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Integrating Scientific Argumentation to Improve Undergraduate Writing and Learning in a Global Environmental Change Course

Bess G. Koffman,[1,2,*,a] Karl J. Kreutz,[1,3] and Kim Trenbath[4,5]

ABSTRACT

We present a strategy for using scientific argumentation in an early undergraduate laboratory course to teach disciplinary writing practices and to promote critical thinking, knowledge transformation, and understanding of the scientific method. The approach combines targeted writing instruction; data analysis and interpretation; formulation of a hypothesis; and construction of an argument. Students submit and receive feedback on two drafts of two different argumentation essays, providing the opportunity for guided practice. Each written argument is intended to draw on several weeks' course material, including short lectures, discussions, readings, and problem sets. Thus our aim with these writing assignments is to help students synthesize content and concepts, deepening their learning. We have found that this inquiry-based approach to writing engages students in course material, and significantly improves both writing and learning. We observed the greatest improvement among students with the lowest initial scores, suggesting that lower-achieving students benefitted disproportionately from this approach. Students have responded positively to the use of writing in the course, many stating on course evaluations that this is the first time they have received instruction in scientific writing. They have also pointed to a greater "big-picture" understanding of the course gained through writing. We describe the course and our curriculum, and provide suggestions for implementation as well as rubrics used to evaluate problem sets and student argumentation essays. © *2017 National Association of Geoscience Teachers*. [DOI: 10.5408/16-232.1]

Key words: writing, learning, argumentation, inquiry-based, undergraduate education

INTRODUCTION

Active learning has become well established as a more effective strategy than traditional lecturing for teaching and retaining students in science, technology, engineering, and mathematics (STEM) fields (Springer et al., 1999; Handelsman et al., 2004; Haak et al., 2011; Ruiz-Primo et al., 2011; Freeman et al., 2014). The geosciences naturally lend themselves to active learning approaches, as many undergraduate courses emphasize fieldwork and hands-on study. Although overall course design is therefore often in line with pedagogic best practices, recent work has suggested that there is still room for improvement, especially regarding written laboratory reports (Alaimo et al., 2009). Specifically, writing tasks need to be authentic and appropriate to the course level, giving students meaningful practice with writing (Rivard, 1994; Lerner, 2007; Moskovitz and Kellogg, 2011). This practice, in turn, helps train students in disciplinary norms ("writing-as-professionalization," WAP) and can enhance learning of course concepts and content as well as science literacy more generally ("writing-to-learn," WTL; Hand et al., 1999); Moskovitz and Kellogg, 2011).

Writing as an integrated component of laboratory courses has powerful potential to lead to knowledge transformation—but only if students connect new ideas to prior knowledge rather than recapitulating factual information, as is often done within traditional lab reports (Newell, 1983, quoted in Rivard, 1994; Scardamalia and Bereiter, 1987; Burke et al., 2006). In our experience, traditional lab reports follow the Abstract, Introduction, Methods, Results, Discussion, and Conclusion format and are written for the professor and/or teaching assistant as the audience. As such, they are essentially a "pseudo-academic or school genre" (Alaimo et al., 2009) that does not provide practice with disciplinary writing (WAP) nor challenge the student to transfer knowledge gained through the laboratory exercise (WTL). For this reason, alternative approaches to the traditional laboratory report have been gaining recognition. One approach that integrates inquiry-based activities, collaborative work, and writing within a structured framework is the science writing heuristic (SWH; Burke et al., 2006). A study comparing the inquiry-driven SWH and traditional (teacher-centered) approaches in biology, chemistry, and physics classes (grades 7–11) found that although its effectiveness depended on the quality of teachers' implementation, the SWH had great potential to close science achievement gaps (Akkus et al., 2007). In other words, whereas high-achieving students are often able to adapt to different teaching styles, including traditional memory-intensive, content-heavy approaches, "low-achieving science students benefit most from the implementation of the SWH approach" (Akkus et al., 2007, 1762). Similarly, low- and average-achieving students in a college physics classroom gained the greatest benefit from writing essays focused on explaining everyday physical phenomena (Kirk-

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[1] School of Earth and Climate Sciences, 5790 Bryand Global Sciences Center, University of Maine, Orono, Maine 04469, USA
[2] Department of Earth Sciences, 6105 Sherman Fairchild Hall, Dartmouth College, Hanover, New Hampshire 03755, USA
[3] Climate Change Institute, 300 Bryand Global Sciences Center, University of Maine, Orono, Maine 04469, USA
[4] Maine Center for Research in STEM Education, 5727 Estabrooke Hall, University of Maine, Orono, Maine, 04469, USA
[5] National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, Colorado 80401, USA
*Current address: Department of Geology, 5800 Mayflower Hill, Colby College, Waterville, Maine 04901, USA
[a] Author to whom correspondence should be addressed. Electronic mail: bess.koffman@colby.edu

patrick and Pittendrigh, 1984). Together, the aforementioned studies suggest that by incorporating active learning, including discussion, reflection, and writing into laboratory courses, we can improve student learning and potentially close achievement gaps.

Whereas laboratory writing assignments can be improved to enhance learning following WTL best practices (e.g., Reynolds et al., 2012), students often suffer from a lack of writing instruction in science courses. We have observed that students in introductory-to-mid-level geoscience courses often have not received training in scientific writing, yet are expected in their college careers to produce full-length research papers. At the same time, students often perform well on weekly exercises that ask focused questions, but struggle to integrate material across topics and through time. Thus, we see a combined need for synthesis exercises to enhance and deepen learning, and guided writing practice to improve student mastery of composition.

Here, we describe an approach for integrating inquiry-based writing into a mid-level undergraduate course focused on global environmental change. Each writing task requires students to reflect on what they have learned from multiple weekly problem sets (conducted during a laboratory period), and to form an argument in support of a hypothesis. They are asked to include evidence from the literature, as well as data figures that they have generated. We emphasize the importance of making a claim and supporting it with evidence, as this is the basis of scientific interpretation and the type of thinking and writing that is needed to write the Discussion section of a paper. Our goals are two-fold: give students instruction and practice in scientific writing, and use writing to deepen students' understanding of course material. In this way, the described approach aligns with both WAP and WTL teaching strategies.

COURSE OVERVIEW

We describe an undergraduate course within the School of Earth and Climate Sciences at the University of Maine, a public university with ~11,000 undergraduates. Students enter the program by taking an introductory Earth Science course, the focus of which varies across a wide spectrum of Earth Science topics (e.g., solid earth, hazards, environmental geology, coastal processes, energy and climate, humans and global change). The course described here is the second in a required two-course sequence (ERS200: Earth Systems, offered every fall semester, and ERS201: Global Environmental Change, offered every spring semester) for incoming majors, and is therefore targeted at a sophomore level. The goal of the ERS200/201 sequence is to provide a bridge between introductory and specialized, upper-level courses. The first course focuses on solid earth processes, whereas the second, described here, takes a systems approach to studying the interaction of surface processes linking the atmosphere, hydrosphere, biosphere, lithosphere, cryosphere, and anthrosphere. We focus on the carbon cycle and climate as a way to investigate the interplay of these components within the earth system.

Course enrollment traditionally has been ~20 students, with at least half being declared Earth and Climate Science majors. The remainder of students comes from a wide range of natural science, engineering, and liberal arts majors. Although the course is intended for sophomores, in practice, the scheduling, transfer of majors, and interest in the course usually lead to a mixture of academic levels from first- to fourth-year students. The instructional team is composed of an instructor and a graduate teaching assistant (TA), augmented by 1 to 2 undergraduate Maine learning assistants (MLAs) who have taken the course in a previous year. Most of the content instruction and all grading is done by the instructor and TA. The primary role of the MLAs is to help students with software issues, and to serve as a liaison for student questions during activities. Because the course relies heavily on hands-on activities, this structure facilitates a high level of instructional support.

CURRICULUM DESCRIPTION

Pre- and Post-Assessment

The course pre-assessment consists of a multiple-choice concept survey followed by a series of short-answer and free-response questions, some involving the creation and interpretation of diagrams (see Supplementary Material, File 1; available in the online journal and at http://dx.doi.org/10.5408/16-232s1). We developed the climate change survey by compiling questions from prior research (Boyes and Stanisstreet, 1992; Gowda et al., 1997; Dove et al., 2003; Cordero et al., 2008; Geoscience Concept Inventory, 2011; National Assessment of Educational Progress, 2012) and created others based on our prior research experience (Trenbath, 2012). The questions fit into one of the following categories: weather and climate (one question), climate feedbacks (five questions), ozone (four questions), natural versus anthropogenic climate change (six questions), greenhouse effect (six questions), carbon cycle (six questions), and climate change causes (10 questions). We validated the questions through think-aloud interviews with two professors and one undergraduate student. After each interview, the questions that confused the subject were revised or deleted. We worked to ensure that the questions captured understanding of the topic as intended. For example, we expected the survey to accurately assess the professors' expert knowledge, so if a professor missed a question, we determined that the cause of the inaccuracy was due to an inadequate question and revised or deleted as necessary.

We focus here on a specific systems-oriented question involving the carbon cycle, as that is the topic of the writing prompts that we discuss in this paper. We ask students to draw a plot of four coordinate (x, y) pairs representing atmospheric CO_2 concentrations and eustatic sea level data from four periods in Earth's history (data from Alley et al., 2005). Two values of each data type provide uncertainty estimates. We do not specify which parameter should be plotted on which axis. The drawing exercise is followed by the question, "Is there a relationship between atmospheric CO_2 and sea level, and if so, why?" As we describe in the following sections, this exercise allows us to assess students' data literacy (i.e., conventions relating to dependent and independent variables; labeling of axes and units; how to represent uncertainty) as well as their knowledge of the greenhouse effect and its impact on the cryosphere. In addition, we are able to capture some student misconceptions about the climate system. Examples are shown in Fig. 1 and discussed later in this paper.

For course post-assessment, we administer the same multipart assessment that we give on the first day. We also

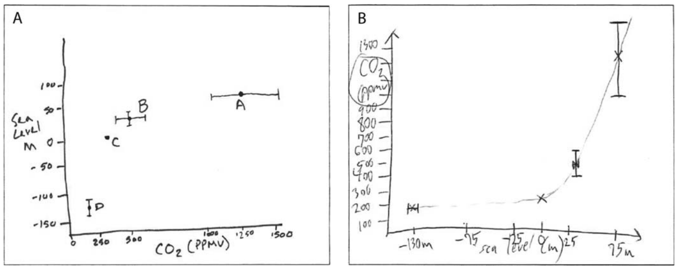

FIGURE 1: Examples of student-drawn plots from the CO_2-sea level pre-assessment question showing (A) correct relationship, with sea level plotted as a function of atmospheric CO_2 concentration; and (B) incorrect relationship, with CO_2 plotted as function of sea level. Both students did well labeling their axes and giving uncertainty estimates (which we provided).

ask students to provide us with feedback through both formal evaluations and our own course-specific evaluation, both given anonymously.

Problem Sets

Throughout the course, we use problem sets that involve some combination of data generation (in a laboratory, in the field, or via database search), system diagramming and/or modeling, data interpretation, and literature exploration. The topic of each problem set is tied to the overall goals for the week (and the semester), and in some cases involves a field trip. Some problem sets require group work and presentation to the entire class. Many of the problem sets make use of isee systems STELLA dynamic modeling software, so that students can experiment with model parameters and component interactions, and generate model output. We also use online archived datasets of modern observations and paleo reconstructions to promote data literacy. A key aspect of the problem sets is that the results require students to demonstrate specific skills in graphical form, and these skills (and often the graphs themselves) are designed to be used later in the writing assignments. Each problem set contains a series of questions that are aimed at engaging students in thinking about the underlying ideas for each activity, similar to the SWH approach used in chemistry courses (Burke et al., 2006). The problem set grading rubric is included in the Supplementary Material, File 2 (available in the online journal and at http://dx.doi.org/10.5408/16-232s2).

Writing Assignments

We require students to write two short (1,200-word maximum) argumentation essays, each addressing a major question related to the central theme of the course, namely, the relationship between temperature and CO_2 through time in the Earth system. We encourage students to style their writing after *Science* Perspectives articles, which they have encountered in the course. They are instructed to write using their own voice to a smart, scientifically literate audience, and to think of themselves as scientific journalists writing an article for a popular science magazine. Each essay should synthesize information from in-class work, including class discussions and problem sets, as well as a small amount of outside reading (students must cite at least one peer-reviewed article). The questions we ask students to address are: (1) Is modern atmospheric CO_2 anomalous in Earth history? and (2) What will the global mean temperature be in 2100 AD? The writing assignments are thus intended to challenge students to think about what they have learned to date, and to form a coherent argument related to each question.

Given the important role of the thesis statement in science (i.e., as a hypothesis) and in writing, we make a point of encouraging strong thesis statements. We remind students that a thesis statement is a *testable* scientific assertion written as a statement, a positive declaration that the whole paper then seeks to support with argument and evidence. For example, one possible thesis statement that would address the first question is, "The current atmospheric CO_2 concentration is within the observed range of natural variability." We emphasize the importance of evaluating the thesis statement on different timescales, as appropriate, and ask students to be quantitative in their assessments. The thesis statements receive their own category in the rubric to underscore the key role they play in persuasive writing.

In support of their argument, students must include *relevant* figures, including at least one that they have created as part of another ERS201 class assignment (i.e., within a problem set). This reinforces the synthesizing role the writing assignment plays in spanning multiple weeks' worth of coursework. We give explicit guidance on figures, including examples of different types of plots formatted in ways that show the data clearly (Tufte and Graves-Morris, 1983; Webber et al., 2014; see Supplementary Material, File 3; available in the online journal and at http://dx.doi.org/10.5408/16-232s3). Each figure should be referenced in the text and given a concise, informative caption. As with the thesis statement, graphical quality receives its own rubric category. We also assess how well students integrate graphics into their arguments and the choice of figures that they include. The goal here is to get students to think about what they are doing and why, rather than simply throwing in all figures they have made up to that point in the course. The rubric and examples of low- and high-scoring graded student essays are included in the Supplementary Material (Files 4–8; available in the online journal and at http://dx.doi.org/10.5408/16-232s4 ; http://dx.doi.org/10.5408/16-232s5 ; http://dx.doi.org/10.5408/16-232s6 ; http://dx.doi.org/10.5408/16-232s7 ; and http://dx.doi.org/10.5408/16-232s8).

Data Literacy

In addition to providing guidance on figures, we also addressed data literacy explicitly in the course, as it is fundamental to conceptual learning in the sciences. We have found that students in this sophomore-level course often benefit from a refresher and/or introduction to basic topics related to data and data visualization. For example, we developed an activity focused on assigning dependent and independent variables. The exercise involved a series of related phenomena, such as level of sleepiness and number of all-nighters in a week. Students were asked to determine the likely causal relationship between the two (if present) and assign one variable as independent (e.g., number of all-nighters) and the other as dependent (e.g., level of sleepiness). One "story problem" involved the relationship between chocolate chips and the cohesiveness and "deliciousness" of banana bread. We ended the course by

TABLE I: Student responses to pre-assessment question on atmospheric CO_2 and sea level. The correct graph has CO_2 on the x-axis (independent variable) and sea level on the y-axis (dependent variable). The correct response includes some form of the following: CO_2 traps heat in the atmosphere; higher temperatures cause glaciers to melt and ocean waters to expand, raising global sea levels. In this summary table, if students got the answer mostly right we included it as correct even if there were minor misconceptions (such as a role played by sea ice).

2013–2015 Data	Incorrect Response (%)	Correct Response (%)
Incorrect Graph ($n = 33$)	55	45
Correct Graph ($n = 22$)	18	82

revisiting the topic of dependent and independent variables with a banana bread taste test (and class plotting exercise!). Engaging with the topic in this way made an otherwise bland topic more fun and more memorable for all involved. Moreover, it improved students' understanding of conventions in data visualization (e.g. independent variable on the x-axis), which in turn improved their skill and confidence in data visualization and interpretation.

Student Reflection and Rubric Development

Before giving the first writing assignment, we ask students to reflect on what makes a good scientific argument. To date, all responses have indicated a need for evidence or data. One student wrote, "A good scientific argument uses graphical evidence and data to help prove a point. It interprets and synthesizes data, it doesn't simply restate it. A good scientific argument is based off of experimentation or observation. It is logical. A good scientific argument answers a question." Most answers have cited a need for hypothesis testing, limited and/or clearly defined assumptions, error estimation, comparison with accepted research and ideas, and clear presentation of data. Many also have noted the value of addressing alternative hypotheses or viewpoints. A second student responded, "Any argument being made needs to have backbone. There must be some sort of evidence or data to base the argument on. In an argument it is also a good strategy to acknowledge opposing viewpoints and state why one may be better than the other." Altogether, we have found that students understand the nature, and to a good extent the structure (claims, reasons, evidence, counterargument), of a scientific argument.

We incorporated the criteria listed by students into the rubric used to evaluate their writing in order to increase student buy-in. This was possible because their criteria largely corresponded with our own planned measures of assessment. Our rubric consists of six categories: Thesis Statement, Organization, Critical Analysis, Integration of Graphics, Graphical Quality, and Voice and Style (see Supplementary Material, File 4; additional Citations category has recently been added). Of these, Critical Analysis and Integration of Graphics (i.e., evidence) are weighted most heavily, reflecting the central role these factors play in forming a strong argument. The rubric was used consistently for all assignments, and scores reported in this paper reflect those assigned to student work. Grading of writing assignments was performed by one graduate teaching assistant per year.

Writing Instruction

In addition to providing feedback on first and second drafts of each writing assignment, we developed writing workshops to help guide students through the writing process. We incorporate these into dedicated lab time. Because this course tends to attract first- and second-year Earth Science majors as well as non-majors, we have found this extra instruction helpful for orienting students to common practices and expectations in the field. Each workshop focuses on a specific aspect of scientific writing, such as how to structure a paragraph or how and when to cite sources. Each activity lasts 20 min to 30 min. We use examples from our own work as much as possible both to exemplify the idea that writing is a skill improved through practice, and to make ourselves vulnerable to critique. In one exercise, we provide students with an introductory paragraph from a paper in preparation and ask them to vote on which sentences ought to have citations. This interactive exercise has shown that students correctly intuit the critical data-driven points requiring citation, and disagree somewhat on whether more general statements need citations. We conclude by showing the fully cited paragraph and a corresponding correctly-formatted references section. Another exercise focuses on how to structure a paragraph. We take several published paragraphs, remove their topic sentences, and ask students to write new topic sentences for each paragraph. We also discuss a range of topic sentences, asking students what type of information they would expect to find in the following paragraphs. All in all, we have found that these short, focused activities help to improve student writing performance in the longer composition assignments.

RESULTS

Pre-Assessment Question on CO_2 and Sea Level

With the pre-assessment question, "Is there a relationship between atmospheric CO_2 and sea level, and if so, why?" we are interested to see whether there is a relationship between how students choose to plot the data, and the accuracy of their responses. We pooled results from three years of pre-assessment data (2013–2015), representing responses from 55 students (the total number enrolled). The results show that students who plotted the CO_2-sea level relationship correctly (i.e., with CO_2 as the independent variable, on the x-axis; Fig. 1A) were almost twice as likely (82% versus 45%; Table I) to correctly describe the fundamental relationship between atmospheric CO_2 and sea level (namely, that increased CO_2 leads to increased temperatures, which in turn lead to melting of glaciers and ice sheets and thermal expansion of ocean waters, raising sea levels) as those who plotted the data in the reverse orientation (Fig. 1B). Answers were considered correct if they included this basic relationship, even if there were minor misconceptions. For example, a mostly correct response might read, "Yes there is, as CO_2 levels rise, temperatures increase. As temperatures increase, Arctic ice melts raising the sea level. CO_2 levels do not change because of sea levels, sea levels change because of CO2 levels."

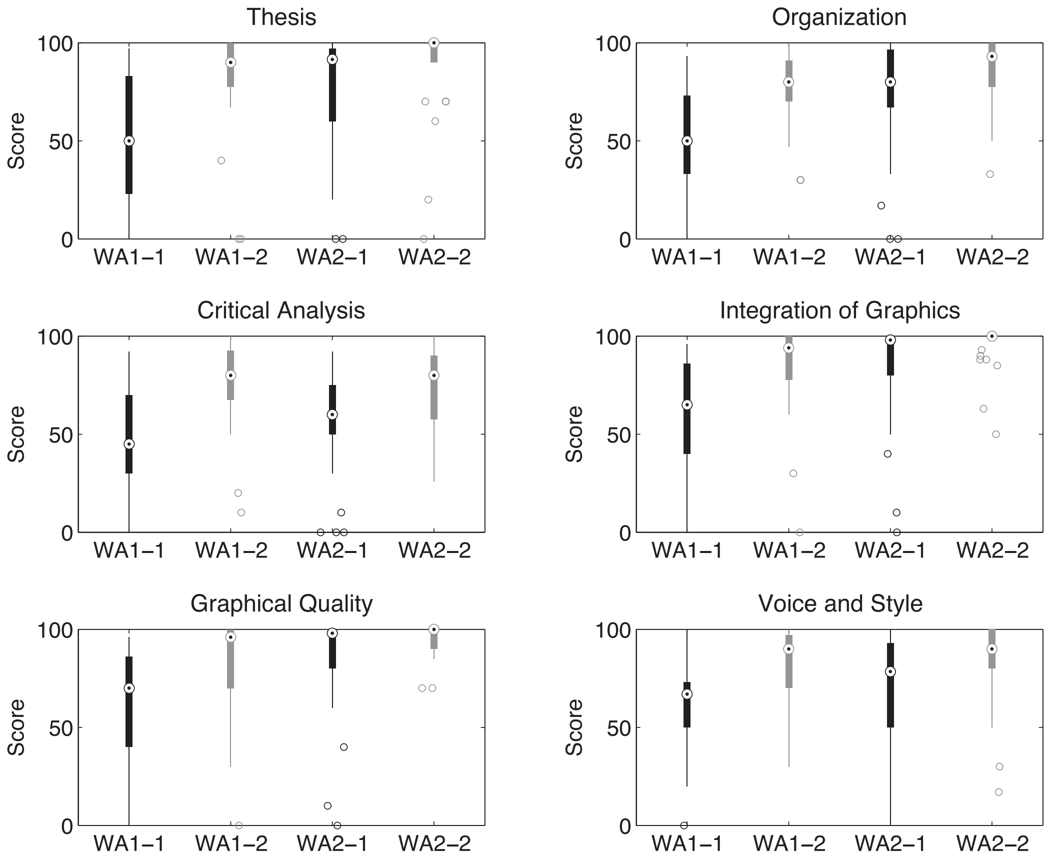

FIGURE 2: Aggregate writing assignment scores from 2014 and 2015 for each of the six rubric categories. In each pane, the values represent combined data for each writing assignment (WA) and each draft, as indicated on the *x*-axis (e.g., WA–1-1 represents the first draft of the first writing assignment, and WA1-2 represents the second draft of the first writing assignment). Boxplots represent the median (circle with dot), 25th to 75th percentile values (wide bars) and ranges (narrow bars) of each dataset. Statistical outliers are represented by open circles. WA2-2 Integration of Graphics scores were consistently high (25th percentile = 100%); hence, there is no bar visible.

Those students who plotted CO_2 on the *y*-axis, as a function of sea level, tended to give answers that linked CO_2 concentration in the atmosphere to elevation above sea level. Because of the way they plotted the data, they may have inferred a relationship that does not exist in the real world. For example, one student wrote: "This curve demonstrates that CO_2 levels increase with altitude, suggesting that CO_2 is lighter than other components in the atmosphere or that it is generated at high altitudes and diffuses to lower ones through a process not suggested by the data itself." Incorrect responses took several forms. Another student wrote, "The ocean contains/acts as a reservoir for CO_2 so if the sea level goes down, then the CO_2 in the atmosphere should go up." Although our observations of student responses over the years suggests a relationship between data plotting and interpretation, we cannot rule out alternate explanations. For example, it is also possible that students were confused about what the data represented.

Student responses to this pre-assessment question highlighted a number of important misconceptions common to all three years' classes. Number three, in particular, reinforces the importance of correctly assigning variables to axes for making interpretations of graphical data.

Student misconceptions (*explanations in parentheses*):

(1) CO_2 breaks down ozone molecules, allowing more solar radiation to enter the atmosphere. (*Incorrect. CO_2 does not react with ozone, and the loss of stratospheric ozone causes a minor cooling of the atmosphere, not a warming. The two phenomena are related, however, as the buildup of anthropogenic CO_2 changes the thermal structure of the atmosphere, which in turn affects ozone concentrations. Source: NASA Earth Observatory)*

(2) CO_2 traps incoming solar radiation. *(Incorrect. CO_2 absorbs and re-emits outgoing infrared radiation.)*

(3) CO_2 increases with elevation above sea level. *(Incorrect. CO_2 is well mixed in the atmosphere, with essentially uniform concentrations in the troposphere and decreasing concentrations with elevation in the stratosphere. Source: Foucher et al., 2011.)*

(4) Sea ice contributes to sea level rise (a common misconception likely related to media coverage of melting Arctic sea ice). *(Incorrect. Sea ice is, by definition, floating. Given the densities of ice and water, sea ice displaces a volume equal to its liquid volume once melted. Thus it has no impact on sea level.)*

We address these misconceptions throughout the course, through lectures, problem sets, essays, and class discussions.

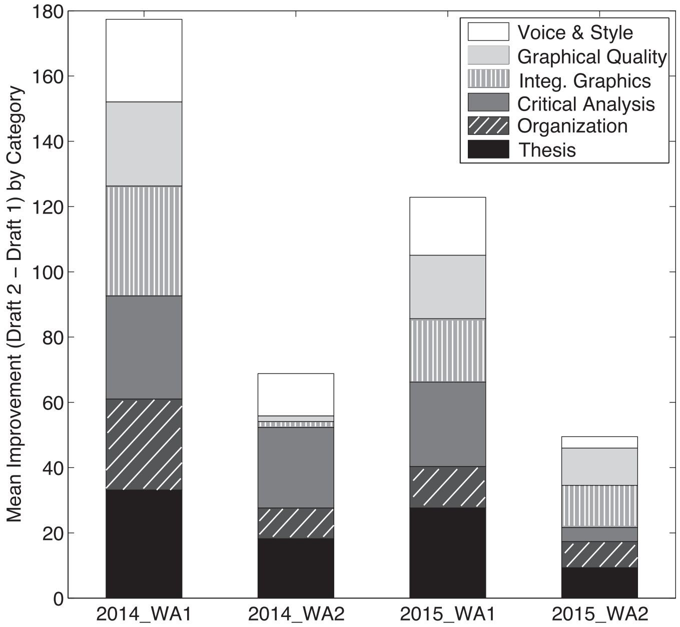

FIGURE 3: Stacked bar plot showing mean improvement (Draft 2 − Draft 1) by rubric category for both writing assignments (WA1 and WA2) in 2014 and 2015. The greatest mean improvement between drafts is seen on the first writing assignment, with smaller draft-to-draft improvement on WA2 reflecting higher student achievement overall.

Writing Assignments

Student writing has shown significant improvement, both draft-to-draft and assignment-to-assignment. Figure 2 shows student scores for 2014 and 2015 rubric data, including a total of 34 students (19 enrolled in 2014 and 15 in 2015; we made significant changes to the course design and writing curriculum between 2013 and 2014, so data from 2013 are not included). To evaluate student improvement, we use a two-tailed signed-rank test to assess the significance of paired differences in scores. The test assumes a symmetric distribution about the median but does not require normality. We found the greatest improvement between first and second drafts of the first writing assignment (WA1) in each year, with continued improvement across most categories of the second writing assignment (WA2). In 2014, all rubric categories of WA1 showed significant change from the first to the second draft ($p < 0.001$). 2014 WA2 scores improved from the first to the second draft in Thesis, Voice, and Style, and Organization ($p < 0.05$) and Critical Analysis ($p < 0.001$). Median scores for Graphical Quality and Integration of Graphics remained at 100% on both drafts of WA2, showing that students rapidly learned how to produce and incorporate satisfactory data visualizations. In 2015, WA1 draft-to-draft improvement was significant at the 99.9% level for all categories except Thesis ($p < 0.005$) and Organization ($p < 0.05$). 2015 WA2 scores were consistently high, with significant draft-to-draft improvement only in Organization ($p < 0.1$), Integration of Graphics ($p < 0.001$) and Graphical Quality ($p < 0.005$). Figure 3 shows the mean draft-to-draft improvement for each assignment, by category, illustrating some of the patterns described above. For instance, in 2014 students made significant improvement in Graphical Quality and Integration of Graphics from the first to the second drafts of WA1, but negligible improvement in WA2, reflecting rapid learning in these categories.

Importantly, we found that lower-achieving students improved disproportionately through revising and resubmitting their work compared to higher-achieving students. The percentage of improvement in scores was significantly nonlinearly related to the first-draft score for all writing assignments (Fig. 4). Although to some extent this reflects the fact that higher-scoring students have less "room for improvement" within the framework of our assessment approach, nevertheless, it demonstrates that lower-scoring students made significant, disproportionate gains in their understanding of how to construct a scientific argument as a result of the described writing curriculum.

Improvements made by working through critical feedback and revising the first writing assignment appear to have translated to improved performance on the first draft of the second assignment, as can generally be seen in Fig. 2. In 2014, scores from the second draft of WA1 to the first draft of WA2 improved significantly in the following categories: Thesis ($p < 0.05$), Critical Analysis and Integration of Graphics ($p < 0.001$), and Graphical Quality ($p < 0.005$). In 2015 we saw similar improvement from the second draft of WA1 to the first draft of WA2 in Critical Analysis and Voice and Style ($p < 0.05$) and in Integration of Graphics and Graphical Quality ($p < 0.005$). Overall these data demonstrate that the opportunity to receive feedback on writing and the requirement to incorporate that feedback into a revised essay is essential to student learning, and that student writing improves as a result of instruction and practice.

DISCUSSION

Using argumentation to improve student writing and learning has had clear benefits in this course. We have found that taking a structured, step-by-step approach to teaching writing, including giving explicit practice in writing thesis statements, paragraphs, and short arguments, helps students understand the mechanics of scientific writing at an appropriate (early undergraduate) level. At the same time, we tackle data literacy through problem sets and in-class exercises. Students gain writing process knowledge through the use of rubrics, written feedback on assignments, and required revisions of papers (Alaimo et al., 2009). According to Moskovitz and Kellogg (2011), the alignment of laboratory tasks (in this course: generating model output; analyzing data from online archives) with student writing at an appropriate level is a key aspect of inquiry-based writing. For example, we do not ask students to recapitulate methods that have already been provided for a laboratory assignment, or to review a body of literature with which they are unfamiliar—both shortfalls of traditional lab report assignments (Alaimo et al., 2009). Both of these tasks are better suited to more advanced undergraduates and graduate students undertaking their own research. At the early undergraduate level, grappling with evidence and what it means, and forming an argument based on evidence, builds the foundation for critical thinking and analysis skills that will be developed throughout students' college careers.

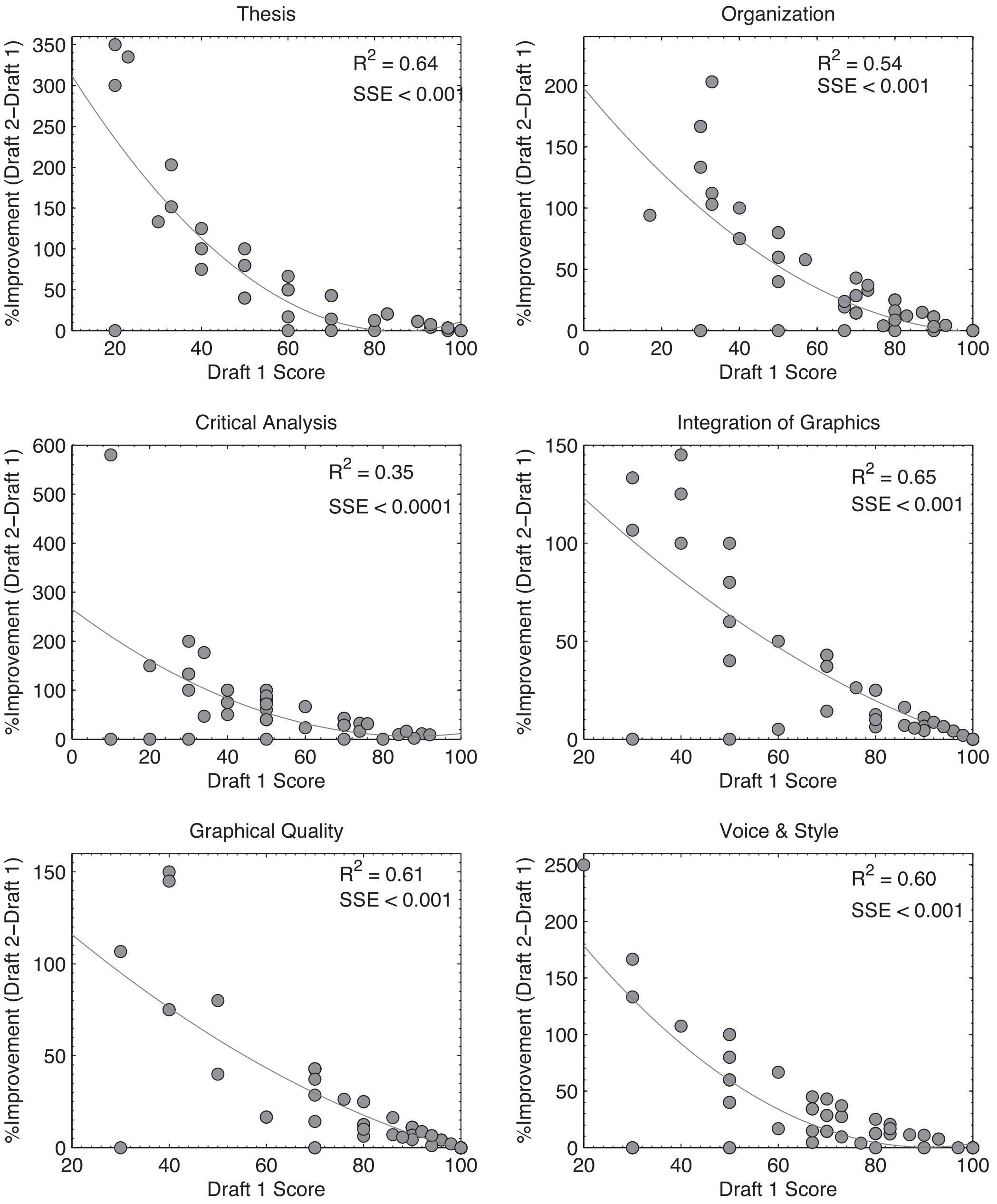

FIGURE 4: Aggregate writing assignment scores from 2014 and 2015 plotted as % improvement relative to the first-draft score for each rubric category (i.e., 100 * (Draft 2 − Draft 1) / Draft 1). Lines show second-order polynomial regressions, with R^2 and sum of the squared errors (SSE) values given in each panel. The statistically significant nonlinear relationships suggest that lower-achieving students benefited disproportionately from the iterative nature of the writing curriculum.

In both 2014 and 2015, we saw significant improvement in student writing and graphical presentation of data, suggesting that this approach was effective in helping students learn to present and discuss evidence in support of an argument. Improvement was greatest between the first and second drafts of the first writing assignment of each year, and students' writing continued to improve (though to a lesser degree) on subsequent assignments. We saw the greatest increase in scores among students with the lowest initial scores, suggesting that lower-achieving students benefited disproportionately from the inquiry-based, iterative writing approach described here. This result is consistent with studies that have shown that active learning strategies, including writing as a part of lab-based science courses, can close achievement gaps (Kirkpatrick and Pittendrigh, 1984; Akkus et al., 2007). Although our aim with this paper is to describe our course curriculum and its effectiveness rather than to evaluate specific teaching practices, these results hint at the power of writing as an active learning approach, and may warrant further investigation.

In addition to improving student writing, the assigned essays challenge students to synthesize information from multiple assignments to form a coherent argument, enhancing learning of the material. In this regard, the assignments support the WTL model: learning through meaningful reflection (Moskovitz and Kellogg, 2011). A review of research on WTL approaches has found that assignments that "engage the student in formulating a reasoned argument" (Reynolds et al., 2012) are among the most effective. Although our pre- and post-course concept survey did not explicitly test for the higher-order cognitive skills shown to be most impacted by WTL practices (Lord, 1997), many students cite the argumentation essays as an important component of their conceptual learning in the course. On post-course evaluations, students consistently highlight instruction and practice with writing as one of the most important elements of the course. One student wrote, "By requiring multiple scientific essays throughout the course, this course improved my writing skills and my understanding of scientific writing. Practice helps a great deal." Students also reflected on how the writing assignments impacted their data literacy: "I think that my data analysis skills have benefited significantly from the scientific writing style used for this class." Many listed the writing process, including learning how to find and cite references, as particularly challenging. Many wrote that they had not been exposed to scientific writing in prior classes. They appreciated the opportunity to synthesize concepts from lectures and problem sets, and said that writing helped them to better understand the material. "The most valuable part of ERS 201 was taking everything we learned and using them [sic] to fully understand the full picture as well as the paper writing process." Despite the challenges associated with writing (or perhaps because of them), students often write that scientific writing is something they will "take away" from the course and use in the rest of their lives. Overall, the writing curriculum developed for this course has received strongly positive student reviews. Although students often cite the challenges involved in learning to write scientific arguments, none have questioned the value of these exercises nor doubted the importance of developing their writing skills. Thus we argue that writing synthesis essays is a valuable way not only to train our students in persuasive writing, but to get them to reflect on what they have learned in a meaningful way.

Since our initial implementation in 2013, we have updated the questions students are required to address. For example, our second writing assignment now asks, "Is there justification for reducing carbon emissions during the 21st century?" One benefit of the approach outlined here is that it can easily be tailored to a wide range of topics—provided that open questions are posed that require students to formulate an argument.

Although we are largely satisfied with the approach and outcomes described herein, we have several suggestions for how to improve implementation of this writing curriculum in the future. The first would be to establish a more authentic audience for the written pieces (Moskovitz and Kellogg, 2011). For example, Lane (2014) had students write letters home describing results from college-level physics experiments. This approach encouraged students to explain concepts in straightforward terms and to connect with their audience. Often they described their own misconceptions, and made connections between earlier physics courses and labs, and the current laboratory assignment (Lane, 2014). Other potential outlets for student writing could be editorials in their hometown newspapers, educational activities for K–12 schoolchildren, or public service announcements on campus. A second modification would be to incorporate structured debates into the curriculum. Adding debate and discussion within the classroom prior to writing individual argumentation essays can enhance the learning benefit, especially for low-achieving students (Akkus et al., 2007). For example, an organized classroom debate could take place following out-of-class research conducted by teams of students and prior to handing out the writing assignment. This approach has been used successfully in political science classrooms to enhance active learning and student engagement (Oros, 2007), and would fit well with our writing curriculum. Finally, the writing curriculum (and related grading burden) could benefit from incorporating peer review. One option would be to use Calibrated Peer Review, a program that streamlines the logistics involved in organizing peer editing in the classroom (Robinson, 2001). Peer review would likely enhance students' familiarity with scientific writing practices, engagement with argumentation strategies, and depth of content knowledge (Timmerman and Strickland, 2009).

CONCLUSIONS

To conclude, we have presented an approach for incorporating inquiry-based writing into a mid-level geoscience course. We have found that guided practice, including formulation of a hypothesis, evaluation of data, and construction of an evidence-based argument, improves student writing and enhances student understanding of course concepts. Moreover, the inclusion of writing instruction and practice (including multiple drafts of essays with feedback) improves students' confidence with writing, as shown by their comments on course evaluations. Our writing curriculum bridges the WAP and WTL approaches by providing both writing instruction within disciplinary conventions and a structured framework for students to engage with real-world, open questions while formulating evidence-based arguments. We offer suggestions for implementation, including peer review and the incorporation of class debates prior to writing the argumentation essays; the latter has been shown to have particular positive impact on low-achieving students within an inquiry-based laboratory setting (Akkus et al., 2007). Overall, it is our hope that the described curriculum will be of use to geoscience teachers and that others will continue to build upon it.

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