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'Let your data tell a story:' climate change experts and students navigating disciplinary argumentation in the classroom

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ABSTRACT

Science education trends promote student engagement in authentic knowledge in practice to tackle personally consequential problems. This study explored how partnering scientists and students on a social media platform supported students' development of disciplinary practice knowledge through practice-based learning with experts during two pilot enactments of a project-based curriculum focusing on the ecological impacts of climate change. Through the online platform, scientists provided feedback on students' infographics, visual argumentation artifacts that use data to communicate about climate change science. We conceptualize the infographics and professional data sets as boundary objects that supported authentic argumentation practices across classroom and professional contexts, but found that student generated data was not robust enough to cross these boundaries. Analysis of the structure and content of the scientists' feedback revealed that when critiquing argumentation, scientists initiated engagement in multiple scientific practices, supporting a holistic rather than discrete model of practice-based learning. While traditional classroom inquiry has emphasized student experimentation, we found that engagement with existing professional data sets provided students with a platform for developing expertise in systemic scientific practices during argument construction. We further found that many students increased the complexity and improved the visual presentation of their arguments after feedback.

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The *Framework for K-12 Science Education* and the Next Generation Science Standards (NGSS) were the first science education policy documents in the U.S.A to position scientific practice on equal footing with science content knowledge (NGSS Lead States, 2013; NRC, 2012). This approach to science learning emerged from the non-profit foundation Achieve's (2010) *International Science Benchmarking Report* that reviewed the science standards and programmes of countries whose students consistently earned high scores on international achievement tests, and found that standards that integrated skills and knowledge through application had the highest levels of student achievement in science

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(Achieve, 2010). It was through this lens that the *Framework* and NGSS developed a three-dimensional science-learning model that partnered specific student performance expectations with related disciplinary core ideas, practices, and cross-cutting concepts around contemporary topics in science, including climate change.

According to the Framework, the term *practices* is used instead of *skills* 'to stress that engaging in scientific inquiry requires coordination of both knowledge and skill simultaneously' (National Research Council (NRC, 2012, p. 41)). This practice turn in science education shifts focus away from knowledge accumulation to its construction and application in context, with the intention of making visible to learners the diverse, everyday, performative aspects of research that comprise the enterprise of scientific discovery (NRC, 2012; Pickering, 1995). This approach extends inquiry-based models of science education by rooting learning in context, with the goal of connecting students to authentic research questions and real-world applications (NRC, 2012). Traditional inquiry approaches to science learning often centred on classroom-based investigations, which positioned students as scientists, but out of the context of the broader scientific community (Olson & Loucks-Horsley, 2000; NRC, 1996, 2012). The result was that science practices were often reified through reductionist models, such as the scientific method, and students had limited opportunities to engage in the important social aspects of learning that emerge from engagement with professional communities of practice (Bruner, 2009). This traditional approach to science education led Collins and Pinch to write that, 'it is no coincidence that those who feel most certain of their grip on the scientific method have rarely worked at the frontiers of science themselves' (Collins & Pinch, 1993, p. 141). Further, formal learning environments also prioritise generalisable representations of scientific knowledge and practices that can mask the actual diversity of application found in professional and community settings (Gutiérrez & Penuel, 2014; Kelly, 2014; Penuel, 2014). As new standards and approaches in and out of the U.S.A work to create more authentic science learning experiences in the classroom, more research is needed to add to our understanding of what knowledge of disciplinary practices looks like in diverse contexts, and how to support the cultivation of teachers' pedagogical content knowledge for disciplinary practices (Davis & Krajcik, 2005), and students' and teachers' *disciplinary practice knowledge*.

Davis and Krajcik (2005) defined pedagogical content knowledge for disciplinary practice as the knowledge that teachers must have to help students understand the authentic activities of a discipline, including an understanding of how knowledge is constructed in that discipline. However, most science teachers and curriculum designers have limited experience with disciplinary communities of practice related to their instructional content areas, which restricts how disciplinary practices are framed and taught in the classroom (Collins & Pinch, 1993; Nussbaum-Beach & Hall, 2011). Building on Davis and Krajcik's definition, we describe disciplinary practice knowledge as the ability of students to engage in the social aspects of science knowledge construction on the boundaries of the classroom and related communities of practice with the support of curriculum-based boundary objects. Boundary objects are artefacts or scaffolds that facilitate boundary crossing between the classroom and professional world. They are flexible enough to be used across contexts without losing a shared meaning between diverse users (Star & Griesemer, 1989). Cultivating disciplinary practice knowledge necessitates innovative approaches to curriculum design and classroom instruction that build on and expand existing project-based, inquiry curricula. Since practices are learned through social networks and access to authentic communities of practice, engaging students in the broad arrangement of disciplinary practices that apply related content knowledge requires curriculum designers and practitioners to engage students in learning experiences beyond the traditional classroom (Nussbaum-Beach & Hall, 2011). Online tools and media including social networking, professional data sets, collaborative learning platforms, and videos of disciplinary communities in real-world contexts can all help situate learners on the boundaries of professional science communities in ways that help students understand the everyday practice and contexts of scientists. This study leveraged these boundary-crossing tools through an online media platform with embedded sociomaterial scaffolds to engage students in authentic argumentation and communication practices in partnership with disciplinary experts around the impacts of climate change on a student-selected species of interest. Our research focused on how a visual argumentation scaffold, an infographic, and shared analysis of professional climate-related data sets enabled disciplinary experts to support students' development of disciplinary practice knowledge for evidence-based argumentation on the boundaries of their shared communities of practice (Bell, 2000; McNeill & Krajcik, 2011). We asked:

1. How did experts model disciplinary argumentation practices for students, and which sociomaterial tools supported boundary-crossing interactions between students and experts?
2. How did students use expert feedback to revise visual argumentation around climate change?
3. How can expert feedback be leveraged to support the development of disciplinary practice knowledge for evidence-based argumentation around climate change in the classroom?

Although our analysis in this paper focuses on NGSS-specific practices, we intend our findings and discussion to apply to a variety of science learning models that partner content knowledge and application in the classroom, specifically around climate change communication and using professional data sets to support evidence-based argumentation.

Learning on the boundaries of disciplinary communities

Our analysis leveraged social practice theory to understand how students became engaged in a system of disciplinary practices as they constructed evidence-based arguments in partnership with disciplinary experts to communicate the ecological impacts of climate change. Social practice theory perspectives describe people with shared practices, professions, and pursuits as a community of practice. This description of learning locates individuals within a broader context in which learning is distributed among people and artefacts that are situated in time, space, and history (Holland & Lave, 2009; Lave & Wenger, 1991; Wenger, 1999). Transparency and visibility can make communities of practice more accessible to novices (Wenger, 1999), but these types of arrangements are difficult to construct within the constraints of formal learning environments. However, the notion of situated learning is beginning to change with increased access to transportation and technology that can remotely position learners on the boundaries of multiple communities of practice (Nussbaum-Beach & Hall, 2011; Wenger, 1999). In this virtual context, learning can be considered situated without being 'situation bound' (Dreier, 1999). Online tools and media including social networking, professional data sets, collaborative learning platforms, and videos of disciplinary communities in real-world contexts can all help situate learners on the boundaries of professional science communities in ways that help students understand the everyday practice and contexts of professional scientists without compromising their existing community memberships or identities (Nussbaum-Beach & Hall, 2011; Wenger, 1999). Boundaries can be exclusive to newcomers, but reification at boundaries can facilitate boundary crossing so that participation in multiple communities at once is possible (Wenger, 1999). Boundary crossing not only enables connections, but can also facilitates the construction of new meanings and practices at these borders (Wenger, 1999).

Boundary objects are artefacts that maintain shared meaning across contexts, and can enable learners to broker knowledge on the edges of classroom and disciplinary communities of practice. Akkerman and Bakker (2011) defined three boundary domains: work, school, and everyday settings, and argued that learning across these boundaries required coordination with the help of boundary objects. In this sense, disciplinary practices such as argumentation should be constructed in ways that allow students to trace a coherent framework of engagement across settings (Barron & Bell, 2015; Bell, Bricker, Reeve, Zimmerman, & Tzou, 2013). Broadening what counts as disciplinary practices allows students to use their everyday knowledge and interests as a foundation for disciplinary learning in ways that are personally relevant and consequential to the learner (Barton & Tan, 2010; Bell et al., 2013; NGSS Lead States, 2013; NRC, 2012). Our definition of disciplinary practice knowledge builds on these perspectives by framing disciplinary practices through both disciplinary and community-based lenses (Kelly, 2014; Penuel, 2014). The curriculum design in this study incorporated everyday technologies including an online platform, social networking, and virtual communication tools to situate high school biology students on the boundaries of related disciplinary communities of practice in ways that leveraged students' existing knowledge and experiences as foundations for science learning. In partnership with scientists, students developed a scientific communication artefact, an infographic, which served as a boundary object to mediate and scaffold scientific discourse between learners and scientists. As students engaged in infographic revisions, they were able to take up elements of expert argumentation practices and apply them to their infographic in ways that built on the students' existing sense-making practices.

Methodology

Study context and participants

This study draws on data from a larger curriculum development project to create year-long courses in Life Sciences and English Language Arts. The curriculum design aimed to reimagine what is possible in a classroom setting by incorporating cutting-edge technologies, social networking, contemporary content, disciplinary practices, and access to world-class experts. Design principles included giving students opportunities to engage in authentic scientific problems and scientific practices such as performing fieldwork, analysing and using computer models, and writing scientific texts. The curriculum used a social media platform that connected students to each other, and also to disciplinary experts.

Both courses were created using a design-based research approach (Barab & Squire, 2004; The DBR Collective, 2003) in which individual modules were designed, implemented, and revised based on findings over the course of two years at several sites in the Pacific Northwest. After each module had been piloted twice, a full year-long pilot was enacted at schools nationwide. This study examines the student–scientist interactions that occurred in the first two pilot enactments of a six-week module on the Ecological Impacts of Climate Change in the Life Science course.

Central to the design of this curriculum was bridging students' out-of-school experiences and interests; leveraging students' existing knowledge, attitudes, and expertise on the subject matter; and positioning youth as developing experts. To this end, this climate change module began by having students surface their initial understandings of and experiences with climate change. Students then examined the portrayals of climate science in the popular media, and analysed the arguments and evidence made by figures on both sides of the social controversy around climate change. Throughout the unit, students conducted fieldwork related to phenological (timing of life cycle) shifts and climate change, investigated a case study of climate change impacts on a species of interest using Geographic Information System (GIS) tools and climate model data, and worked in groups of two to four to create infographics that communicated their findings. During the unit, they received feedback from ecologists and climate scientists on their work, talked with them via Skype, and answered questions about scientific content and careers on the social networking platform. Scientists provided direct feedback approximately every two weeks on three different pieces of student work throughout the unit, the last of which was the infographic draft.

The first pilot implementation occurred from March to April 2011 at Shale High School, an alternative school in a rural town (population ~17,000) outside of a major city. Students at this school tended to be guided there because they were working, parents, or had other circumstances that made a traditional school schedule challenging. Eight students participated in this initial pilot. Students ranged from the 9th to the 12th grade, and the teacher designed her science class so that students could move at their own pace through the curriculum.

We conducted our second pilot study from October to December 2011 in two 9th-grade classrooms at Quartz High School, an alternative school in an upper-middle-class suburb of a major city. Our study took place during the first year that Quartz High School was open, and the teacher was a first-year teacher. In conversations with teachers, students, and administrators, we were told that families chose Quartz High School because of its student-centred pedagogical approach and the opportunity for students to engage in internships during the day. We observed two periods of a biology class, and forty students from these classes participated in the study.

In the climate change pilot enactments, disciplinary experts included ecologists, oceanographers, atmospheric scientists, glaciologists, and others, who reviewed student work, interacted with students via Skype, and visited the classroom. Between the two pilot studies, a total of fourteen scientists – one male professor, two female post-docs, and eleven graduate students (three male, eight female) – reviewed student work, interacted with students via Skype, and visited the classroom to facilitate lessons and as an audience for the final project presentations. For both pilots, the scientist–student interactions occurred at the same points and were facilitated in the same way, and the same scientist worked with a student group throughout the unit; while curricular materials including student scaffolds were changed slightly between pilots, the overall assignment and framing of the assignment remained the same.

Data sources

This study targets the interactions between scientists and students that occurred during the two pilot enactments. Specifically, we analyse:

1. *Scientist feedback on students' infographic drafts* (5 from Pilot 1, 17 from Pilot 2). Students uploaded their draft work to the social media platform for review (Figure 1). Scientists reviewed the work and provided feedback to student groups on how to improve the infographic. Feedback usually consisted of either track-changes comments in a Microsoft Word document or comments on a pdf, in addition to long-form comments in an email. In both enactments, scientists were instructed how to use the social media platform, told what the assignment was, and encouraged to be positive and constructive in their comments.
2. *Student infographic drafts* (17 from Pilot 2). Infographic drafts from the second pilot were analysed, including matched sets of students' initial drafts and revised drafts completed after receiving scientist feedback.

Analysis

Documents containing student work and scientist feedback and transcripts of scientist–student interactions were analysed using the online mixed-methods software Dedoose. Feedback was coded first. We began with three main parent codes: *Content*, *Practice*, and *Values*, and added sub-codes based on scientist feedback using an open coding process (Strauss & Corbin, 1990). Child codes in parent code *Content* encompassed the ways scientists supported student conceptual understandings, including providing just-in-time content, clarifying concepts, asking questions about content, etc. For parent code *Practices*, we began with child codes based on the eight science and engineering practices included in the NGSS and further built out this coding structure to nuance dimensions of these practices (e.g. *counterarguments* or *logic/organisation* as child codes to the *Argumentation* practice). In the parent code *Valuing*, we captured each time scientists highlighted a particular aspect of student work as important, scientific, or valuable (e.g. *Valuing specificity*, *Valuing the topic or idea*). A key move of the scientists was to ask various kinds of questions; so the parent code *Questions* was added and child codes were created emergently to describe the questioning moves scientists made (e.g. *Wondering or speculating* – a question for which the scientist does not appear to know the answer, *Source of information* – asking where data or information came from). Each line or sentence of feedback was coded as an individual excerpt; excerpts could and often did have multiple codes. After this coding iteration, co-occurrence of codes indicated emergent themes around interrelation of practices and connection of practices to content, values, and scientist questioning. The data were then analysed through a practice lens to connect specific scientist feedback types and value statements to disciplinary practice. Using that lens, we organised all excerpts related to a specific science and engineering practice, including any codes that fell under the parent code for that practice and any *Valuing*, *Content*, and *Questions* child codes that co-occurred with that scientific practice. Below, we report our findings in thematic arrangements guided by the NGSS science and engineering practices. Our finding headings reflect the facets of the practice that were most apparent in and elucidated by the data.

The 17 matched student infographic initial/final pairs were analysed through the comparison of initial and final versions using an emergent coding strategy. Codes were generated to represent the changes that students made from one version to another, such as removing or adding visual elements and text, or changing visual elements (e.g. colour and shape). In addition, both the initial and final work were scored using a five-item rubric, with scores ranging from 1 (low) to 4 (high). The rubric included the quality of the visual communication, a connection to human relevance, the presence and quality of comparisons between disparate types of evidence, the depth of student explanations, and the logical construction of the argument. The mean and standard deviation for each rubric category were calculated for the initial and final drafts, and the change between the drafts.

Both authors coded all data in a collaborative, iterative process. For both scientist and student data, after the coding structure was established, each researcher made an individual pass through the data and coding was compared for validity. In instances in which researchers' codes differed, a consensus was researched after discussion and triangulation across data sources. Assertions were generated based on emergent themes from the triangulation of sources and we searched the data corpus for disconfirming evidence (Erickson, 1986).

Findings

Student work

Every student or student group made at least one change to their infographic between the initial and final drafts, with students making on average four of the *types* of revisions coded for (e.g. adding a graph, and removing a visual element), with multiple possible occurrences of that type of revision (i.e. adding two graphs). The most common types of changes between initial and final drafts are summarised in Table 1. All students or student groups added some kind of text to their infographic, with seven groups adding text that was directly related to explaining, analysing, or discussing data presented in a graph and all seventeen groups adding text to support their claim, provide new evidence, or develop reasoning that was not directly related to a graph. More than half the groups also added data in the form of graphs to their infographic in the revision process, and more than half reorganised or rearranged the visual elements to improve visual communication. Common changes students made also included adding figures that were not graphs, including maps or pictures of animals, or removing elements from their infographic.

In rubric-scored ratings, 16 of the 17 infographics scored higher on at least one category in the final revision compared to the initial draft. While the average score for each criterion

Table 1. Student changes to the visual elements and text of their infographics between the initial and final drafts, including the revision type and frequency ($N = 17$).

Revision type	Description	Frequency	Percentage (%)
Visuals			
Graph	Addition of evidence in the form of a graph	11	65
Figure	Addition of evidence in the form of a figure other than a graph	4	24
Removal	Removal of a graph, figure, or other visual element	6	35
Reorganisation	Rearrangement of the display of visual elements and/or text	10	59
Text			
Explanatory text – graph	Adding explanatory text that corresponds directly to a graph	7	41
Explanatory text – other	Adding text to an explanation that does not directly relate to a pictured graph	17	100

rose between the initial and final drafts, due to the variance in student scores and the small sample size these changes should not be interpreted as statistically significant. Rather, the mean and standard deviation are presented to show the range in student work (Table 2).

Of the criteria examined, the one that was most often improved upon in the revision was *Evidence Comparison*, with 9 of 17 student groups increasing their score. This was due to an increase in the type of data used by students, such as adding graphs, and an increase in text that explained and made connections between new and existing types of evidence. The second most common improvement was in *Depth of Explanation*. This improvement often resulted from students adding in a component for *why* something happened (a mechanistic, theory-grounded explanation) in addition to a descriptive account of *what* was happening or *how* it was happening. Improvements in the *Logic* criteria (6 out of 17 infographics) reflected incorporation of additional or more valid reasoning in addition to their claims, and an increase in the consideration of counterarguments. Most infographics did not take into account variance or error, so even if students improved their logic, few attained the maximum rating in that category.

Table 2. Rubric categories and scores of student work on initial infographic drafts and final infographic drafts post scientist feedback, with standard deviation and the number of student groups ($N = 17$) that increased within a rubric category.

Category	Description	Average initial score ± SD	Average final score ± SD	# Students with increased scores
Visual communication	Message and data are appropriately represented, well laid out, accurate, and easy to read and interpret	2.8 ± 0.5	3.1 ± 0.6	4
Connection to humans	Clear and persuasive statement about why the species and impacts are relevant and consequential to humans	2.2 ± 1.0	2.5 ± 0.9	5
Evidence comparison	Comparison of multiple kinds of evidence and consideration of counter-evidence	2.5 ± 0.9	3.1 ± 0.9	9
Depth of explanation	Student describes how and explains why something happens; explanations include links between observable data and theoretical constructs	2.6 ± 0.6	3.2 ± 0.9	8
Logic	Student constructs a logical argument including a claim, evidence, and reasoning that is appropriate for the degree of certainty in the evidence; addresses counterarguments and accounts for variance and error	2.5 ± 0.5	2.9 ± 0.6	6

Despite the number of students who changed their visual display by adding, removing, or reorganising evidence, only 4 of 17 groups increased their rubric score on this item. This was because often the reorganisation or rearrangement did not improve the clarity or accuracy significantly.

Of the 17 groups, 5 increased in *Connection to Humans.* Many initial infographics were missing a connection to human interests, and increased scores generally occurred in cases in which a group who had not mentioned humans added in text about the consequences for humans. Fewer students who had mentioned human relevance in their initial draft added significantly to that area in their final draft.

Example: examining the initial draft–feedback–revision process

The Hawaiian monk seal infographic (Figure 1) is used as an example case to explore the relationship between student revisions and scientist feedback (Table 3). This case provides an example of one scientist's input on an initial draft and how students did or did not make revisions to their infographic in response to comments. In responding to the feedback, the students made many of the common revisions, including adding additional explanatory text, changing visual elements, and revising features such as a graph and images of species (Figure 1). Many of these changes are directly related to specific feedback from the scientist (Table 3).

In her comments, the scientist critiqued both the scientific evidence presented and the visual presentation of the evidence. In addition, she provided ideas about how to improve the infographic as a communicative artefact. For example, she critiqued the initial title for lacking specificity and not capturing the main objective of the poster. In their revision, the students used an altered version of one of her suggested wordings for the title. The scientist also made several suggestions about the type of evidence used, such as the value of including data about sea level rise in the future, the timescale of sea level rise, and more scientific evidence supporting the students' claims about the impacts of sea level rise on monk seal's breeding. The students addressed these concerns in their final draft by changing their graph to one that included sea level rise, and adding or revising text about timescales of change and the impact of sea level on breeding. However, the scientist made several specific suggestions about types of scientific evidence that could strengthen the students' claims, such as 'topography' and 'observations from biologists' that the students did not incorporate. In addition, the scientist included an 'Other thoughts' section that consisted of open-ended questions about possible factors to consider and avenues to consider: 'Did you get a chance to look into increased predation from sharks? Did you get a chance to research a little about how ocean acidification might impact the food sources of Monk Seals?' There was no evidence of these more speculative, open-ended questions being addressed in the final version.

The scientist made several suggestions about visual presentation that are reflected in the final version. For example, though she said she was 'a huge fan of bold, bright colors!' she suggested 'playing around with the colors to get a better contrast' to make the infographic more readable. The students changed their background colour from green to blue, resulting in a higher contrast and greater readability. She also pointed out elements of the graphic that were confusing to her, including the location of some of the errors and the

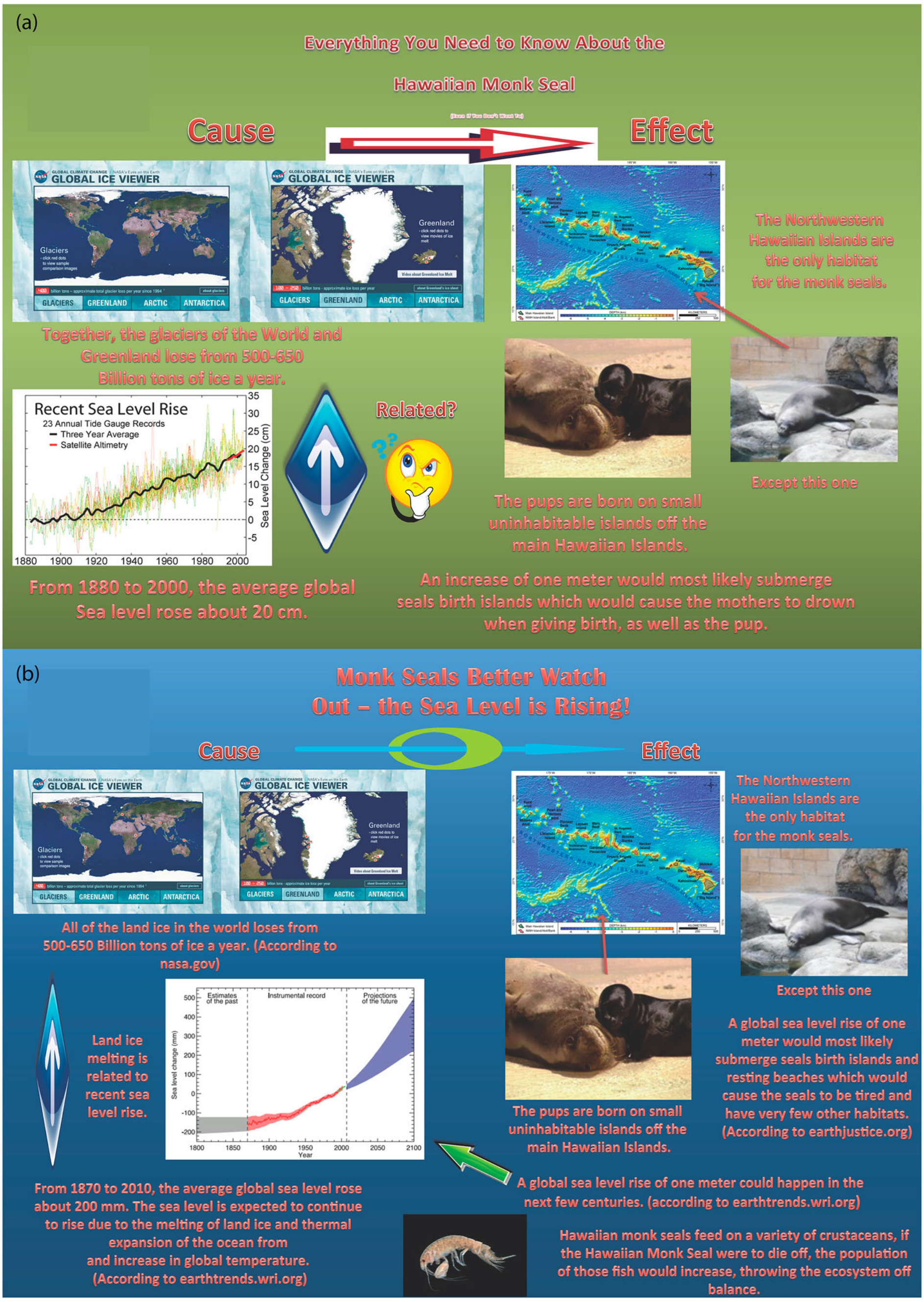

Figure 1. An example of a student group's (a) initial and (b) final versions of their infographic on the Hawaiian monk seal. Circled numbers correspond to sections of the infographic that received feedback from experts, as shown in Table 3.

presence of an icon. Her arguments about these elements were framed as improving the logical structure of the claims (what might 'make more sense') and the infographic's ability to communicate effectively ('it might confuse other readers'). She summarised

Table 3. Case study of initial and final infographic drafts and scientist feedback for the Hawaiian monk seal infographic shown in Figure 1. Numbers correspond to the number of changes in the infographic drafts in Figure 1. A description of the relevant parts of both the initial and the final infographic and the scientists' comments that address that part of the infographic are displayed. Note that not all changes or feedback are included in this table.

Number	Initial draft	Scientist feedback	Final draft
1	Title: 'Everything You Need to Know About The Hawaiian Monk Seal'	'Think about a title that reflects the main point of the poster – certainly "Hawaiian Monk Seal" is a necessary component of the title, but maybe you want to cut the first part "Everything You Need to Know About the" since the poster doesn't go into details like diet, lifespan, evolutionary history, etc. Perhaps something like "The Effect of Climate Change on Populations of Hawaiian Monk Seals" or something funny like "Hey Monk Seals, You Better Watch Out – the Sea Level is Rising!" as long as it reflects the main objectives of your infographic.'	Title: 'Monk Seals Better Watch Out – the Sea Level's Rising!'
2	Explanatory text: 'Together, the glaciers of the World and Greenland lose from 500–650 Billion tons of ice a year'	'Who said that glaciers of the World and Greenland (why list both – Greenland is in the World isn't it?) lose 500–650 billion tons of ice a year? I want to know because that is a big number and I might not believe you unless you provide a source!'	Revised text: 'All of the land ice in the world loses from 500–650 Billion tons of ice a year. (According to nasa.gov)'
3	Graph showing 'Recent Sea Level Rise' from 1880–2010.	'You use evidence from the past 120 years of sea level rise – but go one step further and suggest that there will continue to be sea level rise from ice melt (you didn't include this but thermal expansion due to warmer temperatures will also play a role in sea level rise – maybe you can fit that in?) … where did the recent sea level rise graph come from?'	Replaced original graph with one showing estimates of the past, instrumental record and projections of the future.
4	Description of graph stating that sea level rose over the time period.		Addition of text that describes the mechanism by which sea level rises, and addition of a citation.
5	Blue arrow and icon of person scratching head with question marks and word 'related?' by an upward arrow.	'The Blue arrow on the left bottom I think is emphasising that sea levels rose – or is it there to make a connection between the recent sea level rise, and sea level rise that might happen in the future? Since it isn't clear to me – it might confuse other readers, think about if you really need that arrow.' And 'What is the dude doing scratching his chin? And what is he asking about? Related? Is what related?'	Repositioning of blue arrow, removal of icon, and addition of explanatory text: 'Land ice melting is related to recent sea level rise.'
6	Impacts explanation does not indicate what the timescale for impacts might be.	'Can you use the information … to predict when will sea level increase by 1 meter in Hawaii?'	Addition of text about sea level rise of one metre happening in the 'next few centuries'
7	Discussion of where monk seals live, but no direct connection made to how sea level rise impacts them.	'Your Effect section is pretty straightforward. However, you don't actually use any scientific evidence to back up your claim that mothers will drown when giving birth, or that their breeding grounds will be covered. All you need to do is provide information about the topography of the seal's present breeding grounds, and maybe some observations from biologists that suggest it is impossible for seals to give birth in the water. You also don't consider counter arguments to your claim – (can't the seals just migrate to another island that isn't drowned to give birth?).'	Revision of placement of wording of text and addition of wording about 'resting beaches' and 'having few other habitats'
8	No reference made to Hawaiian monk seal's place in the ecosystem or relevance to humans	'Why do I care if all the Monk Seals die? Maybe I don't care at all … Does there existence support any other life? Do they keep crab populations in check so the crabs don't eat all the snails or something? Total speculation but maybe they serve some role that humans care about.'	Text added about Hawaiian monk seals' diet and consequences of extinction on ecosystem balance

her visual feedback as: 'Everything on your graphic should serve a specific purpose to get your point across – otherwise it is confusing and busy.'

Overall, from the initial to the final draft, the students made changes that increased the depth of explanation of phenomena, increased the amount and type of evidence used, and improved the visual display. This student group initially received rubric scores of one in Connection to Humans, two in Evidence Comparison, and three in Visual Communication, Depth of Explanation, and Logic. In their revised version, rubric scores in Logic remained the same and scores increased to a two in Connection to Humans, four in Visual Communication and Evidence Comparison, and 4 in Depth of Explanation. Many changes were tied directly to specific critiques in the scientists' feedback. However, not all of the suggestions made by the scientists were addressed in the revision.

Characterising expert feedback

In analysing expert feedback, we created 328 excerpts from the 22 instances of infographic feedback. The number of excerpts per infographic varied from 6 to 32, generally depending on how much feedback a scientist had provided. The amount of feedback by the scientists depended on several factors, including the critique styles of individual scientists, the file format of the student work or feedback (pdf files generally received fewer comments than other formats), and the level of completion of the student draft (more complete drafts tended to receive more and more nuanced feedback).

In their critiques, scientists modelled ways in which they would approach a problem or improve the argument or communication. Scientists asked open-ended questions that revealed their own thought processes through wondering or speculating, evaluating the effectiveness of evidence or visual elements, and asking probing questions that suggested further avenues for research. In some cases, they also made direct references to what scientists do, though that was less common.

In the infographic assignment, students were asked to create a 'visual representation of a scientific argument'. As such, the initial focus for the assignment was on the argumentation and visual communication practices. In the feedback from the scientists, however, the construction of successful arguments and communication artefacts was deeply entwined with other scientific practices. In fact, scientists' feedback included connections to every other scientific practice described in the NGSS. Below we describe the intersections of the practices as seen in the scientists' feedback, as well as the habits of mind that both supported and transcended the specific practices.

1. *Wondering, Speculating, and Asking Questions.* Scientists' open-ended questions allowed them to engage with student work by using the evidence students provided as a starting point for further investigation. In doing so, they revealed their own problem-solving processes. For example, in the case described above, the scientist responded to a student group's work on sea level rise and the monk seal by considering other climate parameters that could be affecting the monk seal:

> I wonder if rainfall plays a major role in the Monk seal life … for instance – do they only go to the breading[sic] ground during the dry season or the wet season? If you can figure that out – then you might be able to argue that a change in climate can lead to a change in rain patterns and that might have some sort of impact on the seal life cycle?

In this excerpt, the scientist pursued a line of thought that would supplement and fortify the students' initial argument about the impact of climate change on monk seals by providing a second line of evidence about impacts. She 'wonders' if changes in rainfall could potentially have consequences for the monk seal's mating. This is an open-ended, speculative question in that it is not a question that the scientist knows the answer to *a priori*. Instead, she modelled what her own practice would be in theorising about relevant variables and interactions, offering a hypothesis that she encouraged the students to 'figure out' if it was supported or not by available evidence. If it was supported, the scientist suggested that having multiple lines of evidence would improve the argument.

As opposed to a standard view of scientists as sources of information, through wondering or speculating questions, scientists did not supply any new 'facts' or evidence; instead, they demonstrated how they would approach thinking through possible relevant interactions and evaluating whether or not evidence supported a particular argument. In another instance, a scientist made a connection between the students' work and the kinds of open questions he himself and another scientist pursued in their own research. In this case, the students' argument included warming, but did not include precipitation. The scientist asked the students what they thought might happen if both variables changed:

> What if it started raining harder and harder, at the same time as it gets warmer over the next century? (This question is closely related to my own research, and to [name of another scientist]'s research!)

In this question, the scientist presented a scenario for changes (increased warming and temperature) that could have the same or a different impact on the species the student was considering, and asked the student to consider this new scenario. Like the previous example, the scientist did not necessarily know the answer to the question he was asking. This is underscored by the connection he made to ongoing scientific research in the second sentence. By drawing this parallel, he not only modelled his own thought process, but also positioned the students' work as connected to an authentic problem and demonstrated how scientists are currently investigating climate and ecological changes.

The two above examples demonstrate the connection between two key practices in the NRC *Framework* and the Next Generation Science Standards: asking scientific questions and developing arguments from evidence. In their feedback to students, scientists modelled their own open-ended question-asking practice. Asking these questions was a necessary step in developing rigorous, convincing arguments by obtaining additional evidence and pursuing alternate contingencies.

In many instances, scientists asked questions that were open-ended, but it can be reasonably assumed the scientists already knew the answers, either in full or in part. These were coded as 'probing questions' and were the most common question type. These kinds of questions also modelled scientific questioning practice, and supported argumentation through the elucidation of pathways to evidence that students could use in their infographics. Feedback of this type included questions like the following:

> Do you think sea ice changes might be connected to changes in temperature?

> What is the evidence that South America has already been getting warmer because of global warming?

> Here are some questions a critic might ask in response to your statement above: Why is it a problem that temperatures will increase in areas where the lynx and hares live? Aren't there places north of where the lynx and hares live that are too cold for these animals right now but will become suitable with warming? Couldn't the lynx and hares just move north from their current habitat to this new habitat and be fine?

Through these kinds of questions, scientists modelled their own process of building arguments, as they highlighted the need for more evidence, more explanation, or clearer logic. In the third example, the scientist also introduced the idea of thinking like a 'critic' or a critical third party. The ability of a scientist to anticipate counterarguments is an important aspect of scientific argumentation, and here the scientist modelled how to think about an argument from multiple perspectives. The most common theme throughout the probing questions was a call for more evidence to support the arguments. Scientists consistently commented on how important evidence in general, and specific kinds of evidence were in crafting arguments. Asking questions was an integral part of determining what kind of evidence could or should be used to strengthen the argument.

2. *Analysing, Interpreting, and Using Data and Mathematics to Construct Arguments.* In their infographics, students used a variety of visual elements, including maps of species' ranges, climatological variables, and time-series graphs of various factors. In order to create a convincing infographic, students needed to use quantitative and qualitative data to support their argument. Scientists critically examined the data students used, how the students interpreted the data, and whether there were data the students had not included that would be helpful for their argument, leveraging two practices described by the NGSS in support of argumentation: (1) analysing and interpreting data and (2) mathematical and computational thinking. For example, scientists provided feedback on the alignment between the data used and students' interpretation of the data in their text. In one instance, a student showed graphs of temperature and carbon dioxide, but did not provide any interpretation of those data. The scientist's feedback reflected the need to further explore the meaning of the graphs: 'The top graph shows both CO2 and temperature over the same time period as the bottom graph. How are temperature and CO2 connected?' In this statement, the scientist not only encouraged the student to explain the data, but also analysed potential connections between the two data sets.

Scientists emphasised the value of data and graphs in argument construction, noting both instances when it was missing and instances when it was present. For example, in one infographic, a scientist suggested a student's argument about species impacts due to sea ice loss would be more convincing if data were shown: 'Can you show any evidence for how sea ice has been melting and how we expect it to melt in the future?' This statement encouraged the student to quantify their initial claim that sea ice is melting. In another infographic, the students had included maps showing how sea ice had changed over time, and a scientist noted that this made the argument strong: 'The maps of sea ice change are especially important pieces of evidence supporting your argument about polar bears.' Providing and appropriately interpreting data, and having congruence between graphics and text were noted by scientists as valuable components of argument construction practice.

3. *Scientific Explanation in Argumentation and Communication.* Constructing a persuasive argument relies on sound explanations of the relevant data, relationships, and phenomena. The infographic assignment required students to both explain the scientific evidence and use it in an argument about how climate change might affect ecosystems. In their feedback to students, scientists critiqued the explanations for completeness and correctness, offered supplementary information that supported student explanations, and made suggestions about how to improve coherence between the text and graphics for explanations.

Many of the statements scientists made in their feedback on explanations were coded as both *Content* and *Constructing Explanations* (child code of *Practice*). One move scientists made to support student explanations of content or phenomena was to restate the explanation in their own words, for example:

> You propose that salmon will be negatively affected by climate change due to its impacts on snowmelt, which results in increases in the acidity of the water and removes calcium from the gills of the fish.

In this example, the scientist restated the students' chain of evidence for how climate might impact salmon. However, the scientist's restatement was in a language that was both more concise and incorporated academic phrasing and vocabulary.

Scientists also added comments with supplemental factual information that expanded student explanations. For example, one student group proposed that the Canada Lynx and snowshoe hare would not be able to shift their range north because they already live at high latitudes. The scientist giving feedback added in a comment: 'In addition, the area north of the lynx's range is mostly tundra and lynx are found mostly in forest.' This statement provided new information that not only supported the students' argument, but also built their explanation of constraints on range shifts. In some cases, scientists provided explanations or information that corrected errors in student explanations. For example, in a comment on one group's explanation of the greenhouse effect, a scientist made a distinction between re-emitted and reflected light: 'The "Reflected photons" aren't actually "reflected" but are "re-emitted" (and in all directions, not just down).' By providing this just-in-time content, scientists provided input aimed to help students create more thorough and conceptually accurate explanations.

Scientists also pointed out places that students could improve their argument by incorporating more scientific explanations. For example, in one instance, a scientist encouraged a student to investigate and explain the impacts on plant growth in more detail:

> You might want to help the reader make the connection between climate change and plant growth by explaining some ways climate change might affect plants – what are some things plants need that might be changing?

In this instance, the scientist specifically guided the student to consider what would be helpful for 'the reader' – thus, this scientist was concerned with explanations needed to communicate the student's argument to a third party. Scientists also noted when the text and graphics did not align, specifically when explanations of figures and graphs were missing. Examples include:

> I really like the figure you chose to show the decline in sea ice extent, which you could use to help support that argument by explaining in the text what you want the reader to learn from the figure.

> It is always good to orient the reader to your figures and explain why you show a certain thing. A figure without a clear explanation can be misleading and confusing.

In the first instance, the scientist praised the figure and evidence chosen, but pointed out that in order for the infographic to successfully communicate to the reader, an explanation would be helpful. The scientist was also concerned with the reader's interpretation in the second instance. In this case, the scientist found the students' figure confusing and suggested that they add more information and an improved explanation of what the figure and the components of the figure (e.g. colours and shapes) were. In both of these instances, scientists' feedback centred on the importance of not only including data, but also explaining it well in order to clearly communicate to an outside audience.

4. *Models in Argumentation.* Projecting future climate changes necessarily relies on models. One of the most common models students chose to use were maps of climatological parameters. Students had access to two different online software programs that could overlay current and future climatological parameters on global and regional maps. Students used future modelled temperatures in these visual map models as key elements in their infographic. On one infographic, a scientist commented on the efficacy of maps as visual models the students appropriate and supported the argument: 'I really like this, because you showed both global evidence (the global temperature graph) and local evidence (the maps … zooming in on South America).' In this instance, the scientist's feedback emphasised that having two lines of evidence represented by two different maps (complementary models) strengthened the argument.

Scientists also pointed out limitations of the models the students were using and suggested the use of supplemental models. For example, one scientist suggested that the model the student used was not sufficient to create a strong argument. In this case, the student had included a graph of potential future changes, but not models of current changes. The scientist pointed this out, saying: 'One thing scientists might say, though, is that the [model of future changes] maps show what is going to happen … but what has already happened?' Though the climate model provided some important information, it was limited in its scope, and a scientist critically examining and presenting this evidence would look to other models to better understand the phenomena.

5. *Designing and Carrying Out Investigations and Argumentation.* In the unit, students designed and carried out an investigation into the effect of changing climate parameters (e.g. temperature and water) on the phenology and fitness of Wisconsin Fast Plants, a fast-growing *Brassica* species. They also conducted fieldwork on phenology through the National Phenology Network citizen science effort. While students reported that they enjoyed both activities and were encouraged to use their own data, students did not use the data they collected themselves through these investigations on their infographic. Rather than using their own data, they pulled data

from established data sets, such as the climate model results discussed above. This deviates from a common inquiry model in science classrooms in which students carry out their own investigations through physical manipulation. Instead of using their own results, students engaged in an investigation more similar to data mining, in which individuals query existing data to answer questions. This is an authentic practice in climate science, as much work is conducted as an analysis of large, shared data. The feedback scientists provided on this kind of investigation overlapped with feedback on data analysis, use, and interpretation, and there were no instances in which scientists gave specific feedback on how to carry out empirical investigations or collect data.

6. *Obtaining and Communicating Information through Multimodal Arguments.* The infographic assignment provided students with the opportunity to employ multiple modalities in the construction of their argument. This is congruent with common scientific communication practices in which both visual elements (e.g. graphs, tables and pictures) and text are used. One scientist noted the authenticity of the infographic product as similar to scientific poster presentations. She used the idea of a story to frame the construction of a poster (or infographic):

> When scientists give a presentation, they think of the presentation like a story. We often give poster presentations, which is exactly what you're doing. Poster presentations can be hard, though, because someone has to be able to look at the poster and understand the story that you are telling.

In this comment, the scientist positioned the student's work as part of a real scientific practice and also provided insight into how a scientist might think about constructing a poster. A 'story' provides a different connotation from an 'argument' or 'infographic'. In the story, like in a picture book for example, the text and visuals work together to relay a message. This, the scientist notes, can be challenging. In the rest of her feedback, the scientist gave suggestions of how to visually tell the story. For example, the scientist suggested displaying 'facts' with the 'pieces of analysis' that go with each fact next to each other so that 'the person reading it understands they go together'. She suggested adding additional visual elements that would also help tell the story: 'You could even draw an arrow between the facts and analysis or put a box around them so that it's very clear that they're connected.' This feedback highlighted the role that the design of the infographic has on its success as a communication tool.

Many scientists made comments about the appropriateness of visual elements, and the placement and arrangement of the elements, and suggested new visual elements to include to improve either the ability of the infographic to communicate to a particular audience, or the validity of the argument. For example, scientists evaluated whether or not visual elements actually provided support for the argument. Referencing the inclusion of a map of Florida sea level rise in an infographic about polar bears, one scientist asked: 'Are changes in Florida relevant to polar bears?' suggesting that the visual element might not be appropriate.

In some cases, scientists made comments about visual elements they thought would be appealing or helpful to readers from a communication standpoint. One scientist suggested including a 'graphic of some of the prey of polar bears living on the ice too, to help your readers make the connection (they might not know what polar bears eat!)'. This suggestion was of a picture, not data or what would normally be considered 'scientific evidence', and its role was to aid in the reader's interpretation of the infographic.

Finally, some scientists provided feedback on how to use visual elements to explicate the logic of an argument. For example, in one instance, a scientist commented that students' discussion of the greenhouse effect could be made more clear using arrows: 'Maybe you could make this logic clear with arrows from cars to petroleum use to increased CO2 to a warmer Earth to dying trees somehow.' This kind of feedback modelled how scientists considered visual flow; that is, how the reader should follow and interpret the elements provided in the visual scientific story.

One key aspect of scientific practice is obtaining relevant, reliable data and information to use in an argument. In some instances, scientists actually did the legwork of finding useful pieces of information for students, and then shared both their information and their process with the students. In these cases, the scientist might point out evidence that was missing and could be useful, and then supply an avenue for the student to obtain that evidence. Examples include:

> And how much precipitation is there? Hint: I looked at this link for Barrow, AK weather: [website link redacted]

> I just googled it (you could too) and found a kind of interesting website: [website link redacted] this talks about biodiversity and why it is important. A link from there is specifically about corals: [website link redacted].

> You are talking mostly about temperature and the two are very related but it would be great to use a temp graph (the IPCC has some great ones if you google something like 'IPCC climate warming graph' or do a google image search).

In each of these, the scientist identified an element that would improve students' argument construction: precipitation in Alaska, the importance of corals for biodiversity, and graphs of temperature over time. The scientists then described a possible resource, and in the last two cases described how they found their information. While 'googling' something may not at first glance appear scientific, there is significant expertise demonstrated in both of the examples presented. In the biodiversity example, the scientist identified the site she has found as 'interesting'. In doing so, she is placing this particular site as of potentially higher value, more scientific, or more helpful than the other sites the students might see in a Google search, drawing attention to one site out of a large number of possibilities. In the second example, the scientist gives a suggestion for how the student might use Google to obtain a scientifically appropriate result by providing the correct language ('IPCC climate warming graph') and suggesting a particular feature (image search). In this way, the scientists are modelling how to use a familiar tool – Google – in a scientific way by using appropriate language and evaluating the results. These results can then be incorporated into their infographics, combining the practices of obtaining information and argumentation.

In their feedback, scientists presented themselves as learners and demonstrated enthusiasm about their own learning processes, as related to the NGSS practice of obtaining information. Scientists pointed out when students taught them something or caused them to learn something new. One scientist stated early in her feedback: 'I'm excited to see you add to your infographic so I can learn more about how climate change affects the Harlequin poison frog!' This statement positioned the students as capable of taking on an expert role, with the scientist in a learner role. Further, the scientist is 'excited' to learn more. Unlike the common view of scientists as experts and keepers of facts and correct answers, this scientist positions herself as someone who does *not* know everything but is instead an enthusiastic learner.

Scientists not only demonstrated their own learning processes, but also communicated through their expressions of excitement and enthusiasm the centrality of learning, exploration, research, and investigation to their work. One scientist tells the students that their work was of such high value, it prompted her to learn more:

> I thought the data you explained was so interesting I looked up the scientific paper (by M. Zhao and S.W. Running, published in Science in 2010) showing that terrestrial plant growth had decreased between 2000 and 2009 and found this figure that I thought you might like to see.

Here, the scientist uses the paper he has found as a conduit for discussion around scientific phenomena (plant growth). In their exit surveys and interviews, scientists confirmed that one thing they liked about participating in the project was being able to learn about new things.

Discussion

Expert feedback guides students' scientific stories

The goal of this climate change unit was to develop students' disciplinary practice knowledge of climate change argumentation through a sociocultural lens of learning that allowed students to make sense of climate change data in ways that were congruent with their existing knowledge, identities, and interests, but grounded in scientific evidence. In partnership with scientists, students were able to take up disciplinary models of argumentation that significantly improved their infographic scores, and were able to incorporate recommendations that built on their existing argumentation and sense-making practices around climate change science. Before receiving and incorporating expert feedback, the students' visual argumentation artefacts reified traditional school-based representations of scientific experimentation and inquiry (Windschitl, Thompson, & Braaten, 2008). Students' initial infographic designs often constructed arguments based on single variable, cause-and-effect relationships, such as the effect of direct temperature shifts on a single species. In contrast, the scientists modelled multivariate and systems-thinking approaches to scientific argumentation and encouraged students to seek out additional forms of evidence to support their claims. The process of seeking out additional evidence engaged students in a holistic set of scientific practices in which the construction of strong scientific arguments inherently relied on other scientific practices such as constructing explanations, asking questions, or using mathematical and computational thinking. This suggests that scientists brought students into a holistic set of scientific practices, in which learning one practice was embedded in engagement with multiple practices. The notion of using evidence-based arguments to 'tell a story' fuelled further engagement with a set of practices when the story's accuracy or coherence required more evidence or explanation. These findings place the eight NGSS science and engineering practices in a connected framework of instruction in which practices are intrinsically connected in the process of scientific sense-making both professionally and in the classroom (Bell, Bricker, Tzou, Lee, & Van Horne, 2012).

During infographic revisions, students chose which aspects of expert feedback to incorporate in their revised drafts. The option to selectively include scientists' feedback enabled students to construct personally relevant arguments that incorporated knowledge across multiple settings including the home, classroom, and professional contexts. Working on the boundaries of these diverse communities of practice created a hybrid argumentation space that enabled students to engage in practice-based learning in the classroom without having to adopt a predetermined lens for their arguments (Roth & Barton, 2004; Rosebery, Ogonowski, DiSchino, & Warren, 2010; Walsh & Tsurusaki, 2014). While selective uptake of expert feedback gave students authorship over their final infographics, it also surfaced potential limitations of practice-based learning in traditional classroom settings. Scientists regularly suggested alternate and additional lines of research for students to follow as a way to gather additional evidence in support of their arguments; however, constraints around classroom time, project deadlines, and available resources restricted students' ability to extend the research process to generate more evidence for their claims. In these bounded settings, expert framing of disciplinary argumentation became particularly important as it modelled the iterative and holistic process of argument construction in science, and enabled students to observe disciplinary community practices from the boundaries of their own classroom even when they could not engage in extended research processes themselves. Wenger (1999) refers to this as an immersion boundary, a one-way connection that allows onlookers to visit a practice in authentic settings. Teachers with strong pedagogical content knowledge for disciplinary practices can act as brokers along these immersion boundaries to help students reify disciplinary practices for their own use in the classroom.

Expert-framed pedagogical and disciplinary practices for scientific argumentation

In our study, professional data sets and the climate change infographic emerged as boundary objects that facilitated student learning of evidence-based argumentation in partnership with scientists. Although our designed curriculum included two classroom-based phenology experiments, student-generated data were not robust enough to mediate student–scientist discourse across the classroom boundary (Star & Griesemer, 1989). These findings suggest that practice-based, science instruction should broaden what counts as experimentation in the classroom to include the analysis and mining of publicly available, professional data sets in addition to classroom-based experimental design. Unlike student-designed experiments, professional data sets are layered with disciplinary perspectives and offer students a lens into professional scientific practices including the questions scientists asked before collecting data, and the processing, arrangement, and description of data to communicate an evidence-based story. In this sense, professional data sets are layered with disciplinary sense-making of scientific phenomena, which Latour and Woolgar (1986) described as 'literary inscription'. Literary inscription allowed students to observe disciplinary sense-making processes embedded in discrete artefacts, such as graphs and data, and provided a familiar context for scientist–student discourse around a shared data set.

The Next Generation Science Standards include interpreting and analysing large data sets for linear and non-linear relationships in the middle school and high school standards, and our findings support the boundary-crossing role of incorporating these data sets into classroom instruction, while recognising that it is a new pedagogical practice for many teachers who are still developing pedagogical content knowledge for disciplinary practices (Davis & Krajcik, 2005). Expert feedback from this study modelled pedagogical strategies that teachers can take to support practice-based learning of argumentation in the classroom. Table 4

Table 4. Suggested strategies for teachers based on scientist feedback examples for each NGSS disciplinary practice.

NGSS disciplinary practice	Guidelines for teachers	Example from scientist feedback
Asking questions	Ask open-ended questions that model disciplinary thinking, especially around contemporary problems with no 'known' answer.	'I wonder if rainfall plays a major role in the Monk seal life … do they only go to the breeding ground during the dry season or wet season?'
Developing and using models	Arguments around models should include historic, current, and predictive values.	'One thing scientists might say, though, is that the [GIS map] is showing what is going to happen … but what has already happened?'
Planning and carrying out investigations	Encourage students to investigate data around related research questions.	'Can you show any evidence for how sea ice has been melting and how we expect it to melt in the future?'
Analysing and interpreting data	Introduce multiple variables for analysis, and non-linear lines of argumentation. Engage students in the analysis and data mining of large-scale professional data sets.	'What if it started raining harder and harder, at the same time as it gets warmer over the next century?' 'Does the last 30 years of data give you some different insights into climate change?'
Using mathematical and computational thinking	Students should provide accurate, written interpretations of all data used in support of arguments.	'The top graph shows both CO2 and temperature over the same time period as the bottom graph. How are temperature and CO2 connected?'
Constructing explanations	Ask probing questions that elicit more evidence seeking by students. Provide supplementary information that can support students' claims. Explanations should draw from multiple strands of evidence.	'What is the evidence that South America has already been getting warmer because of global warming?' 'In addition, the area north of the lynx's range is mostly tundra and lynx are found mostly in forests.' 'I really like this, because you showed both global evidence and local evidence.'
Engaging in argument from evidence	Encourage students to incorporate more explanations. Pose counterarguments to the students' claims to illicit more evidence seeking. Restate student claims in ways that bridge everyday language with disciplinary terms and content.	'What are some things plants need that might be changing?' 'Couldn't the lynx and hares just move north from their current habitat to this new habitat and be fine?' 'You propose that salmon will be negatively affected by climate change due to its impacts on snowmelt, which results in increases in the acidity of the water and removes calcium from the gills of the fish.'
Obtaining, evaluating, and communicating information	Students should construct evidence-based arguments to tell a coherent story of a phenomenon around related data sets. Model and provide multiple pathways for students to engage in continued research.	'When scientists give a presentation, they think of the presentation like a story.' 'You are talking mostly about temperature and the two are very related but it would be great to use a temp graph (the IPCC has some great ones if you Google something like "IPCC climate warming graph".'

summarises the pedagogical moves that experts modelled through their feedback on student infographics, and offers specific suggestions for how teachers can support student engagement in a holistic set of practices as they construct evidence-based arguments in the classroom. Although this table uses a list to distinguish specific NGSS practices and related pedagogical moves, this was done for clarity purposes only. We argue that practices co-occur in authentic settings, and suggest that teachers draw on multiple pedagogical moves to engage students in a holistic view of practice-based learning.

Implications

Scientific experts are not a common resource in secondary classroom settings; however, their role in this course design helped elicit key disciplinary practices related to constructing and communicating authentic scientific arguments around climate change. The findings from our research can be used to inform curriculum design and instructional practices aimed at cultivating teachers' pedagogical content knowledge for disciplinary practices, and students' disciplinary practice knowledge related to evidence-based argumentation. Future research should look at how teachers apply expert-modelled pedagogical moves to support students' argumentation practices, and what additional educative and instructional supports are needed to support teacher development of pedagogical content knowledge for argumentation. In addition, Wenger (1999) noted that technology is making boundary crossing easier; so efforts should be made to connect students to disciplinary experts via technology, and with the use of sociomaterial tools that can situate students as learners on the boundaries of related scientific communities of practice.

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References

Achieve. (2010). *Taking the lead in science education: Forging next-generation science standards*. Washington, DC: Achieve. Retrieved from http://achieve.org/files/InternationalScienceBenchmarkingReport.pdf

Akkerman, S. F., & Bakker, A. (2011). Boundary crossing and boundary objects. *Review of Educational Research*, *81*(2), 132–169.

Barab, S., & Squire, K. (2004). Design-based research: Putting a stake in the ground. *The Journal of the Learning Sciences*, *13*(1), 1–14.

Barron, B., & Bell, P. (2015). Learning environments in and out of school. *Handbook of Educational Psychology*, 323–336.

Barton, A. C., & Tan, E. (2010). *We be burnin'!* Agency, identity, and science learning. *The Journal of the Learning Sciences*, *19*(2), 187–229.

Bell, P. (2000). Scientific arguments as learning artifacts: Designing for learning from the web with KIE. *International Journal of Science Education*, *22*(8), 797–817.

Bell, P., Bricker, L., Reeve, S., Zimmerman, H. T., & Tzou, C. (2013). Discovering and supporting successful learning pathways of youth in and out of school: Accounting for the development of everyday expertise across settings. In *LOST Opportunities* (pp. 119–140). New York, NY: Springer.

Bell, P., Bricker, L., Tzou, C., Lee, T., & Van Horne, K. (2012). Exploring the Science Framework Engaging learners in scientific practices related to obtaining, evaluating, and communicating information.

Bruner, J. S. (2009). *The process of education*. Cambridge, MA: Harvard University Press.

Collins, H., & Pinch, T. (1993). *The Golem. What everybody should know about science*. Cambridge: Cambridge University Press. c1993, Canto edition 1994, 1.

Davis, E. A., & Krajcik, J. S. (2005). Designing educative curriculum materials to promote teacher learning. *Educational Researcher*, *34*(3), 3–14.

Design-Based Research Collective. (2003). Design-based research: An emerging paradigm for educational inquiry. *Educational Researcher*, *32*(1), 5–8.

Dreier, O. (1999). Personal trajectories of participation across contexts of social practice. *Outlines. Critical Practice Studies*, *1*(1), 5–32.

Erickson, F. (1986). Qualitative methods in research on teaching. In M. C. Wittrock (Ed.), *Handbook of research on teaching* (3rd ed., pp. 119–161). New York, NY: Macmillan.

Gutiérrez, K. D., & Penuel, W. R. (2014). Relevance to practice as a criterion for rigor. *Educational Researcher*, *43*(1), 19–23.

Holland, D., & Lave, J. (2009). Social practice theory and the historical production of persons. *Actio: An International Journal of Human Activity Theory*, *2*, 1–15.

Kelly, G. J. (2014). The social bases of disciplinary knowledge and practice in productive disciplinary engagement. *International Journal of Educational Research*, *64*, 211–214.

Latour, B., & Woolgar, S. (1986). *Laboratory life: The construction of scientific facts*. Princeton: Princeton University Press.

Lave, J., & Wenger, E. (1991). *Situated learning: Legitimate peripheral participation*. Cambridge: Cambridge University Press.

McNeill, K. L., & Krajcik, J. S. (2011). Supporting grade 5–8 students in constructing explanations in science: The claim, evidence, and reasoning framework for talk and writing. *Pearson*.

National Research Council. (Ed.). (1996). *National science education standards*. Washington, DC: National Academy Press.

National Research Council. (2012). *A for K-12 science education: Practices, crosscutting concepts, and core ideas*. Washington, DC: National Academies Press.

NGSS Lead States. (2013). Next generation science standards: For states, by states.

Nussbaum-Beach, S., & Hall, L. R. (2011). *The connected educator: Learning and leading in a digital age*. Chicago: Solution Tree Press.

Olson, S., & Loucks-Horsley, S. (Eds.). (2000). *Inquiry and the National Science Education Standards: A guide for teaching and learning*. Washington, DC: National Academies Press.

Penuel, W. R. (2014). Studying science and engineering learning in practice. *Cultural Studies of Science Education*, *11*(1)89–104.

Pickering, A. (1995). *The mangle of practice: Time, agency, and science*. Chicago: University of Chicago Press.

Rosebery, A. S., Ogonowski, M., DiSchino, M., & Warren, B. (2010). 'The coat traps all your body heat': Heterogeneity as fundamental to learning. *The Journal of the Learning Sciences*, *19*(3), 322–357.

Roth, W. M., & Barton, A. C. (2004). *Rethinking scientific literacy*. New York: Psychology Press.

Star, S. L., & Griesemer, J. R. (1989). Institutional ecology, translations' and boundary objects: Amateurs and professionals in Berkeley's Museum of Vertebrate Zoology, 1907–39. *Social Studies of Science*, *19*(3), 387–420.

Strauss, A., & Corbin, J. (1990). *Basics of qualitative research* (Vol. 15). Newbury Park, CA: Sage.

Walsh, E. M., & Tsurusaki, B. K. (2014). Social controversy belongs in the climate science classroom. *Nature Climate Change*, *4*(4), 259–263.

Wenger, E. (1999). *Communities of practice: Learning, meaning, and identity*. Cambridge: Cambridge University Press.

Windschitl, M., Thompson, J., & Braaten, M. (2008). Beyond the scientific method: Model-based inquiry as a new paradigm of preference for school science investigations. *Science education*, *92*(5), 941–967.