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Abstract

With recent U.S. government efforts to develop policy procedures for addressing climate change, public understanding of basic aspects of climate change is imperative in order for people to understand such policy. However, widespread misconceptions of basic atmospheric principles exist among the public. In this study, we document levels of misunderstanding that undergraduate students at a large U.S. research institution have with respect to atmospheric carbon budgets and factors that may account for variability in their understanding. Students enrolled in an introductory geology course (n = 947) completed a survey on atmospheric carbon budgets in two sequential semesters. Results indicated that most students did not have a basic understanding of mass-balance problems and that their misunderstanding varied according to gender and their interest in science but not according to factors, such as students' opinions of the seriousness of climate change. Students also tended to exhibit poor graphical interpretation skills when examining mass-balance graphs.

Keywords

climate change, misconceptions, mass balance, carbon cycle, budgets

Disciplines

Educational Assessment, Evaluation, and Research | Science and Mathematics Education

Comments

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Conceptions of Atmospheric Carbon Budgets: Undergraduate Students' Perceptions of Mass Balance

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ABSTRACT

With recent U.S. government efforts to develop policy procedures for addressing climate change, public understanding of basic aspects of climate change is imperative in order for people to understand such policy. However, widespread misconceptions of basic atmospheric principles exist among the public. In this study, we document levels of misunderstanding that undergraduate students at a large U.S. research institution have with respect to atmospheric carbon budgets and factors that may account for variability in their understanding. Students enrolled in an introductory geology course ($n = 947$) completed a survey on atmospheric carbon budgets in two sequential semesters. Results indicated that most students did not have a basic understanding of mass-balance problems and that their misunderstanding varied according to gender and their interest in science but not according to factors, such as students' opinions of the seriousness of climate change. Students also tended to exhibit poor graphical interpretation skills when examining mass-balance graphs. *© 2014 National Association of Geoscience Teachers*. [DOI: 10.5408/13-052.1]

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INTRODUCTION

The rationale for this study developed out of one coauthor's consistent observations of introductory meteorology students' poor performance on an assignment investigating the relationship between atmospheric radiation balance and temperature. Many students assumed the hottest time of day corresponded with the period of strongest solar radiation (noon) instead of thinking about the balance between incoming solar radiation and outgoing infrared radiation emitted by the Earth. Stock–flow (or budget) systems such as the one above, in which the balance of the inflow and outflow rates of that system controls the level of a stock, are a source of confusion and misunderstanding for many U.S. college students (Gonzalez and Wong, 2011). Many people have been found to apply a simplistic model in interpreting such budget systems, in which they assume a direct match between the inflow rate and the overall stock level, a conception referred to in the literature as a correlation heuristic (Dutt and Gonzalez, 2012). Furthermore, research has indicated that the more complex a stock–flow system becomes, the more likely people are to rely on simple erroneous explanations such the correlation heuristic (Cronin et al., 2009). This type of inaccurate thinking persists even among graduate students with backgrounds in science, technology, engineering, and mathematics (STEM) fields at top-ranked universities (Sterman and Booth Sweeney, 2007). One can assume, therefore, that the U.S. public also largely misunderstands budget concepts.

Understanding budget systems in science settings requires an understanding of the conservation of mass and energy. In addition to being fundamental physical principles, mass and energy have many practical applications in day-to-day life. These misunderstandings of conservation and budget concepts offer possible explanations for some pressing problems in the U.S., including mismanagement of the federal budget, a balance of tax revenue and expenditures, and some of the difficulty many citizens have balancing their personal financial budgets, a balance of their personal income and spending. Researchers have also speculated that budget misunderstandings help explain some of the lack of public support for climate change policy, which requires citizens and policy makers to understand the delayed response of atmospheric carbon dioxide (CO_2) levels decreasing only when emission levels fall below removal rates from the atmosphere (Sterman and Booth Sweeney, 2007; Dutt and Gonzalez, 2012).

Research has shown that although the majority of the U.S. public views the seriousness of climate change as real, this number has fluctuated but declined overall in the last 5 y (Gallup, 2013). Climate change misconceptions are also common in the U.S. and other countries. For example, researchers have demonstrated that many people confuse ozone layer depletion with global warming or assume a cause-and-effect relationship between these two separate environmental problems (Boyes and Stanisstreet, 1992, 1993, 1994, 1997, 2001; Anderson and Wallin, 2000; Daniel et al., 2004). More relevant to this study are the well-documented misunderstandings held by students and the public regarding atmospheric CO_2 and other budgets (Booth Sweeney and Sterman, 2007; Cronin and Gonzales, 2007; Sterman and Booth Sweeney, 2007; Cronin et al., 2009; Sterman, 2008; Moxnes and Saysel, 2009; Gonzalez and Wong, 2011; Dutt and Gonzalez, 2012).

Cronin and Gonzales (2007) examined whether different presentations of budget information, such as through

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a) Currently, the amount of carbon that human activity inputs into the atmosphere is around 8 billion tons per year. The amount of carbon that is removed from the atmosphere by oceans, trees, and other factors is about 50% of that or 4 billion tons per year. The carbon input into the atmosphere by human activity has been increasing and is predicted to continue increasing.	b) If we steadily decreased our carbon input to the atmosphere starting in the year 2025, reached the removal rate (i.e. the amount of carbon removed from the atmosphere by the Earth) by the year 2075, kept emissions constant until 2099 and then dropped below the removal rate in 2100, in what year...

FIGURE 1: Atmospheric carbon scenarios presented to students on the survey. Four of the survey budget questions were based on these scenarios.

nongraphical representations, had an effect on highly educated graduate students' understanding of budgets. The use of graphs was found to improve student interpretation of budget data (as opposed to data presented in a table or text). Furthermore, graduate students were presented with bar graphs, rather than the (time series) line graphs more commonly used by scientists, and with "simpler" line graphs with fewer data points. Results suggested that these different graphical representations of data had no significant effect when students were tested on the material. The effect of having students "primed" about the concepts that they would need to apply to solve a task, i.e., students reviewing relevant concepts prior to performing the task, was also examined, resulting in some improvement in budget understanding, but the majority of students also misinterpreted the priming activity (Cronin and Gonzales, 2007). Of the graduate students who answered incorrectly, 70% simply matched patterns of CO_2 inflow with overall atmospheric CO_2 levels, violating the law of conservation of mass. Cronin et al. (2009) found no significant difference when more familiar budget scenarios, such as bank accounts, were used to present budget data to undergraduate students. Therefore, the above research shows that misunderstandings of budgets persist among highly educated adults regardless of the approaches used in the presentation of the budget content, suggesting that the misunderstandings stem from conceptual gaps rather than unfamiliarity with budget information.

Research into understanding the effect of peoples' background on budget knowledge is limited to the investigation of students from STEM fields versus non-STEM fields (Dutt and Gonzalez, 2012). Research investigating the effect of personal views toward the environment, science, and climate change on the accuracy of understanding budget systems is also limited.

In this study, we examined student understanding of stock–flow relationships using data from a large and diverse group of undergraduate students, and we hypothesize about the relationships among student characteristics and their misunderstandings of stock–flow systems. We focus specifically on students' misunderstanding of budgets related to understanding atmospheric carbon levels, a topic that is important for geoscience majors but also critical for the public to understand. The purpose of the research is to document the extent to which undergraduate students of various backgrounds held misconceptions of atmospheric carbon budgets so that we can begin to systematically address these misconceptions through coursework and experiential activities. The latter is the subject of a separate manuscript in preparation.

METHODS

During two consecutive fall semesters, students enrolled in an introductory geology course ($n = 947$) completed an online survey (see Appendix A) that was used to collect demographic information, opinions about global climate change, views regarding the scientific consensus on global climate change, and atmospheric carbon budget knowledge during the first 2 weeks of class. The multiple choice format was selected to accommodate the large number of students enrolled in the course and the style of exam questions in which the budget questions were embedded. Demographic information was collected to describe the sample and to use in tests for examining relationships among these characteristics and budget knowledge. Survey items addressed the following demographic information: gender, age, college in which they are majoring, year in school, mother's and father's level of education, interest in science, and concern for the environment.

Students also answered eight questions to determine their level of action for environmental protection or conservation: whether students recycled, reduced consumption, conserved water, decreased energy use by decreasing fossil fuel transportation use, decreased domestic energy use, discussed environmental issues with others, learned about environmental issues, or used renewable energy sources. Students chose one of three options to describe whether they engaged in the environmental actions "usually," "sometimes," or "never," and answered "yes" or "no" to usage of renewable energy sources items. Students were coded as having a low environmental action level if they engaged, at least sometimes, in zero to two actions; a medium environmental action level if they engaged in three or four actions, and a high environmental action level if they engaged in five or more actions. The survey was validated for content accuracy by geologists not involved in the study and

TABLE I: Demographic makeup of study participants ($n = 947$).

Demographic	Categories	%
Gender	Female	49.84
	Male	50.16
Age	15–18	26.24
	19–21	60.85
	22–24	9.95
	25–27	1.69
	28–30	0.74
	Over 40	0.53
Year	Freshman	30.79
	Sophomore	35.03
	Junior	20.38
	Senior	13.80
College	Liberal arts and sciences	44.30
	Business	20.13
	Human sciences	14.38
	Agriculture and life sciences	11.71
	Design	6.92
	Engineering	2.24
	Veterinary	0.32
Mother's Education	Did not graduate high school	2.22
	High school	19.32
	Some college	17.00
	Two-year degree program	17.00
	Bachelor's degree	32.63
	Degree beyond bachelor's	11.83
Father's Education	Did not graduate high school	2.43
	High school	24.63
	Some college	12.37
	Two-year degree program	11.95
	Bachelor's degree	31.71
	Degree beyond bachelor's	16.91
Concern for Environment	Very concerned	25.03
	Somewhat concerned	52.90
	Neutral	15.95
	Not very concerned	5.38
	Not concerned	0.74

for comprehension and design by statistical survey experts. The Institutional Review Board evaluated and approved the survey. The general demographic makeup of the participants in this study is presented in Tables I and II.

To determine students' opinions about global climate change and their views regarding the scientific consensus on global climate change, a series of statements were presented from which students selected the statement that most closely matched their views.

Survey questions testing budget knowledge were based on observed carbon emission and removal rates Fig. 1(a) and on projected rates for the remainder of the 21st century in a hypothetical scenario (Fig. 1(b)). Based on the atmospheric carbon budget scenario in Fig. 1(a), students chose an emission projection that they thought would lead to decreasing atmospheric carbon levels (Q1). After examining the hypothetical scenario in Fig. 1(b), students answered questions on what year atmospheric carbon levels would begin decreasing (Q2), in what years atmospheric carbon would be stable (Q3), and in what year maximum carbon levels would be reached (Q4). In addition to textual descriptions, students examined a graph depicting hypothetical carbon emissions and removal over the course of 75 y (Fig. 2). From the graph, students indicated at what point maximum (Q5) and minimum (Q6) levels of atmospheric carbon concentrations would occur.

The survey was administered in 2008 in and 2009 to undergraduates enrolled in an introductory physical geology class at a large U.S. Midwestern university using the WebCT/Blackboard online class management system. Survey completion was required and students received a fixed amount of credit, but students were made aware that accuracy of answers would not count toward their grade since the content had not yet been presented in the course.

Overall percentage correct and percentage correct by category are summarized by reporting the percentage of respondents by year. Two-sample tests of proportion are used to compare two proportions. Chi-square tests of association are used to determine statistical significance for comparing multiple-level items across years and groups. For quantitative measures, a two-sample t-test is used to test for differences in means when there are two groups, and one-way analysis of variance (ANOVA) is used when there are more than two groups.

RESULTS

Initial analysis examined whether data collected during the two sampling periods (consecutive years) could be collapsed into a single sample. Results revealed significant differences between the two groups on science interest and opinion of the seriousness of climate change using Bonferroni correction for 22 independent comparisons (Abdi, 2007). In light of these findings, we kept the two groups separate for science interest and for opinion of the seriousness of climate change and collapsed data for the remaining factors into a single group for analysis.

While an in-depth explanation of what accounts for the differences between students in the first year and those in the second year in science interest and opinions of the seriousness of climate change is beyond the scope of this paper, we speculate that widespread media coverage of local and regional flooding that occurred only months before the first-year survey administration may have played into the first-year group (2008) having more serious perspectives on climate change. Similar relationships among media coverage and public perception of global warming have been demonstrated in other studies (e.g., Yuki and Midori, 2009). Research has also made clear that a person's recent personal experience, such as experiencing extreme weather events, strongly influences perceptions of risk from issues like climate change (Weber, 2006). Furthermore, decreasing concern for climate change among the American public had been documented from 2008 to 2009 (Gallup, 2013).

TABLE II: Percentage of students reporting participation in environmental actions.

Environmental Action	% Usually	% Sometimes	% Never	% Yes	% No
Recycle	50.79	46.67	2.54		
Reduce consumption	15.84	46.46	37.70		
Reduce water use	56.07	39.28	4.65		
Reduce energy use	66.95	29.36	3.69		
Reduce domestic energy use	39.28	51.95	8.77		
Talk about environmental issues	12.35	51.95	35.70		
Learn about environmental issues	21.01	68.43	10.56		
Use renewable energy				7.18	92.82

Budget Items

More than half of the students responded incorrectly on all but one budget question in the first-year survey (Fig. 3). Graphical questions had the lowest percentage of correct student answers, with only 9% answering Q5 and 2% answering Q6 correctly. The highest percentage of correct responses (61%) was observed on Q3, where students recognized atmospheric carbon levels would be stable when inputs remained equal to outputs. The distribution of correct answers on the second-year survey was remarkably similar to that observed in the first year (Fig. 3), indicating that although some differences between students in the first year and those in the second year existed, their knowledge of budgets was almost identical.

In the first four questions, incorrect answers were spread across all options. Responses to Q5 and Q6 were reversed from the correct answers for a large majority of students. On Q1, 31% gave the right answer, but 39% said natural cycles without any human action will decrease the carbon level. The remaining students answered one of response A through D, which do not have adequate reduction in human contribution. On Q2, 49% gave the right answer; 18% said 2025 and 19% said 2075, which are both too early; and 23% said 2125 which is later than needed. On Q3, 61% had the right answer, 7% answered 2025–2075 (increasing period), 22% answered 2100–2125 (decreasing period), and 10% said "none of the above." On Q4, 23% gave the right answer, 60% said 2025 (too early), and 10% and 5% said, respectively, 2100 and 2125 (too late). On Q5 and Q6, 89% selected C (highest point on the graph) in Q5 and 84% said E (lowest point on the graph) in Q6, incorrectly matching overall levels with highest and lowest inflows, respectively.

Opinion of Climate Change Seriousness and Understanding of Consensus

Though there were some significant differences between the two groups, most participants indicated that they think global climate change is a serious issue (Table III) by selecting "somewhat serious" (about 42%) or "very serious" (about 35%). When students reflected on the scientific

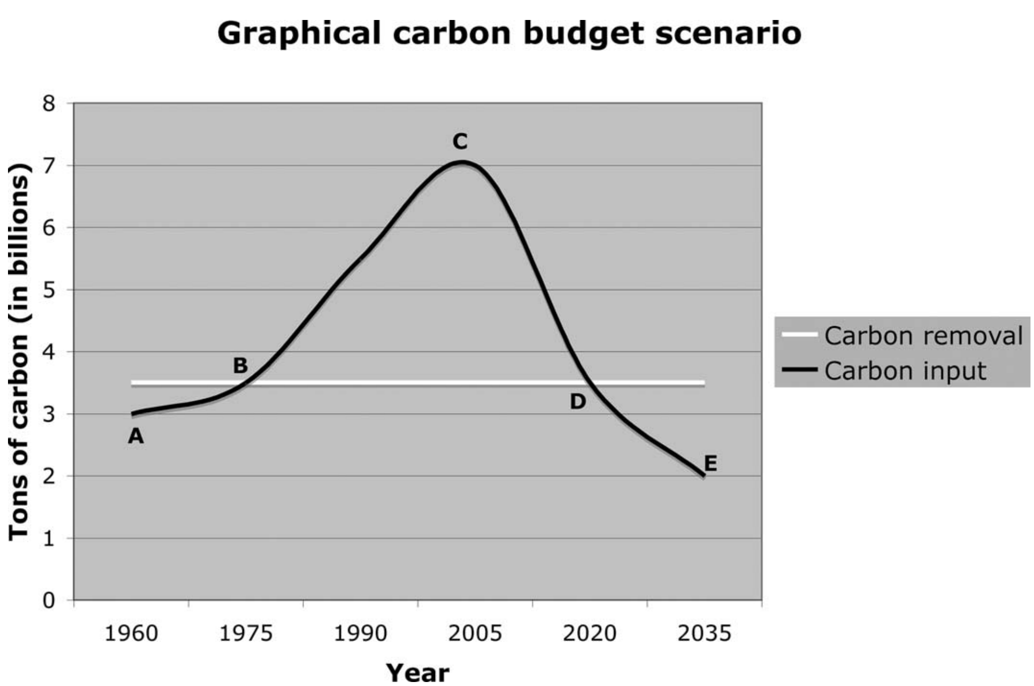

FIGURE 2: Graph presented to students on the survey from which students interpreted maximum and minimum atmospheric carbon levels.

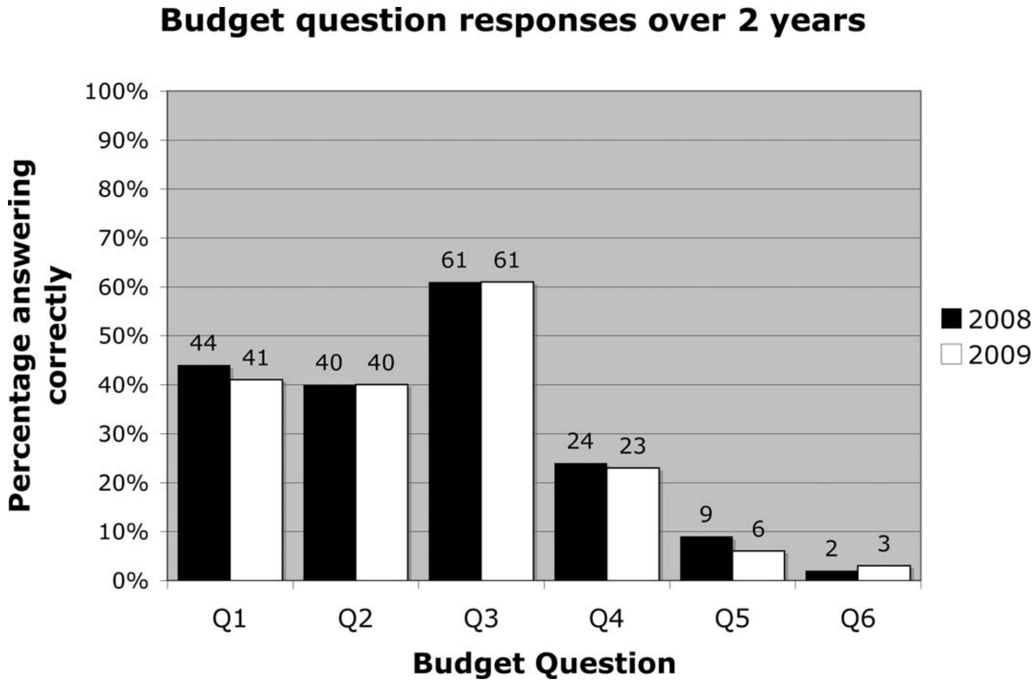

FIGURE 3: Student performance on budget questions over the 2 y of the sampling period. The majority of students answered questions incorrectly except for Q3. Performance is particularly low for graphical interpretation questions Q5 and Q6.

consensus for climate change, 67% had the correct perception of it (Fig. 4). A considerable percentage of students were under the impression there is significant scientific debate about climate change occurring (22%) or that there are insufficient data for scientists to assess climate change (9%). Importantly, no significant differences in budget knowledge were observed among students who held different opinions of the seriousness of climate change or among students who held differing levels of understanding of the scientific consensus for climate change.

Interest in Science

Recall that differences existed between the 2 y of the sampling period with regard to students' interest in science. Science interest levels are presented in Table IV. To address this difference, the effects of analyses of science interest on budget knowledge were conducted separately for each year. For each year of the sampling period, a 1×3 ANOVA was conducted with level of science interest (neutral or less, somewhat, or very interested) as the independent variable and budget knowledge as the dependent variable. For the first year, a main effect was found for level of science interest, with those who were more interested exhibiting greater budget knowledge [$F(2, 479) = 17.04$, $p < 0.001$]; for the second year, a similar main effect was found for level of science interest [$F(2, 462) = 15.19$, $p < 0.001$]. Thus, despite the differences between students in the first year and those in the second year in science interest, the main effect of science interest on budget knowledge was essentially the same for both years (Table V).

Gender

Aside from science interest, the only other demographic predictor variable that reached significance—once the Bonferroni correction was made—was gender. A two-sample t-test revealed an effect for gender ($p < 0.001$). Males (mean = 1.94) scored higher on the six budget knowledge answers than did females (mean = 1.59).

TABLE III: Percentage of students who chose one of five statements that most agreed with their opinions regarding the seriousness of climate change.[1]

Statement Regarding Seriousness of Climate Change	% 1st Year ($n = 482$)	% 2nd Year ($n = 465$)	% Overall ($n = 947$)
Very serious	40.66	28.88	34.88
Somewhat serious	41.08	43.97	42.49
Not very serious	8.51	13.36	10.89
Not a problem	3.94	8.62	6.24
Don't know	5.81	5.17	5.50

[1]The p value for comparing differences between years of the sampling period is less than 0.001. No significant differences were found in levels of budget knowledge and opinion of climate change.

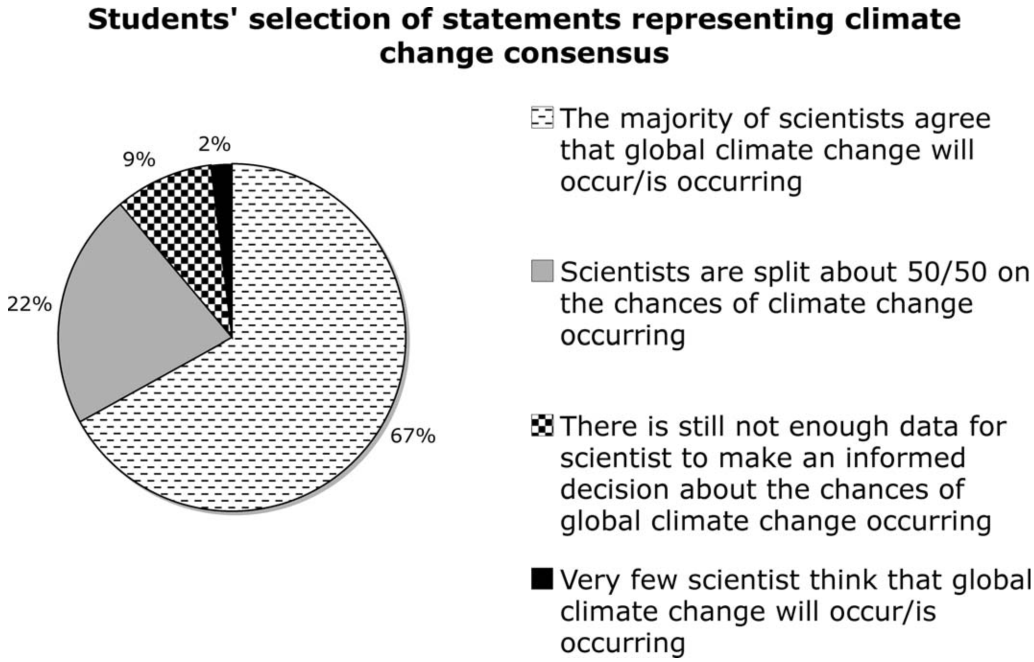

FIGURE 4: Percentage of students selecting one of four statements that most agreed with their understanding of the scientific consensus on climate change. No significant difference in budget knowledge was found among differing levels of students' understanding of the consensus for climate change.

DISCUSSION

The majority of students surveyed did not seem to recognize that emission rates of carbon would have to drop below removal rates from the atmosphere in order to decrease the carbon concentration in the atmosphere (Q1 in Fig. 3). Such thinking suggests that students are under the impression that climate change is easily reversible, with some students perhaps thinking that maintaining emission rates at their current level is sufficient to stop the rise in atmospheric greenhouse gases (i.e., if emission rates stop increasing, so will overall carbon levels). This result matches the results of other studies documenting use of the correlation heuristic in trying to understand budget systems (Sterman and Booth Sweeney, 2007; Sterman, 2008; Cronin et al., 2009; Dutt and Gonzalez, 2012). Our findings indicate that over 80% of students in 2008 and over 90% of students in 2009 matched the points of highest and lowest emissions with maximum and minimum atmospheric carbon concentrations, respectively, when examining a graph of emissions and natural carbon removal.

Although carbon budget misconceptions exist, the majority of students surveyed (77%) felt that global climate change was a serious or a somewhat serious problem. The mismatch in students' concern for climate change and their understanding of some of its crucial aspects could present interesting motivational opportunities for educators. The desire for knowledge and intellectual achievement has been identified as a key motivator for student learning (e.g., Maslow, 1970; Reiss, 2004), which suggests that increased motivation could result from making students aware of their misunderstandings of budgets and stimulating students' desire for deeper knowledge and understanding about a topic that many students find to be at least somewhat concerning. Other researchers have suggested a link between environmental concern and information-seeking efforts, resulting in increased knowledge about global warming (Kahlor and Rosenthal, 2009).

Interestingly, students' understanding of atmospheric carbon budgets was not affected by how serious they thought climate change was or their understanding of the scientific consensus for climate change. This suggests that budget misunderstandings are poorly understood even by

TABLE IV: Percentage of students who chose one of five levels to indicate science interest.[1]

Level of Science Interest	% 1st Year (n = 482)	% 2nd Year (n = 465)	% Overall (n = 947)
Very interested	23.70	17.64	20.72
Somewhat interested	45.12	36.77	41.02
Neutral	20.37	26.88	23.57
Not very interested	09.98	15.05	12.47
No interest	00.83	03.66	02.22

[1]The p value for comparing differences between years of the sampling period is less than 0.001.

TABLE V: Effect of level of science interest on budget knowledge for the 2 y of the sampling period.

Science Interest	1st-Year Mean	2nd-Year Mean
Very interested	2.31	2.27
Somewhat interested	1.76	1.78
Neutral or less	1.44	1.50

those who may support a reduction in emissions; such people still may not understand why such reductions are needed. Results of this study can also be taken to suggest that budget misunderstandings might be persistent regardless of a person's political stance on climate change. Although political affiliation was not indicated on our survey, others have shown that views regarding the seriousness of climate change—which were examined in this study and found not to be correlated with budget knowledge—are sharply divided by political affiliation (Gallup, 2013).

After analyzing our data to identify demographic predictors of budget knowledge, only two variables were found to be significant: interest in science and gender. These two variables likely had some level of dependence on each other. For example, of the students surveyed, only 14% of females reported being very interested in science, while nearly twice as many males—27%—reported this level of interest. Such gender differences likely reflect societal attitudes and experiences toward science that become indoctrinated in young children (Jones et al., 2000). Furthermore, students with greater interest in science have likely participated in more mathematical and science experiences than those not as interested in science. Research has shown that more experienced individuals tend to look for underlying, deeper relationships in information that is presented to them compared to inexperienced individuals (Chi et al., 1981; Schoenfeld, 1982). Gonzalez and Wong (2011) and Dutt and Gonzalez (2012) have used this to explain that those more experienced in math and science would be more likely to think deeply about the relationships presented in budget questions rather than using a superficial analysis of the information, such as when the correlation heuristic is applied.

CONCLUSIONS

A survey completed by 947 students in introductory geology courses reinforces findings showing widely held misconceptions of applications of mass balance as they relate to carbon in the atmosphere. The level of budget misunderstanding significantly varies with the demographic backgrounds of gender and science interest. Males had greater budget knowledge than did females, and those more interested in science (often also males) tended to have greater budget knowledge.

Budget understandings across all demographic variables were poor, and misunderstandings were amplified when students were required to interpret graphical data. Poor graphical interpretation is likely related to students matching overall stock levels in a system with the inflow levels to that system. In a sense, students were visually misled when they examined an inflow–outflow graph and confused the highest rates of inflow with the maximum stock levels and the lowest rates of inflow with the minimum stock levels. Such misunderstandings of budgets, a fundamental application of the law of conservation, demand remediation because so many applications of this fundamental idea exist. The very poor graphical understanding demonstrated by students also needs to be specifically targeted for remediation, since complex data sets (such as budgets) are frequently presented in graphical formats.

Budget misunderstandings and misconceptions documented in this study suggest a pressing need to remedy them specifically within the geosciences. Students exposed to budget concepts in introductory geoscience courses and the public would benefit from a better understanding of stock-and-flow relationships and their multiple practical applications. Geoscience majors will encounter these systems as they learn, for example, about geochemical cycles, glacial mass balance, sediment storage in fluvial systems, and water storage and extraction from aquifers.

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APPENDIX A. Pretest Budget Questions.

Q1. Currently, the amount of carbon that human activity inputs into the atmosphere is around 8 billion tons per year. The amount of carbon that is removed from the atmosphere by oceans, trees, and other factors is about 50% of that, or 4 billion tons per year. The carbon input into the atmosphere by human activity has been increasing and is predicted to continue increasing. Based on this information, what would the world have to do to **decrease** the level of carbon in the atmosphere?

A. Stabilize the amount of carbon input into the atmosphere at 12 billion tons per year
B. Stabilize the amount of carbon input into the atmosphere at 8 billion tons per year
C. Decrease the amount of carbon input into the atmosphere to 6 billion tons per year
D. Decrease the amount of carbon input into the atmosphere to 4 billion tons per year
E. Decrease the amount of carbon input into the atmosphere below 4 billion tons per year
F. Natural cycles of the Earth would decrease the carbon level in the atmosphere within our lifetimes without any human action

Q2. If we steadily decreased our carbon input to the atmosphere starting in the year 2025, reached the removal rate (i.e., the amount of carbon removed from the atmosphere by the Earth) by the year 2075, kept emissions constant until 2099, and then dropped below the removal rate in 2100, in what year would the carbon level in the atmosphere **begin to decrease**?

A. 2025
B. 2075
C. 2100
D. 2125

Q3. During which period of time would atmospheric carbon levels be **stable**?

A. 2025–2075
B. 2075–2099
C. 2100–2125
D. None of the above

Q4. At what point would the carbon level in the atmosphere first reach its **peak (highest level)**?

A. 2025
B. 2075
C. 2100
D. 2125

Q5. In the graph below, the x (horizontal) axis represents time. The y (vertical) axis represents the amount of carbon. The input (black) line shows the amount of carbon that is added to the atmosphere through human activities, and the removal (white) line is the amount of carbon that is removed from the atmosphere by natural processes. At what point would atmospheric carbon levels be **highest**?

A. B. C. D. E.

At what point would atmospheric carbon levels be **lowest**?

A. B. C. D. E.