
Categorising students' evaluations of evidence and explanations about climate change

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Abstract: Just as scientists evaluate explanations of climate change, students should also engage in critically evaluative practices when studying global warming. The purpose of the present study was to investigate middle school students' evaluations when they examined different explanations for the causes of climate change. We observed four distinct categories of evaluation in student explanations about how evidence texts related to climate change models: a) erroneous evaluation; b) descriptive evaluation; c) relational evaluation and d) critical evaluation. These findings allow us to better understand and recognise types of student thinking, so that we may be able to better implement instruction that promotes critical evaluation about climate change and other complex scientific topics, as is called for by recent science education reform efforts.

Keywords: climate change; science education; evaluation skills; critical thinking.

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1 Introduction and purpose

Evaluation is essential to the scientific enterprise involved in understand climate change. Likewise, students should evaluate scientific explanations in order to learn deeply about climate change and other complex phenomena (National Research Council, 2012). A recent report on reforming science education in the USA says that the practice of evaluation requires 'critical thinking' in both "developing and refining an idea (an explanation or a design) or in conducting an investigation" [National Research Council, (2012), p.46]. This process of critical evaluation [e.g., participating in argumentation discourse, posing and/or responding to critical questions (Duschl and Osborne, 2002; Nussbaum, 2011)] demonstrates mature scientific thinking (Kuhn and Pearsall, 2000). However, many students do not naturally express such advanced reasoning (Erduran and Msimanga, 2014; Stanovich and West, 1997). Therefore, deepening students' understanding of climate change may be difficult both because the underlying scientific principles are complex and because students have difficulty understanding why scientists think that Earth's global climate is changing. Students may need instructional scaffolds to actively engage in critical evaluation if they are to fully understanding global warming and, specifically, be able to gauge how well evidence supports scientific explanations (Lombardi et al., 2013; Sinatra and Chinn, 2011).

The purpose of our study was to investigate students' evaluations of two competing explanations about the cause of current climate change. One explanation was the scientifically accepted idea that human activities are the primary cause of global warming

and ice sheet melting (Doran and Zimmerman, 2009). The alternative explanation was that current climate change is caused by an increasing amount of solar energy received by Earth, an idea popular with many human-induced climate change deniers (Hallett, 2014). We specifically examined the underlying evaluative mechanisms expressed by students in a written task associated with a model-evidence link (MEL) diagram activity used during classroom instruction. The mode and structure of the MEL diagram was originally developed by a team of researchers at Rutgers University under the NSF-supported Promoting Reasoning and Conceptual Change in Science project for use in middle school life science classrooms (Chinn and Buckland, 2012). Lombardi et al. (2013) developed the climate change MEL used in the present investigation.

The first author recently conducted a study using a climate change MEL that resulted in significant shifts in both students' plausibility and knowledge of climate change toward the scientifically accepted explanation that humans are the likely cause of global warming (Lombardi et al., 2013). The results of this study suggested that students' plausibility shifts and knowledge gains were related to the MEL's ability to facilitate students' critical evaluation. However, the purpose of our present investigation was to examine the underlying evaluations that may have led to these shifts. We specifically conducted a thorough qualitative analysis of student explanations about the links students drew on their climate change MEL diagrams, a data source omitted from previous analysis by Lombardi et al. (2013). Our research question was: what types of evaluations do students use when considering alternative explanations of climate change during classroom instruction? We argue that the categories revealed by our qualitative analysis may be a useful tool for researchers and instructors to help gauge students' types of evaluation as they learn about climate change.

2 Background

2.1 Thinking critically through evaluation

Evaluation of alternative explanations is one important aspect of critical thinking (West et al., 2008). Critical evaluation often involves judgements about the relationship between evidence and alternative explanations of a particular phenomenon (McNeill et al., 2006), such as the potential causes of global warming. Furthermore, critical evaluations that weigh the strengths and weaknesses in the connection between evidence and explanations are fundamental to science (National Research Council, 2012). When students are critically evaluative in the science classroom, they will explicitly think and reflect about the valid processes by which scientists construct knowledge (Mason et al., 2011). Such reflection may be facilitated when students model practices used by scientific experts (Duschl et al., 2007). Furthermore, critical evaluation may be stimulated when students participate in collaborative argumentation (Chin and Osborne, 2010), where students constructively challenge each other's thinking by comparing, critiquing, and revising ideas (Nussbaum, 2008). As a community, science thrives due to collaborative argumentation because it constructs valid and reliable information (Osborne, 2010; Rudolph, 2014). Students who engage in critical evaluation can observe and embrace the idea that scientific knowledge emerges from collaborative argumentation (Nussbaum, 2008).

Critical evaluation, however, is not necessarily used in argument construction. To be critical, one must avoid confirmation bias – the “inappropriate bolstering of hypotheses or beliefs whose truth is in question” [Nickerson, (1998), p.175] – and disconfirmation bias – the undermining of evidence contrary to beliefs (Edwards and Smith, 1996). These biases happen for scientists and students alike. For example, Nussbaum et al. (2005) found that students with more deeply rooted beliefs, scientific or otherwise, had more difficulty generating counterarguments. Because students might not naturally be critically reflective when engaging in collaborative argument, they may need instructional scaffolds to evaluate the quality of explanations (Nussbaum and Edwards, 2011). A promising scaffold to help students develop deeper levels of evaluative thinking is the MEL diagram (Chinn and Buckland, 2012). The MEL assists students in effectively coordinating evidence with scientific explanations, which in turn may facilitate their critical evaluation and scientific reasoning (Duschl and Grandy, 2011; Kuhn and Pearsall, 2000).

2.2 Critical evaluation and reasoning

Scientific reasoning often involves critical evaluations about the strength of connections between lines of evidence and alternative explanations of phenomenon. In the process of reasoning, scientists construct and use mental models to develop explanations, hypotheses, and theories. Furthermore, to ascertain validity, scientists link observational evidence of reality to explanatory models of how the universe functions (Erduran and Dagher, 2014). Nersessian (1999) argues that such model-based reasoning, whether experimentally or theoretically based, is how scientific concepts are formed and changed over time. However, scientific model-based reasoning does not readily occur in science classrooms. More often, students engage in phenomenon-based reasoning, where students make little or no distinction between scientific evidence and explanation, or relation-based reasoning, where students connect evidence and explanation through simple correlational thinking (e.g., correlation implies causation). Model-based reasoning would occur only when students weigh the strength of the evidence supporting an explanation, and in some circumstances, weigh the strength of evidence supporting multiple, alternative explanations. Instructional scaffolds that promote model-based reasoning by introducing alternative models (e.g., the MEL) may be needed to facilitate construction of arguments that are critically evaluative.

2.3 Critical evaluation and argumentation

Walton’s (2007) argumentation framework posits a dynamic relationship between various argumentation schemes, critical questions, answers or refutations, and abductive inferences [i.e., inference toward the best explanation (Harman, 1965)]. Specifically, individuals gauge the relative plausibility of alternative explanations (e.g., an argument-counterargument) through the process of abduction (Walton, 2004), i.e., an explanation is valid if it is the best possible explanation of a set of known data. In educational research, argumentation interventions based on Walton’s framework have been tested, revealing promising results in promoting students’ critical evaluation (Nussbaum, 2011; Nussbaum and Edwards, 2011). However, in science education, Toulmin’s (1958) argumentation pattern is the default framework of choice (see, for example, Christodoulou and Osborne, 2014; Gray and Kang, 2014; Kulatunga et al.,

2013). We acknowledge that this framework for argumentation discourse provides a situation where students can justify their claims (Erduran et al., 2004), however, it provides little support for the critical thinking skills and reasoning processes necessary to engage in argumentation with more critical evaluation (Zohar, 2007). As such, an approach based on constructing arguments through abductive inferences may better facilitate students' critical evaluation. The aim of the present study is to examine the different types of evaluations demonstrated by students in an explanatory task that detailed their thinking about the evidence to model links constructed on their climate change MEL diagrams.

3 Methods

3.1 Participants and setting

Middle school students from a large urban district in the Southwestern US participated in the study. The school district involved in this study teaches about climate during grade 7, when all students are required to take an Earth science class. Study participants were drawn from the entire middle school's grade 7, each taught by one of four science teachers. For the present study, we only included students who provided both parental consent and self-assent, completed all study activities, and were part of the treatment group that used the MEL materials. Of the 85 students included in the present study, 55 (65%) were Hispanic, 14 (16%) were White, 13 (15%) were African American, and 3 (4%) were Asian/Pacific Islander. Forty-five participants (53%) were male. Eight (9%) of the participants had individualised education plans, 18 (21%) had limited proficiency in the English language, and 40 (47%) were eligible for free or reduced-cost lunch. Again, the present study concerned a detailed analysis on the MEL explanatory task and did not include details of participants from another comparative study used to observe the overall effectiveness of the MEL intervention. However, note that the comparison group was of similar size (81 students) and demographic composition to the participants in the present study (see Lombardi et al., 2013, for more details on the comparison group and associated results).

We conducted the study toward the end of the school year's first quarter. At this time, the grade 7 students were completing an introductory unit on the nature of Earth science. The instructional activities occurred over two class periods (about 90 minutes of instructional time total). Seven classes were involved in the study, with three different teachers as instructors for two classes each and one teacher as the instructor for one class. Details about the procedure and intervention follow the subsequent discussion of materials.

3.2 Materials

Participants used the MEL diagram activity as the instructional intervention for the present study (see Figure 1 for a student-completed MEL). On the first page of the MEL, participants drew different types of arrows linking evidentiary data to the two alternative models of climate change (Model A: human-induced climate change and Model B: solar irradiance causing climate change). Participants drew arrows in different shapes to indicate the relative weight of the evidence. Straight arrows indicated the evidence

supports the model; squiggly arrows indicated the evidence strongly supports the model; straight arrows with an 'X' through the middle indicated the evidence contradicts the model; and dashed arrows indicated the evidence has nothing to do with the model.

Figure 1 The climate change MEL diagram, with explanatory tasks on the second page

Directions: draw two arrows from each evidence box. One to each model. You will draw a total of 8 arrows.

Key:

	The evidence supports the model
	The evidence STRONGLY supports the model
	The evidence contradicts the model (shows its wrong)
	The evidence has nothing to do with the model

Evidence #1
Atmospheric greenhouse gas concentrations have been rising for the past 50 years. Human activities have led to greater releases of greenhouse gases. Temperatures have also been rising during these past 50 years.

Model A
Our current climate change is caused by increasing amounts of gases released by human activities.

Evidence #3
Satellites are measuring more of Earth's energy being absorbed by greenhouse gases.

Evidence #2
Solar activity has decreased since 1970. Lower activity means that Earth has received less of the Sun's energy. But, Earth's temperature has continued to rise.

Model B
Our current climate change is caused by increasing amounts of energy released from the Sun.

Evidence #4
Increases and decreases in global temperatures closely matched increases and decreases in solar activity before the industrial revolution.

1

Provide a reason for three of the arrows you have drawn. Write your reasons for the three most interesting or important arrows.

A. Write the number of the evidence you are writing about.
 B. Circle the appropriate word (**strongly supports** | supports | **contradicts** | has nothing to do with).
 C. Write which model you are writing about.
 D. Then write your reason.

1. Evidence # 1 **strongly supports** | supports | **contradicts** | has nothing to do with Model A because:
 they're both talking about climate change due to human releasing gasses into the air they both support human each other

2. Evidence # 2 **strongly supports** | supports | **contradicts** | has nothing to do with Model B because:
 they both talk about the Sun's energy but from different points. The opposing sides are: Not getting enough Sun or getting too much

3. Evidence # 3 **strongly supports** | supports | **contradicts** | has nothing to do with Model A because:
 Model A is talking about gasses and evidence B is talking about satellites and about the energy being absorbed.

2

Note: These come from different students, so links explained on the second page do not necessarily correspond to those marked on the first page.

On the second page of the MEL activity, which was the focus of the present study, students completed the explanatory task. This task asked participants to select three (out of a possible eight) evidence-to-model links that they had made on their MEL diagrams (i.e., the first page of the activity). In their explanations, participants identified each end of the link, with a line of evidence (numbered 1, 2, 3, or 4; see Figure 1) at one end and a model (A: human-induced or B: solar irradiance) at the other. Participants then circled their judgement about the weighting of the link's strength between the evidence and model (i.e., the evidence *strongly supports* the model, the evidence *supports* the model, the evidence *has nothing to do with* the model, or the evidence *contradicts* the model). The participants also provided a justification for their conviction of the link's strength, starting with the provided prompt 'because'. For example, a full explanation from one participant said, "Evidence #1 strongly supports Model A because atmospheric greenhouse gases have been rising for the past 50 years because of humans".

3.3 Procedures

Students first read a short introduction to the two climate change models. Then the student engaged in a pre-activity, which helped them to understand how scientists weigh connections between evidence and scientific explanations (e.g., scientific models). Specifically, this pre-activity asked students to rank the importance of the following four evidence connections:

- 1 the evidence supports an idea
- 2 the evidence strongly supports an idea
- 3 the evidence contradicts (opposes) an idea
- 4 the evidence has nothing to do with an idea.

Note that these statements correspond to the four types of arrows that the participants would later use in developing their MELs (see Figure 1). After making their initial rankings, participants read a short paragraph discussing falsifiability and, specifically, how evidence that contradicts an idea has a large influence on how scientific knowledge changes. Participants then re-ranked the four types of evidence. After re-ranking, teachers conducted a short discussion with the class on their rankings and directly reinforced that contradictory evidence generally does have the greatest weight in scientific evaluations, per the Popperian notion of falsifiability (Popper, 1963).

During the MEL activity, participants individually read short expository texts discussing each piece of evidence, with one page of text for each line of evidence. These pages also included graphs and figures. Teachers asked the students if they had any questions about the evidence texts, figures, and graphs to clear up any confusion or misunderstandings. Participants evaluated the four evidentiary statements and linked them to each model using different arrows for the weighting scheme. After completing their diagrams, treatment participants individually completed the written explanatory task (i.e., the part of the activity that is the focus of the present study), which allowed students to reflect on the arrows they drew on the MEL.

4 Qualitative analysis

We conducted a content analysis, which is a technique for systematically coding large amounts of text to create a small number of content categories (Stemler, 2001), to examine participants' explanations. The lead, second, and fourth authors independently read through the explanations multiple times. Between reading episodes, we compared coding results. After four iterations, we eventually focused our coding on the types of scientific reasoning being exhibited by students during science instruction. These categories somewhat resembled the groupings coined by Driver et al. (1996) for scientific reasoning. Driver et al.'s framework was based on students' discourse during instruction and categorically divided all of the students' scientific reasoning into three categories: phenomenon-based reasoning, relation-based reasoning, and model-based reasoning. Like Driver et al. (1996), we used these designations as our analytical categories. Additionally, we attended to indicators revealing participants' degree of elaboration (i.e., 'issue-relevant arguments' contained in an explanation [Petty and Cacioppo, (1986), p.128]). Elaboration exists on various levels, with high elaboration associated with deep cognitive engagement and low elaboration with superficial cognitive engagement (Dole and Sinatra, 1998). Thus the final content analysis revealed that explanations fell into four well-defined categories of evaluation, which reflect both participants' scientific reasoning and elaboration in their explanations of evidence-to-model links. These four categories, discussed in more detail below, represent a blend of Driver et al.'s (1996) and Dole and Sinatra's (1998) frameworks.

4.1 *Category 1: Erroneous evaluation*

Many participants had incorrect explanations about evidence-to-model links, a category not addressed in Driver et al.'s (1996) types of reasoning. For example, one participant said that Evidence #2 strongly supports Model B because the evidence "talks about the Sun's energy and the temperature rising and Model B talks about energy released from the Sun". However, Evidence #2 states that solar activity has been decreasing since 1970 and that Earth has received less energy from the Sun, while Earth's temperatures have continued to rise. The participant was clearly incorrect because this evidence contradicts Model B, which states that our current climate change is caused by increasing amounts of energy released from the Sun. Such erroneous evaluations could have resulted from lack of attention to the evidence and/or model text. Alternatively, erroneous evaluations may have emerged from a psychological response where "students sometimes ignore information in science texts that contradicts their existing schemas" [Chinn and Brewer, (1993), p.5].

Given that a clear category of erroneous evaluation emerged from the content analysis, we needed to look carefully at whether a given link between a line of evidence and an explanatory model is correct or incorrect (Table 1). Note that part of correctness is based on participants' judgements about weight of a link's strength (i.e., strongly supports, supports, has nothing to do with, or contradicts). The table combines the weights of 'strongly supports' and 'supports', because from the perspective of correctness, it would be inconsequential to differentiate between the two. We determined correct and incorrect responses based solely on the information provided in the evidence and the cause-effect statement made in a model. Although someone with a sufficient amount of background knowledge (i.e., an expert in climate science) could argue that

other correct options exist, such nuances are beyond the level of these middle school participants, who were clearly novices in the area of climate science. Table 1 also shows if correct links are weak or strong, which reflects other types of elaboration and reasoning as discussed in the next three categories (see below).

Table 1 List of correct (C) and incorrect responses (I) for evidence-to-model links based on participants' judgements

<i>Evidence-to-model link</i>	<i>Link weight</i>		
	<i>Strongly supports/supports</i>	<i>Has nothing to do with</i>	<i>Contradicts</i>
E1_MA	C+	I	I
E1_MB	I	C-	I
E2_MA	I	C-	I
E2_MB	I	I	C+
E3_MA	C+	I	I
E3_MB	I	C-	I
E4_MA	I	C-	I
E4_MB	C+	I	I

Notes: + indicates a strong and correct link and - indicates a weak and correct link.

In the table, evidence-to-model links are coded based on the evidence number (1, 2, 3, or 4) and model (A or B) at each end of the link (e.g., E1_MA therefore shows the link from Evidence #1 to Model A).

4.2 Category 2: Descriptive evaluation

In many of their explanations, students did not clarify reasoning beyond a word-by-word similarity. This was displayed in the form of either a lack of explained reasoning, a connection that required trivial reasoning, or a description of correlation that does not reflect an understanding of evidence-based reasoning. These students make no distinction between evidence and model, and were only finding similarities in topic. Many of the participants' explanations discussed how certain evidence had nothing to do with a particular model. These explanations were often correct, but only tacitly so. In other words, indicating the evidence had nothing to do with a particular model is often a weak level of cognitive processing, with little or no elaboration (i.e., little or no issue-relevant arguments made in the explanation and "superficial or heuristic processing of information" [Dole and Sinatra, (1998), p.121]). For example, one participant wrote, "Evidence #3 has nothing do with Model B because the evidence is about satellites and greenhouses, and Model B is about energy released from the Sun". These types of explanations share some similarity to Chinn and Brewer's (1993) psychological response of excluding data from the domain of the theory. When data are excluded, "they obviously do not lead to any theory change" [Chinn and Brewer, (1993), p.8] nor deep understanding about the topic. Students who consider only the simplest aspects of an evidence text are similarly restricted in evaluating and understanding it. Descriptive evaluations often demonstrated phenomenon-based reasoning, where students made no distinction between a particular line of evidence and an explanatory model. For example, one participant wrote that Evidence #1 strongly supports Model A because "they are both talking about gasses [sic] and greenhouse gases". This student's reasoning was based on

the similarity between the text in Evidence #1 and Model A, with no clear distinction made between the two. In other words, a relationship was identified simply because the evidence discusses the same process as the explanatory model, not for any correlation or cause-effect relationship. Again, these explanations represent a descriptive type of evaluation that participants used to weigh the connections between evidence and explanations.

4.3 Category 3: Relational evaluation

Many of the participants correctly discussed links that had strong connections (i.e., contradicts, supports, or strongly supports) to a particular model. These were indication of a deeper level of processing through demonstration of commitment (i.e., taking a definite positional stance), which in some cases could lead to a greater cognitive engagement (Dole and Sinatra, 1998). However, despite taking a commitment, this type of explanation was often relatively superficial (i.e., lacking depth of analysis). Such an explanation was demonstrated by a participant who explained a strong relationship with simply, “they both [i.e., the evidence and the model] talk about the sun affecting climate.” At best, correct and strong links with superficial explanations reflect a low to moderate level of elaboration because, even though participants are making meaningful connections between evidence and a model, they are still not thinking beyond surface details. These superficial connections may be akin to peripheral cues that are associated with low cognitive engagement (Dole and Sinatra, 1998). These types of participant explanations also showed relation-based reasoning [i.e., the second category in Driver et al.’s (1996) framework]. When students engage in relation-based reasoning, they are associating evidence to explanatory models by making a clearer distinction between the two, but are still focusing on similarity in text more than the implications of its content. As Driver et al. (1996) note, this type of relational reasoning shows that some students think direct correlation implies causation. For example, one participant wrote, “Evidence #1 strongly supports Model A because Evidence #1 talks about greenhouse gases just like Model A”. This example shows how similarity in the discussions of evidence and explanatory models are interpreted based on correlation, but without consideration of the more complex cause-effect relationship.

4.4 Category 4: Critical evaluation

Some participant explanations of strong evidence-to-model links expressed a greater degree of elaboration, reflecting a more analytical approach to the connection between evidence and model. For example, one participant indicated that, “Evidence #3 strongly supports Model A because the satellites are measuring energy being absorbed by greenhouse gases, which makes the Earth’s climate change”. This participant provided an explanation about how a specific mechanism described in the text relates to climate change, and in turn how it corresponds to Model A. In these types of explanations, participants discussed distinctions between lines of evidence and explanatory models, as well as demonstrated more sophisticated types of coherence (potentially involving a nonlinear and/or discontinuous connection). Such explanations reflect model-based reasoning (Driver et al., 1996). For example, one participant wrote that Evidence #1 strongly supports Model A because “human activities have led to a greater release of greenhouse gases....Model A says that climate change is caused by increasing amounts

of human activity". This student identified a more sophisticated cause-and-effect relationship between human activities and climate change, with increased greenhouse gas emissions as the mediating variable. Likewise, another student wrote that Evidence #2 contradicts Model B because "Evidence #2 says that earth's temperature continues to rise without the sun's energy, but Model B says that earth's temperature rises because of the sun's energy". The student was able to clearly differentiate between evidence and explanatory model, and identify how the evidence contradicts the explanatory model. Explanations demonstrating critical evaluation could also concurrently examine the alternative models. For example, one student wrote, "As known, the conflict between the two thoughts [i.e., the models] would show the opposite, usually people would think that evidence 1 would conflict with B, but...my thoughts are from the increased amount of sunspots, the sun gives out more energy, which makes it hot...starting gases from human activity, which also makes it hotter. Showing the two parts are together to make a large answer". In this way, the student was weighing Evidence #1 to Model B (sun-induced climate change), but also considering Model A (human-induced climate change) in constructing the explanation.

4.5 Types of evaluation rubric

Table 2 shows a rubric for the four types of evaluation we identified in our qualitative content analysis. These four categories also represent a natural ordering of evaluation – from a low level of evaluation (erroneous), to a low-moderate level (descriptive), to a moderate level (relational), and a high level of evaluation (critical).

Table 2 Types of evaluation scoring rubric for explanatory tasks

<i>Category</i>	<i>Description</i>
Erroneous evaluation	Explanation contains incorrect relationships between evidence and model, excluding misinterpreting a 'nothing to do with' relationship by elimination-based logic. The explanation may also be mostly inconsistent with scientific understanding and/or include nonsensical statements.
Descriptive evaluation	Explanation contains a correct relationship without elaboration, or correctly interprets evidence without stating a relationship. For example, the evidence-to-model link weight states that the evidence has nothing to do with the model. Explanation does not clearly distinguish between lines of evidence and explanatory models. Explanations could also demonstrate 'elimination-based logic' to come to a positive or negative weight, when evidence-to-model link weight states that the evidence has nothing to do with the model. For example, an explanation states that an evidence supports one model, but uses reasoning that the evidence contradicts the other model.
Relational evaluation	The explanation addresses text similarities, and includes both specific evidence and an associated model or reference to a model. For example, explanation is correct, with an evidence-to-model link weight of strongly supports, supports, or contradicts as appropriate. Explanation distinguishes between lines of evidence and explanatory models, but does so in a merely associative or correlation manner that is often based on text similarity.

Table 2 Types of evaluation scoring rubric for explanatory tasks (continued)

<i>Category</i>	<i>Description</i>
Critical evaluation	Explanation describes a causal relationships and/or meaning of a specific relationship between evidence and model. For example, explanation is correct, with an evidence-to-model link weight of strongly supports, supports, or contradicts as appropriate and reflects deeper cognitive processing that elaborates on an evaluation of evidence and model. Explanation distinguishes between lines of evidence and explanatory models, allows for more sophisticated connections, and/or concurrently examines alternative models.

Participants wrote the greatest number of explanations for the link between Evidence #1 and Model A. Evidence #1 describes how atmospheric carbon dioxide concentrations have increased over time, and how carbon dioxide emissions due to human activities have similarly increased. Model A is the human-induced model of climate change. For this evidence-to-model link, students' evaluations were predominantly relational. This indicates that most of the participants' explanations were accurate, by expressing that the evidence supports the model, but discussed only the similarity in wording between the evidence text and model.

Participants wrote the second greatest number of evidence-to-model link explanations for Evidence #2 and Model B, the only link expressing a contradictory relationship. Evidence #2 describes the association between energy output by the Sun and average global temperatures over the past 100 years. Model B attributes current climate change to increasing amounts of energy released from the Sun. Interestingly, explanations for this link were predominantly erroneous. The fewest explanations were written for the link between Evidence #4 and Model A. Evidence #4 describes paleoclimatic associations between solar activity indicated by sunspots and average global temperatures as measured by tree rings.

5 Discussion

The purpose of this study was to qualitatively examine student's written explanations about the connections between lines of evidence and explanations of climate change. We specifically analysed the types of evaluations that students made in their written explanations when engaging in the climate change MEL activity. Four types of evaluations emerged from the analysis:

- a erroneous evaluations that were inconsistent with scientific understanding
- b descriptive evaluations that only superficially distinguished between lines of evidence and explanatory models
- c relational evaluations that indicated a greater elaborative commitment but still made judgements based in similarity of evidence and model text
- d critical evaluations, where causal relationships between evidence and the alternative models showed the greatest degree of elaboration and reasoning.

A previous study showed that students who completed a climate change MEL expressed greater plausibility toward the scientific model of human-induced climate change, and also greater understanding about the scientific principles underlying the climate change phenomena (Lombardi et al., 2013). This study provides a richer description of the types of evaluations expressed by students when engaging in the activity and some of the reasoning processes which may relate to these gains. Using the types of evaluations rubric as a tool, researchers may be able to gather a stronger line of evidence relating critical evaluation to increased understanding, especially when individuals are learning about the complex topic of climate change. Likewise, as explained below, teachers can use the evaluation rubrics to better understand the meaning making of students as they engage in critically evaluating evidence and models of climate change.

5.1 Implications for instruction

Literacy about climate science inherently involves both the ability to evaluate the validity of information sources and explanations, and a deep understanding of Earth's climate system (U.S. Global Change Research Program, 2009). Such notions of climate literacy helped to formulate a new vision and structure for science education (National Research Council, 2012), which in turn was a foundation for the *Next Generation Science Standards* (NGSS), created by a collaboration involving 26 US states. The NGSS are intended to appreciably deepen students' understanding of science prior to entering college (NGSS Lead States, 2013). Although the topic of human-induced climate change was de-emphasised when translating the vision of the science education framework to the NGSS, there are at least two high school standards that, when taken together, address evaluation of evidence and explanations: Standard HS-ESS3-5, "analyze geoscience data and the results from global climate models to make an evidence-based forecast of the current rate of global or regional climate change and associated future impacts to Earth systems" and Standard HS-ESS3-4, "evaluate or refine a technological solution that reduces impacts of human activities on natural systems" [NGSS Lead States, (2013), p.125]. There is also one middle school standard involving evaluation of evidence: Standard MS-ESS3-5, "ask questions to clarify evidence of the factors that have caused the rise in global temperatures over the past century" [NGSS Lead States, (2013), p.83]. These standards and climate literacy efforts make it clear that instructors need to provide opportunities for students to critically evaluate the connection between lines of evidence and explanations of climate change in order to fully understand the validity of scientific claims that human activities are responsible for global warming. The categories revealed by our qualitative analysis may therefore be a useful tool for instructors to help gauge students' types of evaluation as they learn about climate change.

Students participated in the climate change MEL activity for two lessons, but creating a scientific habit of mind about the topic of global warming would most likely involve repeated use of instructional scaffolds that support active critical evaluation. In addition to MEL diagrams, these scaffolds might include the use of critical questions and argument vee diagrams (Nussbaum and Edwards, 2011), metacognitive prompts (Peters and Kitsantas, 2010), openness to alternatives (Meyer and Lederman, 2013), peer-evaluation of constructed explanations (Wang, 2015), and self-regulation checklists (Peters, 2012). Repeated evaluation of evidence and explanations could help develop students' scientific thinking because a "key activity of scientists is evaluating which...alternative does, or does not, fit with available evidence and, hence, which

presents the most convincing explanation for [a] particular phenomenon” [Osborne, (2012), p.936].

One interesting result suggests that instructors may wish to stress the importance of contradictory evidence in evaluating the validity of explanations about climate change. In this study, students often made erroneous evaluations about contradictory evidence and instructors may need to alert students to be attentive for evidence opposed to a claim. This attention could help strengthen students’ understanding about the process of scientific evaluation and deepen student understanding of scientific content (Erduran and Dagher, 2014). As Bachelard (1968, p.114) states, “two people must first contradict each other if they really wish to understand each other”. Students should deepen their understanding about the nature of science, and specifically, that scientific explanations are tentative (Lederman, 1999). But more importantly, students should know “that alternative interpretations of scientific evidence can occur”, and ultimately “that predictions or explanations can be revised on the basis of seeing new evidence or of developing a new model that accounts for the existing evidence better than previous models did” [National Research Council, (2012), p.251]. Therefore, engaging in critical evaluation may facilitate students’ development of the ability to reason scientifically.

5.2 Implications for public understanding of climate change

Scientists are faced with many challenges when engaging in public communications about climate change. Sinatra et al. (2014, p.134) state that “misunderstanding of science can be at least partly traced to how individuals approach scientific topics, their understanding of knowledge itself, their motivations for holding a particular view, or their motivations to resist change”. These dispositions and motivations are related to cognitive, social, and cultural processes. Furthermore, these processes may be implicit and individuals may be unaware that their judgments, attitudes, and beliefs prevent them from understanding socio-scientific topics, with climate change being a contemporary and very important example. These often implicit “factors hinder rational weighing of evidence and the reflective consideration of alternative explanations – and thereby also hinder change of preexisting ideas” [Sinatra et al., (2014), p.134]. The results of this study support this idea and suggest that scientists should not just strive for clarity, comprehensibility, and coherence when communicating about climate change, but also engage the public in actively considering how lines of evidence support and refute alternative explanations of global warming. A complete focus on just making points that are understandable may stem from a “deficit model of literacy” (Sinatra and Danielson, 2014), which assumes that misunderstandings about climate change are based solely on a lack of information about the phenomenon. However, in addition to more information, individuals need to activate explicit reasoning to effectively evaluate how scientists have come to the conclusion that human activities are the cause of global warming. When communicating to the public, scientists may wish to actively talk about how scientists construct valid knowledge and continuously evaluate the connections between evidence and scientific explanations.

6 Conclusions

This study represents just one step in understanding how students evaluate the connections between evidence and explanations of climate change. As such, the results should be viewed with caution, particularly given how the study participants are drawn from a very specific pool: a predominantly Hispanic middle school with a relatively low socioeconomic status. However, the study does suggest that additional work is needed to understand how individuals evaluate scientific statements about climate change. With evaluation being placed as a pivotal scientific practice in which students should engage (National Research Council, 2012), researchers should endeavour to better understand how to help students evaluate levels of agreement and disagreement between evidence and alternative explanations. Giere et al. (2006, p.31) say that agreement between evidence and explanatory models “may be a matter of degree”. Therefore, evaluation of this connection may be optimised when judging the fit between lines of evidence and an explanation, while simultaneously considering the fit with at least one other alternative explanation. In other words, equipping individuals with the evaluative tools necessary to determine the best of all plausible alternatives is important to help them deepen their understanding of the complex scientific content that is associated with climate change. Such tools may be particularly important for having a society that is equipped to constructively deal with the challenges posed by global warming.

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