to different purposes. • Learners know that objects can be built up from smaller parts.
Alternative Conceptions	• Learners may express the idea that icebergs contribute to sea level rise when they melt, rather than understanding that melting ice must originate from land in order to contribute to sea level rise. • Learners may explain that sea level rise is caused when humans add waste (e.g., trash) to the sea, when increased rainfall enters the sea, and/or when additional wind raises the water to a greater height.

In the description of level two in *Table 27* above, learners hold productive ideas about sea level rise, including alternative conceptions. These ideas and alternative conceptions are more concrete in nature. At level three, described in *Table 28* below, learners develop more abstract ideas about sea level rise, and their use of evidence and reasoning becomes more consistent.

Table 28

Level Three of the Empirical LP

Level 3 Overview	Learners consistently use evidence and reasoning to construct explanations about sea level rise using concepts that are less visible and more abstract.
Explanation	• Learners use evidence and/or scientific reasoning in constructing

Structure	explanations that specify variables that describe and predict phenomena related to sea level rise. • Learner might specify the effect that the variable "temperature" will have on the variable "amount of ice melt" or the effect that the variable "amount of ice melt" will have on the variable "sea levels". • Through targeted instruction, learners can use authentic scientific data as evidence in a consistent way when explaining sea level rise and are able to connect these data to their claims using scientific reasoning.
SLR Content Knowledge	• Learners know that most of Earth's water is in the ocean and much of the Earth's fresh water is in glaciers or underground. • Learners know that because matter exists as particles that are too small to see, matter is always conserved even if it seems to disappear. • Learners know that moving objects contain energy, and that energy can be converted from one form to another form. • Learners are aware of some connections between global warming/climate change and sea level rise and understand that human use of fossil fuels has contributed to global warming/climate change.
Alternative Conceptions	• Learners may express alternative conceptions that involve abstract concepts and/or invisible phenomena. • Learners may express the idea that icebergs contribute to sea level rise when they melt, rather than understanding that melting ice must originate from land in order to contribute to sea level rise. • Learners may explain that the moon's gravity causes sea level rise, conflating the cause of tides and the causes of sea level rise. • Learners may misunderstand some connections between global warming/climate change and sea level rise. For example, participants might explain that the increased sunlight from global warming/climate change causes more ice to melt, which adds to the level of water in the sea. • Learners are aware of connections among fossil fuel use, the atmosphere, global warming, and sea level rise, though they are unable to clearly explain these connections in a scientifically normative way. Instead, learners might explain that fossil fuel use results in the emission of air pollution particles, which causes global warming as the ozone layer works to trap these warming particles.

In level three, described in *Table 28* above, learners have begun to develop more abstract ideas about how sea level rise works and are aware of the role of the atmosphere and global warming in causing sea level rise. However, learners are not yet aware of the role of thermal expansion in sea level rise until level four, described in *Table 29* below.

Table 29

Level Four of the Empirical LP

Level 4 Overview	Learners construct explanations about sea level rise supported by multiple sources of evidence that are generally consistent with scientific ideas, principles, and theories, though learners must gain a stronger grasp on the nature and interaction among energy and particles to gain a stronger understanding of sea level rise constructs, such as thermal expansion.
Explanation Structure	• Learners consistently use authentic scientific data as evidence. • Learners apply scientific ideas, principles, and/or evidence to construct, revise, and/or use an explanation for sea level rise.
SLR Content Knowledge	• Learners know that sea level rise is caused by global warming/climate change, which causes increased ice melt on Earth's surface. • Learners know that water cycles among land, ocean, and atmosphere because the Earth's spheres are interconnected, and that water movement causes weathering and erosion, changing landscape features. • Learners know that the fact that matter is composed of atoms and molecules can be used to explain the properties of substances, diversity of materials, states of matter, phase changes, and conservation of matter. • Learners who have received instruction on tectonic plates and tectonic activity may be able to explain regional variations in sea level change in terms of vertical land movement, using concepts such as tectonic plate subduction.
Alternative Conceptions	• Learners may hold alternative conceptions about constructs related to atomic-molecular theory. • Though learners know that thermal expansion is a significant cause of sea level rise, learners may express the idea that water molecules grow larger in size as temperature increases, which allows them to explain how thermal expansion works. • Learners may hold the alternative conception that both sea ice melt and land ice melt cause sea level rise, since both types of melted water can add to the total volume of liquid water in the ocean.

At level four, described in *Table 29* above, learners begin to incorporate thermal expansion into their explanations about sea level rise. However, learners may hold alternative conceptions about thermal expansion because their understanding of atomic-molecular theory is limited. In level five, described in *Table 30* below, learners have gained a stronger understanding of atomic molecular theory.

Table 30

Level Five of the Empirical LP

Level 5 Overview	Learners construct explanations about sea level rise supported by multiple sources of evidence consistent with scientific ideas, principles, and theories, including an understanding of global warming/climate change, different types of ice melt, thermal expansion, the movement of water across Earth's surface, and local variation in sea level change.
Explanation Structure	• Learners consistently use authentic scientific data as evidence. • Learners apply scientific ideas, principles, and/or evidence to construct, revise, and/or use an explanation for sea level rise.
SLR Content Knowledge	• Learners know that sea level rise is caused by global warming/climate change, which causes increased ice melt on Earth's surface. • Learners know that water cycles among land, ocean, and atmosphere, and is propelled by sunlight and gravity, and that density variations of seawater drive interconnected ocean currents. • Learners know that water movement causes weathering and erosion, changing landscape features. • Learners who have received instruction on tectonic plates and tectonic activity are able to explain regional variations in sea level change in terms of vertical land movement, using concepts such as tectonic plate subduction. • Learners know that the fact that matter is composed of atoms and molecules can be used to explain the properties of substances, diversity of materials, states of matter, phase changes, and conservation of matter. • Learners know that kinetic energy can be distinguished from the various forms of potential energy and that energy changes to and from each type can be tracked through physical or chemical interactions. • Learners know that the relationship between the temperature and the total energy of a system depends on the types, states, and amounts of matter. • Learners know that thermal expansion is a significant cause of sea level rise, and can explain how thermal expansion causes sea level rise using principles of atomic-molecular theory.

Finally, at level six, described in *Table 31* below, learners have developed a model-based view of sea level rise. They are able to connect atomic-molecular theory with large-scale systems to explain sea level change in a consistent way using factors such as terrestrial ice melt, thermal expansion, and vertical land movement.

Table 31

Level Six of the Empirical LP

Level 6 Overview	Learners construct explanations about sea level rise supported by multiple and independent student-generated sources of evidence consistent with scientific ideas, principles, and theories.
Explanation Structure	• Learners consistently use authentic scientific data as evidence • Learners applying scientific reasoning, theory, and/or models to link evidence to the claims to assess the extent to which the reasoning and data support the explanation or conclusion.
SLR Content Knowledge	• Learners know that the planet's dynamics are greatly influenced by water's unique chemical and physical properties. • Learners know that the sub-atomic structural model and interactions between electric charges at the atomic scale can be used to explain the structure and interactions of matter. • Learners know that the total energy within a system is conserved and that energy transfer within and between systems can be described and predicted in terms of energy associated with the motion or configuration of particles. • Learners are able to explain sea level rise using the constructs glacial ice melt and thermal expansion. • Learners are able to explain regional variations in sea level change in terms of vertical land movement, using concepts such as tectonic plate subduction, and recognize that sea level change varies due to multiple factors.

Connections to prior LP research. My study employed the learning progressions theoretical framework described in the research synthesis report *Taking Science to School* (Duschl et al., 2007) and represented in the *Journal of Research in Science Teaching's* special issue on learning progressions (McGinnis & Collins, 2009). In the literature, researchers have distinguished among LPs in multiple ways, choosing to emphasize some aspects over others. Throughout this section, I make connections between my research my findings and this scholarship.

Duschl et al. (2011) wrote a comprehensive literature review of learning progressions research in which he discussed researchers' views of conceptual change, approaches to developing learning progressions, and methods of validating them. Duschl et al. explained that researchers were working from one of two frameworks of conceptual change. The researchers termed these the misconception-based *fix it* view of conceptual change and the intuition-based *work with it* view of conceptual change. When developing the sea level rise learning progression, I consistently employed a *work with it* view of conceptual change. I found that some alternative conceptions about sea level rise indicated a more sophisticated understanding than others. Consequently, specific alternative conceptions were useful in distinguishing among learners at different levels of the LP. For example, the level two description mentions the alternative conception that icebergs can contribute to sea level rise. This is a productive understanding that can be worked with through targeted instruction because learners with this conception are already using ice melt to explain sea level rise.

Another productive understanding for learners is the concept of volume displacement. The level two description reads,

> Learners rely on their experiences with macroscopic and visible phenomena to explain sea level rise. For example, learners may explain that sea level rise is caused when humans add waste (e.g., trash) to the sea, when increased rainfall enters the sea, and/or when additional wind raises the water to a greater height.

This alternative conception about waste is based on a child's intuition and experiences in everyday life. This idea can be built upon through targeted instruction as learners learn that it is additional water from melting land-based ice that displaces water, raising the sea level. At a higher level of the LP, learners can further develop these ideas when learning about thermal expansion, as they learn that an increase in volume can occur through increased kinetic energy of existing water molecules, rather than the addition of new water molecules.

At level three of the LP, learners still have the alternative conception about icebergs contributing to sea level rise, as this was not a useful alternative conception for distinguishing among levels two and three of the LP. However, other alternative conceptions were useful for distinguishing between these levels, and I came to the conclusion that learners described by level three tended to hold alternative conceptions that involve abstract concepts and/or invisible phenomena. For example, the description of level three mentions the conflation of the lunar tides with sea level rise.

The level three description also discusses alternative conceptions about global warming, such as the notion that global warming is caused by increased sunlight. Demonstrating my learning progression's commitment to the *work with it* view of conceptual change, the description of level three explicitly points out the productiveness of these alternative conceptions:

> It is important to note that this alternative conception adheres to both the conservation of energy (the transformation of light into different forms of energy) and the conservation of matter (solid water becomes liquid water, which moves to a new location on Earth).

As prior LP research has shown, understandings about the laws of conservation of matter and energy are critical learning goals for learning progressions (Gunckel et al., 2012; Jin & Anderson, 2012; Mohan et al., 2009).

A final productive alternative conception found in the level three description of my sea level rise LP concerns the ozone layer. As prior research on children's conceptions about global warming and climate change have shown, learners frequently conflate ozone layer depletion with global warming/climate change (Boyes & Stannistreet, 1998). I found these same alternative conceptions in my data, which is reflected in the learning progression:

> Though learners may hold alternative conceptions about global warming/climate change, they understand that human use of fossil fuels has contributed to global warming/climate change. They are aware of connections among fossil fuel use, the atmosphere, global warming, and sea level rise, though they are unable to clearly

> explain these connections in a scientifically normative way. Instead, learners may express alternative conceptions about these connections. For example, a learner might explain that fossil fuel use results in the emission of air pollution particles, which causes global warming as the ozone layer works to trap these warming particles.

As learners learn about the mechanism for global warming and its relation to sea level rise, confusion about the differences between ozone layer depletion and the greenhouse effect seems to be a natural part of the learning progression. Rather than viewing this confusion as a problem that needs to be fixed, educators can instead view this confusion as a productive steppingstone in developing a more sophisticated form of environmental literacy.

Related to distinguishing among LPs based on views of conceptual change, Duschl et al. (2011) also distinguished between *evolutionary* and *validation LPs*. When discussing Alonzo and Steedle's (2008) force and motion LP, Duschl et al. explained,

> Because the progression uses a '*fix-it*' conceptual change focus that seeks to validate the initial sequences and levels of progression we refer [to] LPs like this as '*Validation LPs'* as opposed to '*Evolutionary LPs*' that refine and define the developmental pathway(s) through identification of mid-levels or steppingstones that are then used to bolster meaning making and reasoning employing crafted instructional interventions. (p. 157)

Because my sea level rise LP identifies steppingstones that are used to improve learner reasoning through targeted instruction, it should be considered an evolutionary LP, rather than a validation LP. Throughout my data analysis process, I sought to refine and define the developmental pathways that participants appeared to take when learning to construct scientific explanations about sea level rise.

Besides distinguishing among LPs in terms of views of conceptual change and evolutionary versus validation LPs, Duschl et al. (2011) also evaluated the role of instruction-assisted learning among different LPs. The researchers explained that most LP studies did not report on instructional interventions, even though many researchers agree with the importance of instruction-assisted learning in LPs. Using a case study approach, I was able to investigate how participant explanations about sea level rise were affected by carefully designed instruction. Thus, instruction-assisted learning played a central role in my sea level rise LP research.

Similar to Duschl et al. (2011), Shavelson (2009) emphasized differences in the ways different LP studies approached the role of instruction. Shavelson distinguished between *curriculum and instruction LPs* and *cognition and instruction LPs*, stating that the validity of curriculum and instruction LPs depends on the context of teaching and learning. My study closely aligns with Shavelson's notion of a curriculum and instruction LP because I collaborated closely with the participating classroom teachers to design and implement the targeted instruction. The design and implementation of the targeted instruction shaped the context of learning, which in turn affected the validity of my learning progression. While the validity of my LP depends on the context of teaching and learning, my close collaboration with the classroom teacher helped me to better understand how teachers can use my LP in classroom practice.

For example, I found that learners need significant experience with the construct of thermal expansion before they are able to incorporate this construct into their scientific explanations about sea level rise in a consistent way. I have found that learners would benefit from engaging in inquiry investigations to explore different factors that affect the thermal expansion of water. However, I also found that learners may need to study the atomic-molecular and kinetic-molecular theories in more depth before they are prepared to develop a more sophisticated understanding of thermal expansion, as is stated in the level four description of the learning progression.

I have also found that learners can quickly learn to attend to scientific data about sea level rise, as they did during the observed lesson. However, it is the coordination of the claim, evidence, and reasoning that learners find difficult. Initially, participants in my study explained sea level rise with more reasoning than evidence. But, after exploring various sea level rise graphs during a classroom lesson, their reliance on reasoning diminished, as they relied on the evidence to speak for itself. Therefore, in future iterations of the designed instruction, the teacher should explicitly teach students how to use reasoning to link specific pieces of evidence back to a claim.

Finally, I found that participants experiencing the instructional intervention did not learn to distinguish between sea ice and land-based ice in terms of their contributions to sea level rise. Because the instruction did not explicitly teach participants about this distinction, participants did not incorporate this distinction into their explanations. I found that participants at different levels of the LP (levels two, three, and four) thought that icebergs and sea ice contribute to sea level rise, and an understanding of this distinction was not a useful way to separate learners into different levels of the LP in the context of my study.

Use of situated cognition for a contextual learning progression. Unlike previous LP research (e.g., Alonzo & Steedle, 2008; Mohan et al., 2009; Gunckel et al., 2009) my LP study was informed by situated cognition learning theory (Brown, Collins, & Duguid, 1989). Situated cognition guided my decision to develop a contextual learning progression on sea level rise, rather than a more general LP on matter and energy. My learning progression was about matter and energy but was consistently applied to the conceptual context of sea level rise. Additionally, my LP was developed under clearly defined instructional conditions, which took the learners' instructional histories, cultures, and motivation into account. Unsurprisingly, I found that learners consistently demonstrated a specific level of performance. In contrast to previous LP researcher (e.g., Steedle & Shavelson, 2009), I found that learner performance did not vary by task.

Additionally, both my case study approach and use of situated cognition learning theory allowed me to attend to the relationship between targeted instruction on sea level rise and learners' progress along the learning progression. Previous studies, such as Mohan et al. (2009), Jin and Anderson (2012), and Gunckel et al. (2012) have not reported significantly the role of instruction in supporting learners along a learning progression. One contribution of this study to the LP research literature is an example of how situated cognition learning can be used to attend to the role that targeted instruction plays in learner progress along a learning progression.

Comparison of two LPs on sea level rise. In this section, I compare my empirical LP with the empirical LP I helped to develop from Breslyn et al. (2016). Since both of these LPs focused on learner explanations about sea level rise, they can be compared for similarities and differences. These differences include different possible pathways that learners might take when progressing through the middle levels of sea level rise learning progressions. As Breslyn et al. wrote,

> These pathways may depend to some degree on the type of instruction that students experience and the personal and cultural experiences students have had with the idea (Lehrer & Schauble, 2009). It is possible that another instructional experience would result in a different learning progression. (p. 5)

Since the two LPs were developed using different instructional activities, I was able to compare my LP with the LP from Breslyn et al. to identify a second possible pathway for learners to follow.

Both sea level rise LPs described very similar upper anchors, which was expected, since these upper anchors were created based on societal expectations and our expectations as researchers, rather than empirical data on learner thinking. For example, the upper anchor of my LP (level six), describes learners who consistently apply atomic-molecular theory to explain sea level rise using models to link evidence to claims and to assess the extent to which data support a claim. Similarly, the upper anchor in Breslyn et al. (level four), described learners who have “a more sophisticated, model-based understanding of sea level rise” (p. 17). In both LPs, this more sophisticated, model based approach involves explaining how sea level rise depends on land-based ice melt, thermal expansion, ocean currents, and geographic variation.

In Breslyn et al. (2016), we developed our learning progression using data from five middle school learners who were participating in a summer environmental education camp and pre-service elementary school teachers. Instruction included an online activity that was designed to engage participants with representations of sea level rise and to have them apply their observations to the impacts of sea level rise. Breslyn et al. explained,

> Learners viewed data on the global projected rise in sea level and using an interactive website (www.SurgingSeas.org) to visualize the effects via satellite imagery and maps. This allowed learners to visualize the degree to which land would be submerged under different projections. Based on projections and maps, learners reflected on the Impacts of sea level rise in a selected geographic area. Because they were able to experiment with varying sea level rise projections, from 1 foot to 10 feet, learners could observe the predicted impacts. Their observations were aided by the option to view high resolution satellite imagery of the area and observe structures and environmental features. The online activity also addressed the science content for the Mechanism of sea level rise in the form of explanation, a video modeling thermal expansion at the atomic-molecular level, and an online quiz with immediate feedback. (p. 12)

In my study, my teacher-researcher team focused on having students work in small groups to interpret and discuss authentic scientific data on sea level rise. Additionally, we focused on teaching participants how thermal expansion contributes to sea level rise, also using videos to model thermal expansion. However, participants in my study constructed written explanations following instruction, rather than an online quiz with immediate feedback. Based on the LP products presented in my study and in Breslyn et al., the different groups of learners we studied, with different instructional histories, followed different learning pathways in regards to explaining sea level rise.

One major difference between the LP in my study and the LP in Breslyn et al. (2016) is that my LP comprises six levels of performance, while the LP in Breslyn et al. comprised only four levels. My LP started with only four levels, but I added a new lower anchor of the LP to describe participants in my study who were unaware or confused about sea level rise, as well as a new level after level three to describe learners who explained sea level rise using thermal expansion but had not yet learned atomic-molecular theory to fully grasp how thermal expansion works. In contrast, in Breslyn et al., our data did not indicate that additional LP levels were needed. Thus, it is possible that in my LP, learners pass through a greater number of middle levels before reaching the upper anchor.

Another difference between the two LPs is that the learners at level one of the LP in Breslyn et al. (2016) were able to explain sea level rise in accordance with a consensus scientific perspective, while learners at the lower levels of my LP (levels one and two) either were not aware of or were confused about sea level rise, or they explained sea level rise using alternative conceptions based on readily visible phenomena from everyday experience. Learners at level two of my LP explain sea level rise in terms of volume displacement (as waste is added to the sea), increased precipitation, or increased wind. At level three of my LP, learners explain sea level rise in terms of increasingly more abstract alternative conceptions (such as the conflation of the lunar tides with sea level rise). Thus, learners progressing through my LP become increasingly sophisticated in their explanations of sea level rise, despite not consistently identifying global warming, the enhanced greenhouse effect, and ice melt as the scientifically accepted causes of sea level rise, as they did in Breslyn et al.

In Breslyn et al. (2016), learners at level two of the LP are aware of how global warming-induced ice melt causes sea level rise. However, learners only consider polar ice melt and do not consider glaciers and other sources. In contrast, at levels two and three in my LP, learners identify all different types of ice melt as contributing to sea level rise, including polar ice and glaciers. Through individual interviews, I learned that even though learners used the term glaciers readily, they frequently did not know the scientifically accepted definition of a glacier and often conflated glaciers with sea ice. The conflation of glacial ice melt with sea ice melt contribute to learners' alternative conceptions about which types of ice melt can contribute to sea level rise. The differences between learner knowledge about different types of ice on Earth, which is closely related to what learners have been taught during instruction, is an additional way that the paths of the two sea level rise LPs are different.

A fourth difference between the two LPs is how learners learn to incorporate thermal expansion into their explanations about sea level rise. At level three of the LP from Breslyn et al. (2016), learners make a "qualitative shift" to understand the thermal expansion of water as a major cause of sea level rise. However, these learners are not able to consistently reason about the roles that atoms and molecules play in the mechanism of thermal expansion. Alternatively, it is at level four of my LP where learners begin to explain sea level rise in terms of thermal expansion. In contrast to the LP from Breslyn et al., learners in my LP are only able to explain sea level rise using thermal expansion if they are able to reason about how the water molecules change so that the water occupies a larger volume. At level four of my LP, learners think the water molecules grow larger, while at level five, learners understand that they simply move farther apart to expand. Thus, the way that learners learn to incorporate thermal expansion into their explanations in the middle levels of the two LPs varies. In my LP, learners must first have a strong understanding of the atomic-molecular basis of thermal expansion before using the construct, while in the Breslyn et al. LP, learners are able to cite thermal expansion as a sea level cause before fully grasping the concept.

In both sea level rise LPs, learner thinking becomes increasingly abstract as learners advance to higher levels. However, it appears that learners in the Breslyn et al. (2016) LP hold abstract ideas that are more in line with scientifically normative causes of sea level rise. For example, level one of the Breslyn et al. LP states, "Students identify global warming due to the enhanced greenhouse effect as a cause of sea level rise" (p. 15). In contrast, learners at level three of my LP still hold alternative conceptions about how global warming works, as they explain sea level rise with reasoning such as, "The increased sunlight from global warming/climate change causes more ice to melt, which adds to the level of water in the sea." Learners in the middle levels of my LP hold numerous alternative conceptions about how pollution works, and they provide explanations such as, the hot pollution gases directly melt ice to cause sea level rise. While learners in the middle levels of my LP hold alternative conceptions about pollution and global warming, I never observed participants in my study explaining sea level rise in an anthropomorphic way, which characterizes learners in level two of the LP from Breslyn et al. It is possible that my study's instructional focus on using authentic scientific data as a tool for explaining sea level rise encouraged this difference.

Unlike the learners in the lower and middle levels of the LP from Breslyn et al. (2016), learners in my LP had no difficulty in relating representations of sea level rise and authentic sea level rise data to the physical world. Even when their reasoning about mechanisms for sea level rise were overly simple or involved alternative conceptions, participants who aligned with lower levels of my LP consistently tried to incorporate new data into their ideas, and they used these ideas to explain how sea level change actually happens. For example, participant 6-F-3 came up with the concept of an "off stream" to reconcile her ideas about local water systems, the water cycle, and sea level rise with the map and graphs showing local sea level change around the world (IPCC, 2013, p. 1148). She explained, "When the water cycle happens, the same amount of water stays, or maybe an off stream will have more…have more water to the body." The only reason participant 6-F-3 (who aligned with level two of my LP) came up with the idea of an off stream was that she was attempting to reconcile her theories about sea level rise with the representations she was interpreting in an effort to explain how different factors would play out in the physical world to cause local sea level change.

Though I found that learners in my study followed a different pathway along the LP than the learners in the Breslyn et al. (2016) LP, I did find that both LPs contained many of the same features. Like Breslyn et al. (2016), I found that learners at lower levels of the LP were more concrete in their explanations, while learners at higher levels of the LP were more abstract. Breslyn et al. wrote, "While middle school students focused on the more visual aspects of sea level rise, such as ice melt, preservice teachers, an older sample of successful learners, were able to incorporate causes and mechanisms at the atomic-molecular level into their descriptions of sea level rise" (p. 14). Similarly, level two of my LP involves alternative conceptions that are based on visual phenomena, while higher levels of the LP involve explanations that include thermal expansion, which requires an understanding of atomic-molecular theory.

Interestingly, some of the participants in Breslyn et al. (2016) offered explanations that aligned with level four of my LP. Due to my small sample size, I was unable to find evidence to confirm portions of level four. Yet, Breslyn et al. explained, "A small group of learners believed that the water molecules split apart and formed additional water molecules indicating varying levels of sophistication" (p. 14). Similar to participant 7-F-2 in my study, these learners lack a strong understanding of basic chemistry. Learners must spend time studying basic chemistry concepts about the atomic molecular and kinetic theories before advancing to higher levels of both LPs.

Also similar to Breslyn et al. (2016), I found that learners at lower levels of the LP lacked an understanding of the different forms of ice on Earth's surface. Moreover, they did not adequately understand how these different forms of ice contributed (or did not contribute) to sea level rise after melting. Specifically, participants failed to understand that the melting of sea ice does not contribute to sea level rise.

As mentioned earlier, the upper anchor of my LP is similar the upper anchor of the LP reported in Breslyn et al. (2016) in terms of level of sophistication. Specifically, both LPs describe an upper anchor where learners have a strong grasp of atomic-molecular theory and Earth's systems, which allows them to explain sea level rise in terms of thermal expansion, terrestrial ice melt, and tectonic activity. Though the two LPs describe different pathways that learners can take to achieve the upper anchors, common themes in these pathways can inform future sea level rise LP work. Based on the findings of both LP studies, future iterations of research on sea level rise LPs should include targeted instruction that addresses the following concepts:

1. The atomic-molecular basis of thermal expansion and its contribution to sea level rise
2. The distinction between sea ice and terrestrial ice and their different contributions to sea level rise
3. The incorporation of authentic scientific data in constructing explanations about sea level rise

4. The use of scientific reasoning to link authentic scientific data to a claim when constructing explanations about sea level rise

By studying how learners respond to targeted instruction addressing these important components of sea level rise science, our research team's studies can inform educators and researchers as they seek to further advance learner understanding about sea level rise.

Implications

In this section, I discuss implications of this study for future science education research on learning progressions. Additionally, I discuss implications for curriculum, instruction, assessment, and policy.

Learning progressions research. For researchers studying learning progressions, an important implication of my study is the benefit of placing an emphasis on using qualitative methods (instead of only quantitative methods) in developing an initial LP. Specifically, I employed analytic induction (Denzin, 2007) to develop analytic concepts from the data before making modifications to the learning progression. By explaining in detail why I modified the number of levels and changed the language of each level description, I have enhanced the transparency of my decision-making. A desired outcome of how I have proceeded in my LP development process is that it enables other researchers to critique my LP development by access to my process thinking. Notably, such transparency by an LP researcher in developing an initial LP has not been reported previously in the research literature.

Many researchers have criticized the ways that other researchers have studied LPs (Duncan & Gotwals, 2015; Duncan & Hmelo-Silver, 2009; Duschl et al., 2011; Ford, 2015; Lehrer & Schauble, 2009; Lehrer & Schauble, 2015; Shavelson, 2009; Shea & Duncan, 2013; Sikorski & Hammer, 2010; Hammer & Sikorski, 2015; Smith & Wiser, 2015). I believe that my research has addressed some of these criticisms. For example, my qualitative approach has sought to discover the natural variation and individuality in learner thinking that Shavelson cautioned was ignored in most LP studies. Additionally, I have sought to eliminate any ambiguity in the method of validating my learning progression, which Duncan and Hmelo-Silver identified as a concern. In the context of my LP research, validity is closely tied to the context of teaching and learning.

Typically, LP scholarship as reported in the literature (e.g., Jin & Anderson, 2012; Neumann et al, 2013; Songer et al., 2009) has involved developing hypothetical LPs and then using assessment instruments to revise and validate the LPs using statistical methods (e.g., Rausch modeling). Development of a valid and reliable assessment instrument, along with quantitative validation, are important components for the full validation of learning progressions. However, LP scholarship has usually not included deep, thorough qualitative exploration using case study methods and the rigorous process of analytic induction (Denzin, 1970) to analyze empirical data. These methods allowed me to understand how the collected data were related to targeted classroom instruction on my LP topic, which could not be understood as well using the more rigid quantitative approaches involving multiple choice assessments that prior LP research studies have used (e.g., Neumann et al, 2013).

To date, much of the reported LP scholarship has involved the products of LP research—the already developed learning progressions—rather than the development of those LPs (e.g., Alonzo & Steedle, 2008; Mohan et al., 2009). Other reports about LPs have focused primarily on the validation of an already developed learning progression (e.g., Neumann et al., 2013; Songer et al., 2009). While such reports are informative, I believe it is also imperative to discuss the ways in which individual researchers have interpreted, analyzed, and distilled what children have said in order to construct and revise the levels of LPs (Lehrer & Schauble, 2009).

Another implication for LP research relates to the role of instruction in developing a valid learning progression. The validity of my sea level rise LP is dependent upon the instructional context of my study, and I gave specific examples of how instructional context was used to interpret data on learner thinking (e.g., interview responses). Not only is the validity of a learning progression dependent upon instructional context, but so is its usefulness in terms of transforming classroom practice. In order for researchers to design effective instructional experiences that advance learner thinking along an LP, they need to know how learners respond under different instructional conditions. My study provides the LP research community with one possible model for exploring and describing the interplay among instruction, learner thinking, and the modification of an LP.

I also had the uncommon opportunity to compare my sea level rise LP with the LP I helped to develop earlier, which was reported in Breslyn et al. (2016). My careful comparison indicated that learners followed different pathways as reflected in the two LPs after experiencing different instructional conditions. To my knowledge, my study is the first comparison of two different learning progressions on the same topic. To increase the sophistication of LP research, other researchers should also compare different learning progressions on the same topic to learn whether or not learners follow different pathways (in the "messy middle," in particular) to reach the upper anchor, as they did in my present study.

I also presented a model for LP development using qualitative case study methods. The model for LP development as presented in my study can occur at any stage of the LP development and validation processes. In my research, I started with a hypothetical LP based on the NGSS and began the modification process in response to collected data from middle school learners. However, I could have started with any LP and worked towards modifying and validating the LP based on a particular instructional context. Moreover, this approach can be used with learners at all grade levels. Using this approach would be particularly useful for

LPs that were originally developed under "status quo instruction," rather than targeted instruction (e.g., Gunckel et al., 2012). If these LPs were revisited using my qualitative approach, the science education research community could further learn about the variety of possible pathways that learners can follow as they improve their understanding about a science topic over time.

The sea level rise LP developed using my qualitative approach would be enhanced by next being studied using quantitative methods. This would allow researchers to use statistics to investigate the consistency with which learners demonstrate a specific level of performance on the LP, the distribution of learners at particular levels within a sample, and changes in learners' levels of performance over time. Such studies provide a means for quantitative validation of LPs.

At the same time, I believe other LPs developed using primarily quantitative methods (e.g., Neumann et al., 2013; Alonzo & Steedle, 2008) should also be studied using my qualitative approach. The qualitative approach I employed in this study allowed me to understand in minute detail what thinking should be assessed using quantitative methods. For example, without the flexibility of my qualitative approach, I would not have been able to detect participant reasoning about the role of tectonic activity in determining local sea level change. Thus, that finding about student reasoning would never have appeared in my empirical LP. Additionally, I would never have been able to probe learner thinking to understand that learners were using the term glaciers incorrectly.

It is possible to develop LPs and show their validity by analyzing quantitative data on multiple choice assessment items addressing constructs in the LPs. However, these proposed LPs can only be validated to the extent of the ideas they already contain, rather than the total pool of relevant ideas, which learners may be using to understand a topic. Though Alonzo and Steedle (2008) found that ordered multiple choice questions served a similar purpose to probing questions during interviews, data are limited by the contents of the ordered multiple choice assessment items. Alternatively, in my study, I was able to use probing questions during individual interviews to follow learner thinking in unexpected directions.

More research is needed to compare the differences in LPs developed with a substantial qualitative approach verses those that do not. While quantitative methods are essential to bringing an empirical LP to a highly validated and generalizable level, in the absence of the inclusion of in depth qualitative methods to develop the empirical LP, the resulting LP will be based on a less solid foundation. Inaccurately, it will be presented as complete when additional and relevant information remain to be included. Such a situation will make more likely the Procrustean data fitting of which Shavelson (2009) warned.

Curriculum, instruction, and assessment. My study has implications for curriculum, instruction, and assessment because learning progressions have been promoted as a tool for aligning these three aspects of teaching and learning (Duncan & Hmelo-Silver, 2009; Lehrer & Schauble, 2015; Smith & Wiser, 2015). In the NRC report *Taking Science to School* (2007), Duschl et al. called for science curricula to be reorganized to focus on a narrower set of disciplinary core ideas and scientific practices. Moreover, curricula should aim to develop children's understandings of this narrower set of ideas and practices over a time period of several years (Smith & Wiser). Learning progressions, which describe learning about only the most important topics in science over an extended time period, are intended to inform this curricular overhaul (Lehrer & Schauble).

The ways that classroom instruction can help learners develop these core idea and practices as the narrower curricula revisit them over time and at different grade bands is understudied. However, Hestness, McGinnis, Breslyn, McDonald, and Mouza (2016) found that when presented with LPs, teachers have a tendency to see them in terms of a spiral curriculum, even though LPs are different in that they focus on learners' ideas, rather than curricula. Additionally, Hestness et al. found that teachers think they are intended to move learners along the learning progression over a short time (e.g., over the course of a learning segment). Further research is needed to study the way that classroom teachers actually use LPs, such as the sea level rise LP developed in my study, and the ways in which they view how LPs can inform and support their classroom practice.

Learning progressions research, through studying instruction-assisted learning, is intended to address the ways that classroom teachers and students can focus on a narrower set of disciplinary core ideas and scientific practices over a period of several years (Duschl et al., 2011). An implication of my study is that studying how instruction-assisted learning occurs across a period of several years will require coordinated effort by research teams. These teams should comprise science education researchers and classroom teachers, working together to design targeted instruction to advance learner understanding (Lehrer & Schauble, 2015). Moreover, these teams must respond to collected data on learner thinking as it is collected.

These teacher-researcher teams can only respond instructionally to collected data through assessment of learner thinking. An implication of my study is that written responses, classroom observations, and individual interviews were all necessary and useful for understanding learner thinking, as well as the instructional context. Written responses were open ended, which allowed me to explore unexpected avenues of learner thinking. This has important implications for LP studies that rely primarily on multiple-choice questions (e.g., Neumann et al., 2013), as these questions do not allow learners to express ideas not listed as answer choices. Additionally, the use of multiple-choice assessment limits participants' abilities to demonstrate their abilities to engage in scientific practices, such as constructing scientific explanations.

Lehrer and Schauble (2015) criticized the way that assessments have been used in LP research studies. The researchers explained about research on LP development,

> Assessments are usually developed early in the process, based on content analysis of the content domain, and serve as operationalizations of desirable student performances that can orient curriculum and instruction. Although this approach to LPs may hold value for designers of curriculum and assessments, it has the disadvantage of reifying current educational practice, which, some argue, is far from optimal for supporting learning. (p. 434)

Based on my findings, assessments informing LP research should be developed and modified *throughout* the entire LP development process, not relegated only to the early stages. Moreover, these assessments should be open ended and designed to support learning under specified instructional conditions with the goal of challenging current educational practices.

Policy. My study has implications for policy because multiple states in the USA have formally adopted the NGSS as their science education standards, and the NGSS influence other states, too. The NGSS are based on the concept of learning progressions and prior LP research (NGSS Lead States, 2013). My initial hypothetical LP for SLR was based heavily on the relevant performance expectations for SLR in the NGSS. However, I found it necessary to modify my resulting LP to fit the collected data from middle school learners. For example, the hypothetical LP based on the NGSS stated that learners' abilities to construct scientific explanations should develop in a logical, linear, and consistent manner. Yet, I found that learners' progress with constructing explanations, especially at the lower levels of the LP, was characterized by inconsistency and did not necessarily follow a logical and linear order. For example, I found that, initially, learners' more frequently emphasized reasoning in their explanations, while later, their emphasis on reasoning diminished as they learned to incorporate authentic scientific data.

Thus, an implication from my study is that the NGSS (NGSS Lead States, 2013) do not necessarily describe learner progress in response to instruction in the same way that a carefully conducted learning progression research study informed by learner thinking might. Moreover, the NGSS do not reflect the findings of all LP research. My study provides an example of a learning pathway that was not adequately depicted in the NGSS performance expectations. Also, I have found that learners can follow multiple pathways when learning about sea level rise. While the current NGSS performance expectations do not currently address multiple pathways for learning about specific topics, the NGSS authors should consider building in different options for learner progress towards the upper grade bands, as informed by LP research studies.

The NGSS were published in 2013 (NGSS Lead States), so the NGSS writers were not able to incorporate the findings from LP research studies published after 2013. Consequently, it is important for states that have adopted the NGSS, curriculum designers, researchers, science supervisors, and classroom teachers to use the findings of later LP research studies that update and therefore refine and potentially broaden what the NGSS include. While the NGSS may represent a set of standards to which all students and teachers can aspire at different grade bands, LP research, along with other science education research, provides rich descriptions about the different ways that learner understanding can develop over time.

Currently, in the state in which this study took place, assessment designers are developing a statewide science test that measures student learning progress in terms of the NGSS performance expectations. As Lehrer and Schauble (2015) explained, "Much of the contemporary excitement about LPs is being expressed by policy makers and administrators who seek empirical information about learning that can guide and inform education and assessment at scale" (p. 434). However, LP researchers should not be content to study and describe how learners typically think under the range of status quo instruction and curricula that have typically characterized science education in the USA. Such accounts of learning would underestimate what is possible under instructional conditions “explicitly designed to build developmentally on student thinking and to support coherent and cumulative learning” (p. 434). Rather, LP researchers must develop multiple and flexible accounts of how learning about a topic can occur under different instructional conditions.

Based on my LP research study, the assessments that states are designing to align with learning progressions research and the NGSS (Lead States, 2013) should be viewed only as provisional. These assessments should be revised each year, or at a minimum, every three years, to address new research findings. LP research and these corresponding assessments are best efforts, though they are potentially not fully capturing students’ understandings of a given topic. As Lehrer and Schauble (2015) commented, LPs may help clarify for assessment developers what is worth assessing, but LPs also present new challenges in terms of how to coordinate responses to more conventional assessments with classroom-level information on how students are developing science practices over time. Moreover, LPs may provide coherent visions of learning science for policy analyst and politicians, but they may also raise unexpected challenges as classroom teachers make instructional decisions based on student learning, rather than external accountability measures. Learning research has shown that variability in learner performance is the rule, rather than the exception, and it is unlikely that students will fit neatly into the levels of proposed LPs, which are imperfect models of learner thinking (Lehrer & Schauble, 2009).

My study provides one example of how learning about sea level rise can occur under the instructional conditions that our teacher-researcher team carefully designed. I was also able to compare my learning progression to another sea level rise LP from Breslyn et al. (2016), which I helped to develop. While my study sets an example of what is possible in LP research, it will take a community of teacher-research teams working collaboratively to carefully and systematically study different learning pathways that learners can take when gaining more sophisticated understandings about disciplinary core ideas and science practices over a period of several years.

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Appendix A: Written Artifacts Data Source

Below is the prompt for the baseline written assessment that seventh grade participants were asked to respond to prior to any instruction about sea level rise. This prompt was based on the scaffolding structure used in McNeill et al. (2006).

Write a scientific explanation that answers the question: What causes sea level rise? **Claim** (Write a sentence that answers the question.) ____ ____ **Evidence** (Provide data that support your claim.) ____ ____ ____ ____ ____ ____ **Reasoning** (Connect evidence to claim.) ____ ____ ____ ____

Below are the four different written assessments that were administered to seventh grade participants at the conclusion of the sea level rise lesson. Each participant completed one of the four written assessments based on the class period during which they took science.

Write a scientific explanation that answers the question: How has the sea level around the Chesapeake Bay changed over the past 50 years? **Claim** (Write a sentence that answers the question.) ____ ____ **Evidence** (Provide data that support your claim.) ____ ____ ____ ____ ____

Reasoning (Connect evidence to claim.)

Write a scientific explanation that answers the question: How will the sea level around the Chesapeake Bay change over the next 50 years?

Claim (Write a sentence that answers the question.)

Evidence (Provide data that support your claim.)

Reasoning (Connect evidence to claim.)

Write a scientific explanation that answers the question: How has the global average sea level changed over the past 50 years?

Claim (Write a sentence that answers the question.)

Evidence (Provide data that support your claim.)

Reasoning (Connect evidence to claim.)

Write a scientific explanation that answers the question: How will the global average sea level change over the next 50 years?

Claim (Write a sentence that answers the question.)

Evidence (Provide data that support your claim.)

Reasoning (Connect evidence to claim.)

Appendix B: Classroom Observation Protocol

What are the students doing during the lesson (e.g., a lab activity, group discussion)?

What initial ideas about sea level rise are students expressing?

What alternative conceptions about sea level rise are students expressing?

What ideas scientifically accepted ideas are learners expressing about sea level rise?

How are students using scientific explanations to express their ideas about sea level rise?

Appendix C: Interview Protocol

Purpose: The purpose of this interview is to better understand your thinking about scientific explanations for sea level rise. To help you explain your thinking about sea level rise, I have provided you with graphs and data tables related to sea level rise that you may have used in your science class. Please use these data when appropriate during the interview.

Interview Questions:

1. What does sea level rise mean to you?
2. What experiences have you had with bodies of water outside of school? This includes oceans, bays, and rivers.
3. How would sea level rise affect these experiences, if at all?
4. Can you please provide a scientific explanation for what causes sea level rise? In your explanation, please include a claim, evidence, and reasoning. [Prompt for claim, evidence, and reasoning, if needed.]
5. Can you please provide a scientific explanation for how sea level around the Chesapeake Bay has changed over the past 50 years? [Prompt for claim, evidence, and reasoning, if needed.]
6. Can you please provide a scientific explanation for how sea level around the Chesapeake Bay will change over the next 50 years? [Prompt for claim, evidence, and reasoning, if needed.]
7. Can you please provide a scientific explanation for how global average sea level has changed over the past 50 years? [Prompt for claim, evidence, and reasoning, if needed.]
8. Can you please provide a scientific explanation for how global average sea level will change over the next 50 years? [Prompt for claim, evidence, and reasoning, if needed.]
9. What does “thermal expansion?” mean to you, if anything?
10. What does glacial ice melt mean to you, if anything?

Additional Comments:

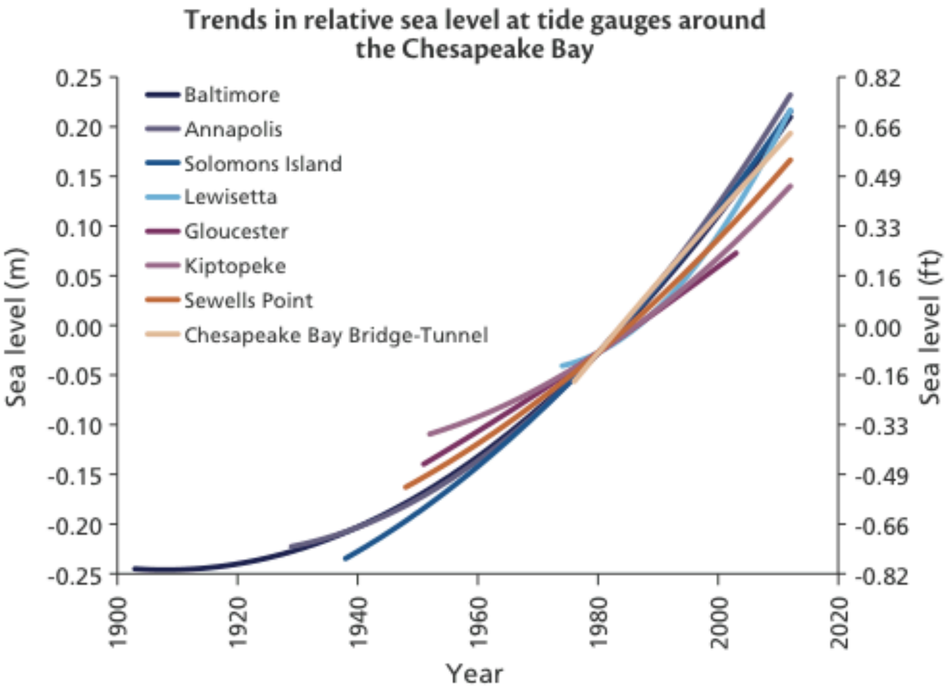
Do you have any additional thoughts about sea level rise that you would like to share with me?

Thank you participating in this interview.

Appendix D: Data about Sea Level Rise for Learners to Use as Evidence

Graph One

Summary of Graph: The graph below shows increasing trends for sea level at several locations around the Chesapeake Bay over the past 50 to 100 years. Though some areas seem to be increasing at a faster rate than others, all areas show an increasing trend.

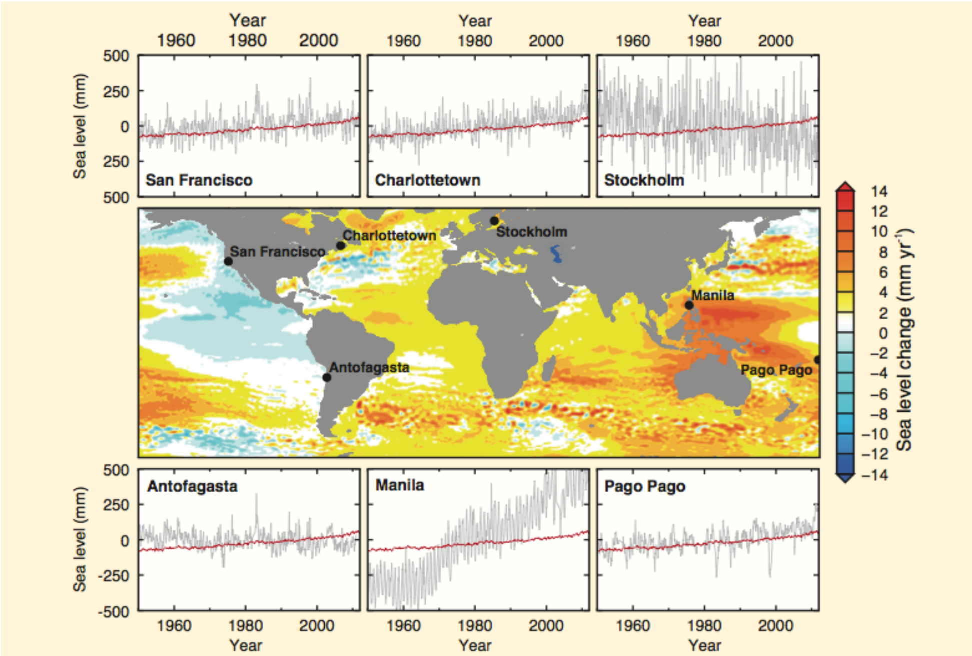


Relative sea-level rise over the past century from analysis of tide gauge records from the Chesapeake Bay; sea level is relative to 1980.[23] The mathematical analysis applied removes oscillating modes to depict the underlying trends.

(Boesch et al., 2013, p. 1)

Graph Two

Summary of Map and Graphs: The map and graphs below show that sea level change has been different in different areas of the globe over the past 20 to 50 years. For example, in Manila, sea level has increased more than the global average, while sea level around Antofagasta has changed relatively little or decreased. For each graph, the red line represents the global average.



FAQ13.1, Figure 1 | Map of rates of change in sea surface height (geocentric sea level) for the period 1993–2012 from satellite altimetry. Also shown are relative sea level changes (grey lines) from selected tide gauge stations for the period 1950–2012. For comparison, an estimate of global mean sea level change is also shown (red lines) with each tide gauge time series. The relatively large, short-term oscillations in local sea level (grey lines) are due to the natural climate variability described in the main text. For example, the large, regular deviations at Pago Pago are associated with the El Niño-Southern Oscillation.

(IPCC, 2013, p. 1148)

Graph Three

Summary of Graph: The graph below shows a decreasing trend for the extent of Arctic summer sea ice over the past 50 years.

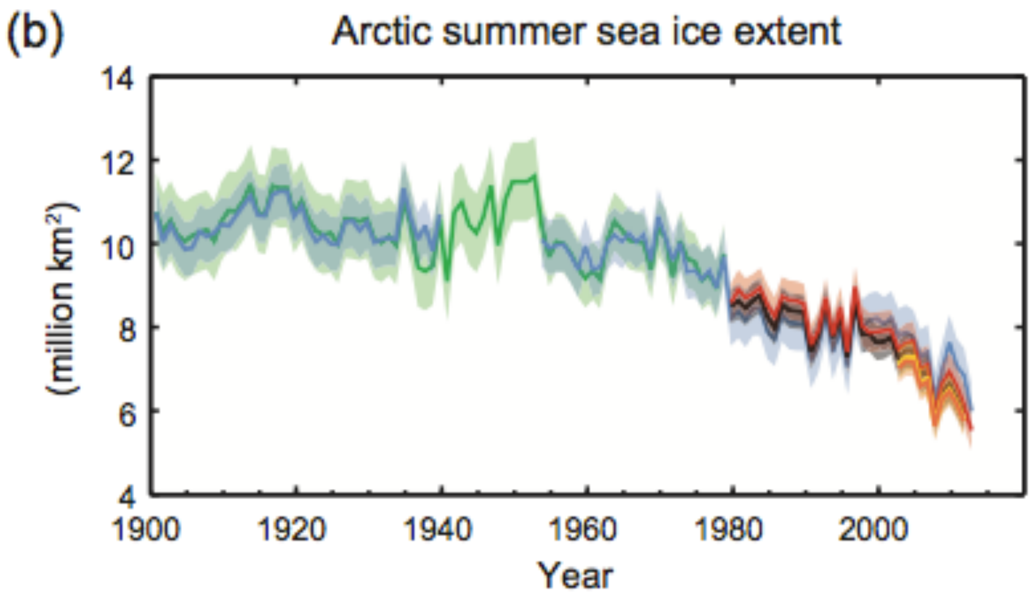


Figure SPM.3b| Extent of Arctic July-August-September (summer) average sea ice. All time-series (coloured lines indicating different data sets) show annual values, and where assessed, uncertainties are indicated by coloured shading.

(IPCC, 2013, p. 10)

Graph Four

Summary of Graph: The graph below shows an increasing trend in the global average heat content of the upper layer of the ocean over the past 50 years.

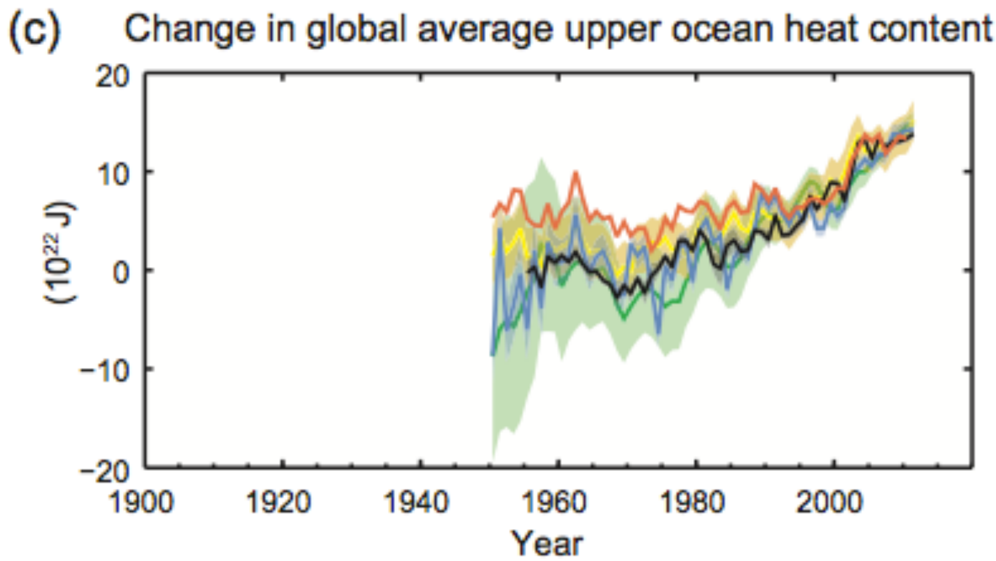


Figure SPM.3c| Change in global mean upper ocean (0-700 m) heat content aligned to 2006-2010, and relative to the mean of all datasets for 1970. All time-series (coloured lines indicating different data sets) show annual values, and where assessed, uncertainties are indicated by coloured shading.

(IPCC, 2013, p. 10)

Graph Five

Summary of Graph: The graph below shows an increasing trend in global average sea level over the past 100 years.

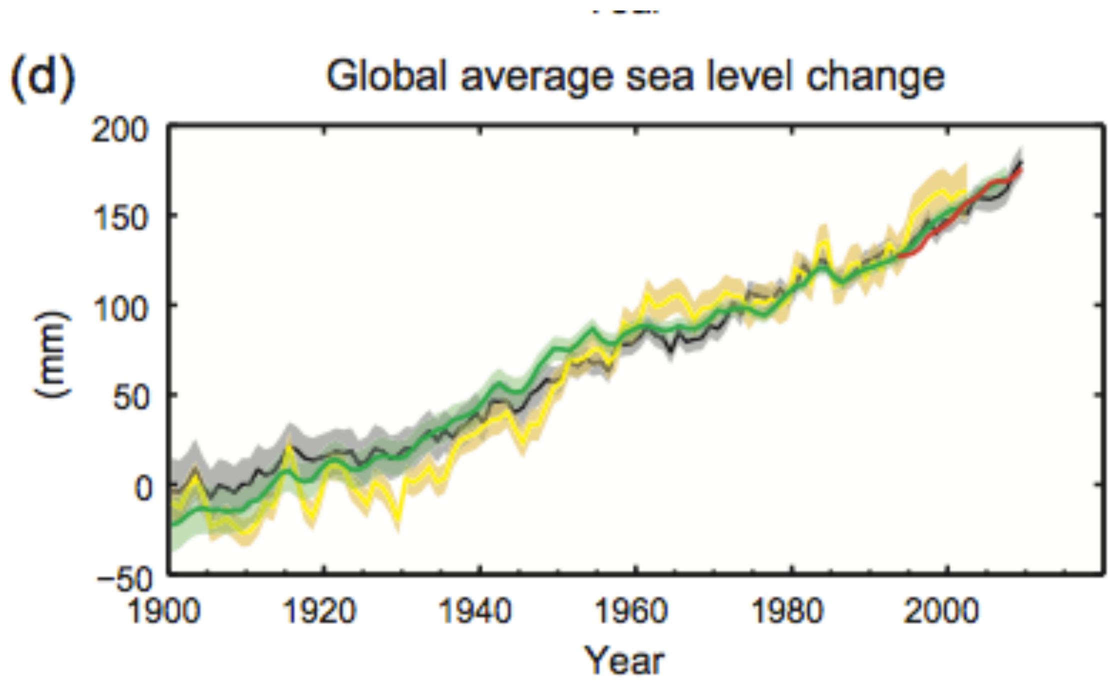


Figure SPM.3d| Global mean sea level relative to the 1900-1905 mean of the longest running dataset, and with all datasets aligned to have the same value in 1993, the first year of satellite altimetry data. All time-series (coloured lines indicating different data sets) show annual values, and where assessed, uncertainties are indicated by coloured shading.

(IPCC, 2013, p. 10)

Graph Six

Summary of Map and Graphs: The graph below shows four different projections for sea level change over the next 90 years. All projections show an expected increase in sea level over the time period.

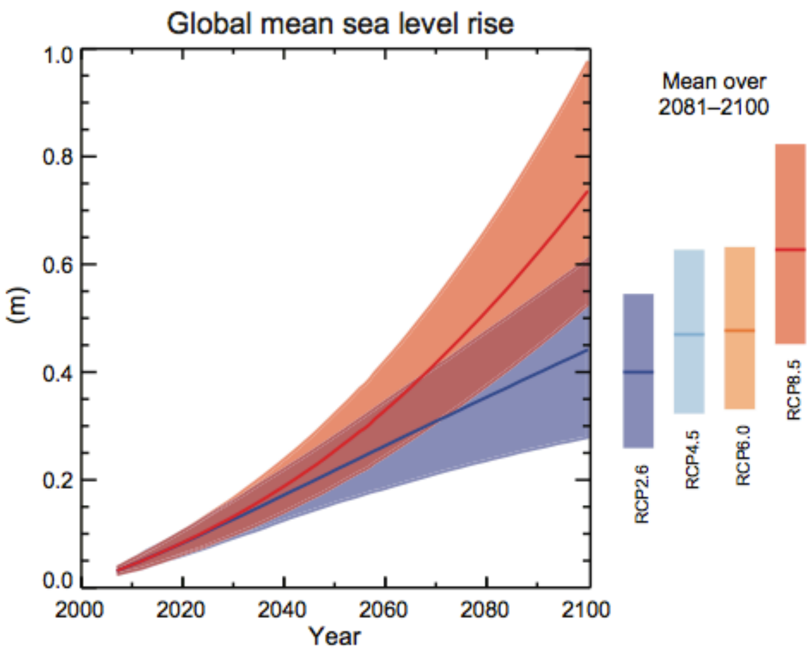


Figure SPM.9 | Projections of global mean sea level rise over the 21st century relative to 1986–2005 from the combination of the CMIP5 ensemble with process-based models, for RCP2.6 and RCP8.5. The assessed *likely* range is shown as a shaded band. The assessed *likely* ranges for the mean over the period 2081–2100 for all RCP scenarios are given as coloured vertical bars, with the corresponding median value given as a horizontal line. For further technical details see the Technical Summary Supplementary Material {Table 13.5, Figures 13.10 and 13.11; Figures TS.21 and TS.22}

(IPCC, 2013, p. 26)

Appendix E: Coding matrices created during the initial and focused coding of the baseline written assessment.

Table A1

Initial Codes for Participant Claims on the Baseline Written Assessment

Learner Name	Claim	Open Code
7-M-1	*Because of global warming melting ice therefore putting more water in the sea to increase sea level.*	Global warming, melting ice, more water
7-F-1	*Sea level rise is caused by change in the climate.*	Change in climate
7-M-2	*Sea level rises because poler ice caps melt wich makes the sea level rise*	Polar ice caps melt
7-F-2	*Global warming melts the polar ice caps, causing there to be more water in the ocean.*	Global warming melts polar ice caps, more water
7-M-3	*The increased sunlight from global warming melts the ice, putting more water in the oceans, so the sea level is rising.*	Increased sunlight from global warming, melts ice more water in oceans
7-F-3	*Through global warming glaciers and ice melts, going into the ocean, causing the sea level to rise.*	Global warming melts glaciers and ice, water goes into ocean
7-F-4	*Sea level rise is caused by increace in water in the oceans.*	More water in oceans
7-M-4	*The main cause of sea level rise is increased temperature.*	Temperature increase
7-F-5	*Sea level rise is caused by the artic glaciers melting due to global warming.*	Global warming makes arctic glaciers melt
7-F-6	*Waste that goes into the sea causes sea level rise.*	Waste added to ocean
7-M-5	*The cause of sea level rise is global warming*	Global warming
7-F-7	*The amount of rainfall and wind increases the sea level's hight.*	Increased rainfall and wind
7-M-6	n/a	n/a
7-F-8	*Global warming melts the ice caps, which means there is more water.*	Global warming melts ice, more water
7-M-7	*Sea level rise is caused by the melting ice berg*	Melting iceberg

7-F-9	n/a	n/a
7-M-8	*Sea level rise is caused by the melting of the polar ice caps.*	Melting polar ice caps
7-M-9	*Sea level rise is due to ice melting and adding more water to the sea.*	Ice melting, more water in sea
7-M-10	*sea level rises due to the moon and polar ice caps*	Moon and polar ice caps
7-M-11	*Global warming from Methane releasing melts polar ice caps*	Global warming from releasing methane, melting polar ice caps
7-M-12	*The raise of atmospheric tempature causes sea level rise.*	Increasing atmospheric temperature
7-M-13	*Global warming causes sea level rise.*	Global warming
7-F-10	*Global warming*	Global warming
7-F-11	*The sea level is rising because of global warming*	Global warming
7-F-12	*I believe that sea level rise is caused and created by global warming.*	Global warming
7-F-13	*The gummy bear is smaller and grows higher*	Gummy bear grows
7-F-14	*The rise of the atmosphere causes the sea level to rise.*	Rise of atmosphere
7-M-14	*Sea level rise is caused from gradual global warming*	Gradual global warming

Table A2

Initial and Focused Codes for Participant Claims on the Baseline Written Assessment

Open Codes	Axial Codes	Selective Codes
Global warming, melting ice, more water	Global warming melts ice on Earth’s surface and adds water to the sea	Melting ice on Earth’s surface
Global warming melts polar ice caps, more water		
Global warming melts glaciers and ice, water goes into ocean		
Global warming melts ice, more water		
Increased sunlight from global warming, melts ice, more water in oceans		
Ice melting, more water in sea	Ice melts on Earth’s surface and adds water to the sea	
Global warming from releasing methane, melting polar ice caps	Global warming melts ice on Earth’s surface	

Global warming makes arctic glaciers melt		
Melting iceberg	Melting ice on Earth's surface	
Polar ice caps melt		
Melting polar ice caps		
Temperature increase	Global warming or climate change	
Change in climate		
Global warming		
Gradual global warming		
Increasing atmospheric temperature		
More water in oceans		
Rise of atmosphere	Alternative conception	
Increased rainfall and wind		
Moon and polar ice caps		
Waste added to ocean		
Gummy bear grows	Confusion about topic of explanation	

Table A3

Final Focused Codes for Participant Claims on the Baseline Written Assessment.

Learner Name	Claim	Final Code
7-M-1	*Because of global warming melting ice therefore putting more water in the sea to increase sea level.*	Melting ice on Earth's surface
7-F-1	*Sea level rise is caused by change in the climate.*	Global warming or climate change
7-M-2	*Sea level rises because poler ice caps melt wich makes the sea level rise*	Melting ice on Earth's surface
7-F-2	*Global warming melts the polar ice caps, causing there to be more water in the ocean.*	Melting ice on Earth's surface
7-M-3	*The increased sunlight from global warming melts the ice, putting more water in the oceans, so the sea level is rising.*	Melting ice on Earth's surface Alternative Conception
7-F-3	*Through global warming glaciers and ice melts, going into the ocean, causing the sea level to rise.*	Melting ice on Earth's surface
7-F-4	*Sea level rise is caused by increace in water in the oceans.*	More water in oceans
7-M-4	*The main cause of sea level rise is increased temperature.*	Global warming or climate change

7-F-5	*Sea level rise is caused by the artic glaciers melting due to global warming.*	Melting ice on Earth's surface
7-F-6	*Waste that goes into the sea causes sea level rise.*	Alternative conception
7-M-5	*The cause of sea level rise is global warming*	Global warming or climate change
7-F-7	*The amount of rainfall and wind increases the sea level's hight.*	Alternative conception
7-M-6	n/a	n/a
7-F-8	*Global warming melts the ice caps, which means there is more water.*	Melting ice on Earth's surface
7-M-7	*Sea level rise is caused by the melting ice berg*	Melting ice on Earth's surface
7-F-9	n/a	n/a
7-M-8	*Sea level rise is caused by the melting of the polar ice caps.*	Melting ice on Earth's surface
7-M-9	*Sea level rise is due to ice melting and adding more water to the sea.*	Melting ice on Earth's surface
7-M-10	*sea level rises due to the moon and polar ice caps*	Melting ice on Earth's surface Alternative conception
7-M-11	*Global warming from Methane releasing melts polar ice caps*	Melting ice on Earth's surface
7-M-12	*The raise of atmospheric tempature causes sea level rise.*	Global warming or climate change
7-M-13	*Global warming causes sea level rise.*	Global warming or climate change
7-F-10	*Global warming*	Global warming or climate change
7-F-11	*The sea level is rising because of global warming*	Global warming or climate change
7-F-12	*I believe that sea level rise is caused and created by global warming.*	Global warming or climate change
7-F-13	*The gummy bear is smaller and grows higher*	Confusion about topic of explanation
7-F-14	*The rise of the atmosphere causes the sea level to rise.*	Alternative conception
7-M-14	*Sea level rise is caused from gradual global warming*	Global warming or climate change

Table A4

Initial Codes for Participant Evidence on the Baseline Written Assessment

Learner Name	Evidence	Open Code
7-M-1	*There was a lot of scientific research showing that a lot of ice is melting making more water in the sea because global warming makes the planet hotter therefore making ice melt into the ocean.*	Ice is melting; planet is hotter
7-F-1	*If there is a lot of rain at the sea and little amount of sun, then the water from the rain wont evaporize very fast. The sea level can rise also when there are large glaciers melting which increases the amount of water in the sea.*	Lots of rain, little sun; large glaciers melting
7-M-2	*because of Global Warming is causing the ice to melt and make the sea rise*	Global warming causes ice to melt
7-F-2	*1. The ice caps are melting, causing there to be more water in the ocean.* *2. If there is more water in the ocean, the sea level will rise because the ocean will over flow.*	Melting ice caps; more water in oceans
7-M-3	*The avg. temp. has risen about 1 degree at the past 20 years or something. Fossil fuels are being used more.*	Increased average temperature; increased fossil fuel use
7-F-3	*Before global warming the sea level was normal and wasn't rising, but after global warming the sea level rose by many inches each day, because of ice melting.*	After global warming, sea level rises many inches each day; ice melts
7-F-4	*Global warming causes temperature to rise. When temperature increases frozen water may reach its melting point, and become a liquid.*	Temperatures are rising; ice melts
7-M-4	*Because of rising temperatures polar ice caps have been melting. Since there is a large*	Temperatures are rising; polar ice caps have been melting; there is a large amount of frozen water in ice caps

	amount of frozen water this causes sea level rise when it melts.	
7-F-5	*Earth's temperature is rising and that is causing the polar ice caps to melt.*	Temperatures are rising; polar ice caps are melting
7-F-6	*When waste goes into the sea, the sea level starts to rise due to the weight of the waste.*	Waste goes into the sea; waste has weight; matter with weight can displace water
7-M-5	*When the ice caps mealt it turns to water and then it would rise. Also if ice is warm it turns to water.*	Melting ice caps turn into water; warming ice turns into water
7-F-7	*Last night, on Monday, November 1st, it rained. Today, on Tuesday, November 2nd, Virginia Beach is probably 1 inch higher in sea level. I have seen the before it rains, wind usually blows and sways the trees.*	It rained last night; the sea level is 1 inch higher as a result; it is usually windy before it rains
7-M-6	*n/a*	n/a
7-F-8	*The sea levels in the Atlantic Ocean have gone up as the weather went up.*	Atlantic ocean sea levels and weather have risen together
7-M-7	*The melting of ice berg (global warming in a sense) ice berg melt in the heat so where does the melted ice go? Exactly the ocean! the ocean takes all the water and with the extra water the ocean sea level rises.*	Icebergs are melting; icebergs melt when heated; water from melted icebergs goes into the ocean
7-F-9	n/a	n/a
7-M-8	*Polar Ice caps have been melting alot in the past fifty years.*	Polar ice caps have been melting
7-M-9	*In the national geographic television network, they had a segment on sea level rise. They said that due to global warming (heat getting trapped in the atmosphere) ice was melting and adding to the sea.*	A television program said ice was melting due to global warming; melted water is adding to the sea
7-M-10	*In some environment channels and in some books it states that the melting of polar Ice caps causes sea levels to rise. The moons gravitational pull also directs when sea levels rise or decrease. The moons gravity*	Television programs and books say polar ice caps are melting and causing sea level to rise; moon's gravitation pull changes the sea level

	pulls water to where it is so the water rises or decreases	
7-M-11	• *The polar ice caps are melting faster than ever before.* • *From certain points in the ocean, you can see thousands of bubbles popping. Scientists proved it was methane* *Methane warms up the atmesphere*	Polar ice caps are melting faster; methane is bubbling out of the ocean; methane warms the atmosphere
7-M-12	*Anartica snow and icebergs are melting and causing heating of water and the water to rise.*	Ice is melting in Antarctica; water is being heated and is rising
7-M-13	*Media says that glaciers are melting and causing sea levels to rise.*	Media sources say glaciers are melting and causing sea level rise
7-F-10	*The ice in the north and south pole is melting, which makes there be an overall higher sea level. It is predicted that it will get at least a foot higher in 5 years.*	Ice in North and South Poles is melting; predictions say the sea level will increase by at least one foot in 5 years
7-F-11	*I learned in science class last year and the videos of global warming that the North and south poles melt to add more water to the ocean, which causes the sea level to rise*	Science class and science videos say ice at the North and South Poles is melting; melting ice adds water to the ocean and causes sea levels to rise
7-F-12	*When I was watching tv once this ad came up that was saying how people (our world) are slowly killing ourselves because of pollution and global warming and that sea level rise was part of that process. The people in the ad were saying that global warming was causing many troubles in our world and I figure one of the troubles may be sea level rise.*	A television advertisement said human pollution and global warming cause sea level rise
7-F-13	*The molecules goes from higher concentration to lower concentration. lots of molecules go into and out of the gummy bear.*	Molecules go into and out of the gummy bear; molecules go from higher concentration to lower concentration
7-F-14	*When the atmosphere rises the sea level rises because the atmospher causes it.*	The atmosphere and the sea level rise together; the atmosphere causes the rise

7-M-14	*Global warming warms up the planet, as a result, many giant ice caps in the North and South poles have been melting. This melting of the ice can cause the sea level to rise a couple inches a year.*	Global warming warms Earth; ice caps in the North and South Poles have been melting; melting ice can cause sea level to rise a couple inches per year

Table A5

Initial and Focused Codes for Participant Evidence on the Baseline Written Assessment

Open Codes	Axial Codes	Selective Codes
Ice is melting; planet is hotter	Temperatures on Earth are rising; ice melt on Earth is increasing	
Global warming causes ice to melt		
After global warming, sea level rises many inches each day; ice melts		
Melting ice caps; more water in oceans		
Temperatures are rising; ice melts		
Temperatures are rising; polar ice caps have been melting; there is a large amount of frozen water in ice caps		
Temperatures are rising; polar ice caps are melting		
Melting ice caps turn into water; warming ice turns into water		
Icebergs are melting; icebergs melt when heated; water from melted icebergs goes into the ocean		
Polar ice caps are melting faster; methane is bubbling out of the ocean; methane warms the atmosphere		
Ice is melting in Antarctica; water is being heated and is rising		
Global warming warms Earth; ice caps in the North and South Poles have been melting; melting ice can		

cause sea level to rise a couple inches per year		
Polar ice caps have been melting	Polar ice on Earth is melting	
Ice in North and South Poles is melting; predictions say the sea level will increase by at least one foot in 5 years		
A television program said ice was melting due to global warming; melted water is adding to the sea	Media sources say melting ice on Earth is causing sea level rise	
Television programs and books say polar ice caps are melting and causing sea level to rise; moon's gravitation pull changes the sea level		
Media sources say glaciers are melting and causing sea level rise		
Science class and science videos say ice at the North and South Poles is melting; melting ice adds water to the ocean and causes sea levels to rise		
A television advertisement said human pollution and global warming cause sea level rise	Television advertisement said pollution and global warming cause sea level rise	
Increased average temperature; increased fossil fuel use	Increased fossil fuel use; increased average temperature	
The atmosphere and the sea level rise together; the atmosphere causes the rise	Alternative conception	
Atlantic ocean sea levels and weather have risen together		
Waste goes into the sea; waste has weight; matter with weight can displace water		
It rained last night; the sea level is 1 inch higher as a result; it is usually windy before it rains		
Molecules go into and out	Confusion about topic of	

of the gummy bear; molecules go from higher concentration to lower concentration	explanation	

Table A6

Final Focused Codes for Participant Evidence on the Baseline Written Assessment

Learner Name	Evidence	Final Code
7-M-1	*There was a lot of scientific research showing that a lot of ice is melting making more water in the sea because global warming makes the planet hotter therefore making ice melt into the ocean.*	Temperatures on Earth are rising; ice melt on Earth is increasing
7-F-1	*If there is a lot of rain at the sea and little amount of sun, then the water from the rain wont evaporize very fast. The sea level can rise also when there are large glaciers melting which increases the amount of water in the sea.*	Alternative conception Polar ice on Earth is melting
7-M-2	*because of Global Warming is causing the ice to melt and make the sea rise*	Temperatures on Earth are rising; ice melt on Earth is increasing
7-F-2	*1. The ice caps are melting, causing there to be more water in the ocean.* *2. If there is more water in the ocean, the sea level will rise because the ocean will over flow.*	Polar ice on Earth is melting
7-M-3	*The avg. temp. has risen about 1 degree at the past 20 years or something. Fossil fuels are being used more.*	Increased fossil fuel use; increased average temperature
7-F-3	*Before global warming the sea level was normal and wasn't rising, but after global warming the sea level rose by many inches each day, because of ice melting.*	Temperatures on Earth are rising; ice melt on Earth is increasing
7-F-4	*Global warming causes temperature to rise. When temperature increases frozen*	Temperatures on Earth are rising; ice melt on Earth is increasing

	water may reach its melting point, and become a liquid.	
7-M-4	*Because of rising temperatures polar ice caps have been melting. Since there is a large amount of frozen water this causes sea level rise when it melts.*	Temperatures on Earth are rising; ice melt on Earth is increasing
7-F-5	*Earth's temperature is rising and that is causing the polar ice caps to melt.*	Temperatures on Earth are rising; ice melt on Earth is increasing
7-F-6	*When waste goes into the sea, the sea level starts to rise due to the weight of the waste.*	Alternative conception
7-M-5	*When the ice caps mealt it turns to water and then it would rise. Also if ice is warm it turns to water.*	Temperatures on Earth are rising; ice melt on Earth is increasing
7-F-7	*Last night, on Monday, November 1st, it rained. Today, on Tuesday, November 2nd, Virginia Beach is probably 1 inch higher in sea level. I have seen the before it rains, wind usually blows and sways the trees.*	Alternative conception
7-M-6	*n/a*	n/a
7-F-8	*The sea levels in the Atlantic Ocean have gone up as the weather went up.*	Alternative conception
7-M-7	*The melting of ice berg (global warming in a sense) ice berg melt in the heat so where does the melted ice go? Exactly the ocean! the ocean takes all the water and with the extra water the ocean sea level rises.*	Temperatures on Earth are rising; ice melt on Earth is increasing
7-F-9	n/a	n/a
7-M-8	*Polar Ice caps have been melting alot in the past fifty years.*	Polar ice on Earth is melting
7-M-9	*In the national geographic television network, they had a segment on sea level rise. They said that due to global warming (heat getting trapped in the atmosphere) ice was melting and adding to the sea.*	Temperatures on Earth are rising; ice melt on Earth is increasing Media sources say melting ice on Earth is causing sea level rise
7-M-10	*In some environment channels and in some books it states that*	Media sources say melting ice on Earth is causing sea level rise

	the melting of polar Ice caps causes sea levels to rise. The moons gravitational pull also directs when sea levels rise or decrease. The moons gravity pulls water to where it is so the water rises or decreases	Alternative conception
7-M-11	• *The polar ice caps are melting faster than ever before.* • *From certain points in the ocean, you can see thousands of bubbles popping. Scientists proved it was methane* *Methane warms up the atmesphere*	Temperatures on Earth are rising; ice melt on Earth is increasing
7-M-12	*Anartica snow and icebergs are melting and causing heating of water and the water to rise.*	Polar ice on Earth is melting Alternative conception
7-M-13	*Media says that glaciers are melting and causing sea levels to rise.*	Media sources say melting ice on Earth is causing sea level rise
7-F-10	*The ice in the north and south pole is melting, which makes there be an overall higher sea level. It is predicted that it will get at least a foot higher in 5 years.*	Polar ice on Earth is melting Alternative conception
7-F-11	*I learned in science class last year and the videos of global warming that the North and south poles melt to add more water to the ocean, which causes the sea level to rise*	Media sources say melting ice on Earth is causing sea level rise
7-F-12	*When I was watching tv once this ad came up that was saying how people (our world) are slowly killing ourselves because of pollution and global warming and that sea level rise was part of that process. The people in the ad were saying that global warming was causing many troubles in our world and I figure one of the troubles may be sea level rise.*	Television advertisement said pollution and global warming cause sea level rise
7-F-13	*The molecules goes from higher concentration to lower concentration. lots of molecules*	Confusion about topic of explanation

	go into and out of the gummy bear.	
7-F-14	*When the atmosphere rises the sea level rises because the atmospher causes it.*	Alternative conception
7-M-14	*Global warming warms up the planet, as a result, many giant ice caps in the North and South poles have been melting. This melting of the ice can cause the sea level to rise a couple inches a year.*	Temperatures on Earth are rising; ice melt on Earth is increasing

Table A7

Initial Codes for Participant Reasoning on the Baseline Written Assessment

Learner Name	Reasoning	Open Code
7-M-1	*Taking in that scientists researched for years about this, it shows that ice is actually melting and that the weather is getting warmer in the poles and making more ice melt.*	Scientific findings are trustworthy; increased temperatures at the poles causes ice to melt
7-F-1	*The less sun there is to evaporate the water the more water is left and the more huge glaciers melt the more the water in the sea which can also mean global warming is causing glaciers to melt at the sea.*	A decrease in sunlight is causing less evaporation; global warming causes glaciers to melt and add water to the sea
7-M-2	*when people use cars, buses, and planes which causes exost which is carbon dixid which melts the ice*	People create carbon dioxide, which melts ice
7-F-2	*Global warming is making the Earth warmer, causing the ice caps to melt. After the ice caps melt, there will be more water in the ocean, causing sea levels to rise.*	Global warming makes earth warmer, which melts icecaps, adding water to the sea, increasing sea levels
7-M-3	*Since global warming is increasing more ice will melt, causing sea levels to rise.*	Global warming causes ice to melt and sea levels to rise
7-F-3	*When global warming melts ice and glaciers melt causing the ocean level to rise above the level it was before.*	Global warming causes ice and glaciers to melt and the sea level to rise

7-F-4	*When the amount of liquid water increases, it will take no more space. Therefore, the sea level will rise.*	More water means more space and higher sea levels
7-M-4	*When temperature increases more of the polar ice melts causing sea level rise.*	Increased temperatures cause polar ice melt and higher sea levels
7-F-5	*As Earth's temperature rises, the polar ice caps melt and the extra water travels down to the oceans, causing sea level rise.*	Increased temperatures cause polar icecaps to melt. Water travels down to the ocean to increase sea levels.
7-F-6	*When waste goes into the sea, the sea levels starts to rise due to the weight of the waste. Therefore, waste causes sea level rise.*	Sea levels rise when matter with weight is added. Waste has weight, so added waste causes the sea levels to rise.
7-M-5	*The cause is global warming because when ice caps/ice mealts it turns to water to rise the sea level*	Global warming melts icecaps, which turn to water and add to the sea level
7-F-7	*If the ocean is made of water, then rainfall will increase the water level.*	Increased rainfall will increase sea level
7-M-6	n/a	n/a
7-F-8	*People pollute and use green gases, which makes the atmoshpere thinner, which makes it hotter, then the ice caps melt to make more water.*	Humans use greenhouse gases, which thin the atmosphere. Thinning of the atmosphere increases temperatures, which melts icecaps, creating more water in the sea.
7-M-7	*ice berg is one of the many reasons the sea level is rising.*	Icebergs cause sea level rise
7-F-9	n/a	n/a
7-M-8	*Polar bears are dying cause there's no Ice for them which shows that the ice is melting.*	Polar bears are dying because the ice they need to live is melting
7-M-9	*National geographic had an article about global warming also it said that heat was getting trapped in the atmosphere and was heating the earth therefore melting ice and making more water.*	Heat gets trapped in the atmosphere and causes ice to melt, which creates more water
7-M-10	*when the Ice melts more water goes into the sea increasing the sea level. The moons gravity pulls water towards it so when it's above the sea water gets pulled under it raising the sea level*	Ice melts and goes into the sea; the gravitational pull of the moon pulls the water up, increasing sea level
7-M-11	*The methane bubbles pop and*	Methane warms the atmosphere, so

	warm up the atmosphere. It melts the ice caps which release thousands of gallons of water into the ocean	icecaps melt, releasing water into the ocean
7-M-12	*Ice melts on water and pushes water up.*	Sea ice melts and pushes water to a higher level
7-M-13	*This is because the water adds on the water already in the sea.*	Additional water raises the sea level
7-F-10	*Since we are using more fossil feuls, the world is getting warmer.*	Increased fossil fuel use raises temperatures
7-F-11	*Because the change in temp, the poles melt, and the water accumulates to the ocean, which causes it to rise. Also, global warming causes more storms.*	Changes in temperature melt polar ice, adding water to the ocean; Global warming increases the frequency of storms
7-F-12	*Overall I believe that sea level rise is caused by global warming which I had gotten from a TV source.*	Global warming causes sea level rise according to a television source
7-F-13	*gummy bear is growing bigger by the molecules.*	Molecules cause the gummy bear to grow larger
7-F-14	*The atmospher causes the sea level to rise.*	The atmosphere causes sea level to rise
7-M-14	*Globol warming does not directly affect sea level rise. However, global warming does causes the polar ice caps to warm up a lot and melt, with a lot of freshly melted water entering the sea, the sea level rises as a result of this.*	Global warming causes polar icecaps to warm and melt, and melted water adds to the sea

Table A8

Initial and Focused Codes for Participant Reasoning on the Baseline Written Assessment

Open Codes	Axial Codes	Selective Codes
Global warming makes earth warmer, which melts icecaps, adding water to the sea, increasing sea levels	Increased temperatures cause ice to melt, and melted water adds to the sea, raising the sea level	
Global warming causes ice to melt and sea levels to rise		
Global warming causes ice and glaciers to melt and the sea level to rise		
Increased temperatures		

cause polar ice melt and higher sea levels		
Increased temperatures cause polar icecaps to melt. Water travels down to the ocean to increase sea levels.		
Global warming melts icecaps, which turn to water and add to the sea level		
Global warming causes polar icecaps to warm and melt, and melted water adds to the sea		
Methane warms the atmosphere, so icecaps melt, releasing water into the ocean		
Heat gets trapped in the atmosphere and causes ice to melt, which creates more water		
Changes in temperature melt polar ice, adding water to the ocean; Global warming increases the frequency of storms		
Humans use greenhouse gases, which thin the atmosphere. Thinning of the atmosphere increases temperatures, which melts icecaps, creating more water in the sea.		
Scientific findings are trustworthy		
Increased fossil fuel use raises temperatures		
Global warming causes sea level rise according to a television source		
The atmosphere causes sea level to rise		
Icebergs cause sea level rise		
Polar bears are dying because the ice they need to live is melting		
Additional water raises the sea level	Additional water occupies space	
More water means more		

space and higher sea levels		
Sea levels rise when matter with weight is added. Waste has weight, so added waste causes the sea levels to rise.	Alternative conception	
Sea ice melts and pushes water to a higher level		
The gravitational pull of the moon pulls the water up, increasing sea level		
People create carbon dioxide, which melts ice		
Increased rainfall will increase sea level		
A decrease in sunlight is causing less evaporation		
Molecules cause the gummy bear to grow larger	Confused about topic of explanation	

Table A9

Final Focused Codes for Participant Reasoning on the Baseline Written Assessment

Learner Name	Reasoning	Final Code
7-M-1	*Taking in that scientists researched for years about this, it shows that ice is actually melting and that the weather is getting warmer in the poles and making more ice melt.*	Increased temperatures cause ice to melt, and melted water adds to the sea, raising the sea level
7-F-1	*The less sun there is to evaporate the water the more water is left and the more huge glaciers melt the more the water in the sea which can also mean global warming is causing glaciers to melt at the sea.*	Alternative conception
7-M-2	*when people use cars, buses, and planes which causes exost which is carbon dixid which melts the ice*	Alternative conception
7-F-2	*Global warming is making the Earth warmer, causing the ice caps to melt. After the ice caps melt, there will be more water in the ocean, causing sea levels to rise.*	Increased temperatures cause ice to melt, and melted water adds to the sea, raising the sea level
7-M-3	*Since global warming is*	Increased temperatures cause ice to

	increasing more ice will melt, causing sea levels to rise.	melt, and melted water adds to the sea, raising the sea level
7-F-3	*When global warming melts ice and glaciers melt causing the ocean level to rise above the level it was before.*	Increased temperatures cause ice to melt, and melted water adds to the sea, raising the sea level
7-F-4	*When the amount of liquid water increases, it will take no more space. Therefore, the sea level will rise.*	Additional water occupies space
7-M-4	*When temperature increases more of the polar ice melts causing sea level rise.*	Increased temperatures cause ice to melt, and melted water adds to the sea, raising the sea level
7-F-5	*As Earth's temperature rises, the polar ice caps melt and the extra water travels down to the oceans, causing sea level rise.*	Increased temperatures cause ice to melt, and melted water adds to the sea, raising the sea level
7-F-6	*When waste goes into the sea, the sea levels starts to rise due to the weight of the waste. Therefore, waste causes sea level rise.*	Alternative conception
7-M-5	*The cause is global warming because when ice caps/ice mealts it turns to water to rise the sea level*	Increased temperatures cause ice to melt, and melted water adds to the sea, raising the sea level
7-F-7	*If the ocean is made of water, then rainfall will increase the water level.*	Alternative conception
7-M-6	n/a	n/a
7-F-8	*People pollute and use green gases, which makes the atmoshpere thinner, which makes it hotter, then the ice caps melt to make more water.*	Increased temperatures cause ice to melt, and melted water adds to the sea, raising the sea level
7-M-7	*ice berg is one of the many reasons the sea level is rising.*	Icebergs cause sea level rise
7-F-9	n/a	n/a
7-M-8	*Polar bears are dying cause there's no Ice for them which shows that the ice is melting.*	Polar bears are dying because the ice they need to live is melting
7-M-9	*National geographic had an article about global warming also it said that heat was getting trapped in the atmosphere and was heating the earth therefore melting ice and making more water.*	Increased temperatures cause ice to melt, and melted water adds to the sea, raising the sea level
7-M-10	*when the Ice melts more water*	Increased temperatures cause ice to

	goes into the sea increasing the sea level. The moons gravity pulls water towards it so when it's above the sea water gets pulled under it raising the sea level	melt, and melted water adds to the sea, raising the sea level Alternative conception
7-M-11	*The methane bubbles pop and warm up the atmosphere. It melts the ice caps which release thousands of gallons of water into the ocean*	Increased temperatures cause ice to melt, and melted water adds to the sea, raising the sea level
7-M-12	*Ice melts on water and pushes water up.*	Additional water occupies space
7-M-13	*This is because the water adds on the water already in the sea.*	Additional water occupies space
7-F-10	*Since we are using more fossil feuls, the world is getting warmer.*	Increased fossil fuel use raises temperatures
7-F-11	*Because the change in temp, the poles melt, and the water accumulates to the ocean, which causes it to rise. Also, global warming causes more storms.*	Increased temperatures cause ice to melt, and melted water adds to the sea, raising the sea level Alternative conception
7-F-12	*Overall I believe that sea level rise is caused by global warming which I had gotten from a TV source.*	Global warming causes sea level rise according to a television source
7-F-13	*gummy bear is growing bigger by the molecules.*	Confusion about topic of explanation
7-F-14	*The atmospher causes the sea level to rise.*	The atmosphere causes sea level to rise
7-M-14	*Globol warming does not directly affect sea level rise. However, global warming does causes the polar ice caps to warm up a lot and melt, with a lot of freshly melted water entering the sea, the sea level rises as a result of this.*	Increased temperatures cause ice to melt, and melted water adds to the sea, raising the sea level

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