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Integrating polar research into undergraduate curricula using computational guided inquiry

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ABSTRACT

Polar research plays a vital role in developing our understanding of Earth's climate system. It is intrinsically interdisciplinary, lending itself to integration into existing undergraduate courses. Here we explore introducing undergraduates to polar research through computational guided inquiry (CGI) modules taught in a variety of courses and disciplines. Students apply course disciplinary techniques to analysis of polar data or research, in the context of climate change, by working through educational modules that include spreadsheets (Excel™) or interactive computer programing (Python in a Jupyter Notebook), over a few class or lab periods. The goals of this exploratory curriculum project are to determine instructor perceptions of effectiveness of the educational modules for teaching preexisting disciplinary course objectives, as well as student perceptions of enjoyment and learning. Evaluation consisted of a student questionnaire and interviews with instructors by an external evaluator. Students and instructors overall reported positive experiences with the modules, highlighted the importance of polar data and climate literacy, and noted increases in student understanding of course learning goals and comfort with the computational tools. Professors further reported that students found the modules motivating, fun and engaging. Taken together, this suggests that the modules are an effective means of bringing polar research into undergraduate classrooms while satisfying instructor goals for course learning objectives. Lessons learned include the importance of providing material such as videos to help transition to the topics of polar research and climate change and of supporting widely varying computational fluency.

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Introduction

Climate change is amplified in polar regions, making them particularly susceptible to anthropogenic climate forcing (Arctic Monitoring and Assessment Programme (AMAP), 2019). Major investments have been made in polar research, resulting in improvements in our understanding of geophysical processes and climate (e.g. Goessling et al., 2016; Yuan et al., 2018; Intergovernmental Panel on Climate Change (IPCC), 2013). The remoteness and cold, snowy environments of the polar regions capture the imaginations of students, but these same conditions make it difficult to provide field experiences to more than a small number of students.

Knowledge about polar regions has been found to be limited among the U.S. population; for example, in the 2010 General Social Survey, respondents correctly answered an average of only 59% of five basic questions about the poles (Hamilton et al., 2012). Furthermore, those who know more polar facts "tend to be more concerned about polar changes such as endangered species, melting ice, and rising sea levels" (Hamilton et al., 2012). Taken together, this points to a need for educational materials that bring polar research into undergraduate curricula, in a way that improves climate literacy and understanding of linkages between polar regions and climate.

This paper describes the development and implementation of a series of educational modules that introduce polar research and climate science to students who might not otherwise experience them. Because courses on climate or polar regions are not standard at many colleges, our approach is to introduce polar research into courses across a variety of disciplines. Polar science is intrinsically interdisciplinary (e.g. Kennicutt et al., 2014; Petrov et al., 2016), making polar research a good candidate for supplying real-

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world examples for teaching existing course learning goals. Moreover, including a climate-related topic has the potential to enhance student interest, since many undergraduate students have significant worries about climate change (Bedford, 2016). Using real-world data has been shown to engage students in "authentic investigations of open-ended questions" (Bellanca & Brandt, 2010), to lead them to develop "defensible explanations of the way the natural world works" (Windschitl, 2008), and to confront them with real-world complexity (Ellwein et al., 2014).

Natural fits for investigating real-world data are active learning and the process of inquiry. In active learning, students are involved in "doing things and thinking about what they are doing" and "must engage in higher order thinking tasks such as analysis, synthesis, and evaluation" (Bonwell & Eison, 1991). Active learning has been shown to increase student performance relative to lecture-based classrooms (Freeman et al., 2014). In guided inquiry, the instructor guides students as they assume the role of scientists investigating the natural world (Martin-Hansen, 2002; Caspari et al., 2007). Inquiry-based learning has been shown to lead to improved student academic performance, growth, and retention (Apedoe et al., 2006; Lewis & Lewis, 2008; Weaver et al., 2008; Grissom et al., 2015), and can help students develop skills in scientific inquiry at the same time as developing content knowledge (Apedoe et al., 2006). Active learning pairs well with guided inquiry: students engage directly with content, conceptual models, and data under the guidance of the instructor.

The educational modules developed in this work use a type of guided inquiry we refer to as *Computational Guided Inquiry* (CGI). In CGI, the instructor guides the students as they use a computational tool (e.g. Excel^{TM}) or a programing language (e.g. Python) to manage, analyze, and visualize data. A CGI module provides a hands-on, scaffolded, inquiry-based pathway for students to develop the climate literacy and computational skills needed to interpret polar research and data. For example, Excel spreadsheets contain descriptive text and data while at the same time allowing students to create graphs or perform calculations that update in real time. Similarly, Jupyter Notebooks are structured into blocks that can contain either formatted text or executable Python code. This architecture makes it easy to set up exemplars of some computational task (such as graphing); students can then refer to these exemplars when tasked with performing similar operations. Enabling students to conduct their own calculations is ideal for allowing students to carry out prediction followed by analysis, which has been shown to be a key component of student learning, especially on computational assignments (Battista, 1999; Bowers et al., 2002; Tversky et al., 2002; Kim & Kasmer, 2009; Lim et al., 2010). Placing computing power in the hands of students creates opportunities for rich, inquiry-focused experiences as well as concept-oriented interactions between teachers and students.

Purpose and learning goals

The purpose of this work is to determine whether computational modules can effectively bring polar research to undergraduate students in a variety of courses while satisfying instructor expectations for student learning of course content. Additional goals include enhancing climate literacy, increasing student comfort with computation, and providing an opportunity for students to conduct inquiry in an active-learning framework (Table A1). Our measure of success is through gauging instructor and student perceptions of the module in terms of meeting these goals. Because inclusion of polar research and analysis of polar data required class time, it was important to assess the extent to which instructors felt that the modules were an effective means of teaching course content. Since modules were typically designed to be taught over just a few class meetings, learning objectives specific to each module (described below) were typically limited to providing students an initial, but meaningful exposure to polar research, and pathways for further learning.

Materials and implementation

Development of CGI modules

The CGI modules were developed using backward design (Wiggins & McTighe, 2018) by a curriculum development team consisting of project leaders, polar scientists, undergraduate instructors, a specialist in science education, and upper-level undergraduate students. Instructors in 2-year and 4-year colleges were identified through existing networks, word of mouth, and the Community College Undergraduate Research Initiative (CCURI) program. Development began by interviewing instructors about their course learning objectives and content and brainstorming possible overlaps with topics that arise in polar research. For example, learning how to use the heat of fusion to calculate the energy needed for melting (the disciplinary learning objective) taught in a thermodynamics course was recognized as being relevant to melting of sea ice and seasonal variability of sea ice extent (the polar science context). Pilot CGI modules were then developed that merged disciplinary learning objectives, polar research, and climate literacy within the computational framework of an Excel workbook or a Jupyter Notebook. Computational skills necessary to complete the module were specified and refined as modules were developed, and scaffolded into modules or included in pre-module tutorials.

Backward design was further informed by climate literacy principles (U.S. Global Change Research Program (USGCRP), 2009, p.4), including "Climate is complex," "Climate affects life," "Climate is variable," "Humans affect climate," "Climate change has consequences," and principles regarding data collection, models, and uncertainty, grouped under "Our understanding of climate". As examples, a module on heat diffusion links to thawing of permafrost in the Arctic, and a module on image processing links to the opening of a navigable summertime northern sea route due to declining sea ice, which are both consequences of humans affecting climate.

Instructor training took place at a workshop. For Python modules, instructors worked through a tutorial on

Table 1. Computational Guided Inquiry (CGI) modules and corresponding goals related to course topics, climate and polar literacy, and polar data used.

Module	Course Topical Goals	Climate/Polar Literacy	Polar data
Economics: Arctic EV (Excel)	Be able to apply the total economic valuation framework. Understand the impact of assumptions on estimated values. Learn how to adjust for inflation, convert currency and organize data.	Understand the value of lost ecosystem services in the Arctic due to climate change. Engage in academic research on climate and polar regions.	Research papers on polar ice melt.
Economics: Sea Level Rise (Excel)	Develop skills with tools used to apply decision-making given uncertainty in sea level rise and flooding. Be able to calculate and graph marginal damage curves.	Connect sea level rise due to ice melt in the polar regions to local impacts (at the nearest coastal city).	Polar ice melt scenarios
Quantum: Polar Spectra (Python)	Know shapes of spectral features due to ro-vibrational transitions. Model populations of rotational states according to degeneracy and temperature (T) to infer T. Understand the Planck function, its variation with T, and Wien's Law.	Develop a basic understanding of the greenhouse effect and the role of gases and T, the uniqueness of polar regions, and the importance of water vapor.	Polar downwelling infrared radiance spectra
Thermodynamics: Ice Melt (Python)	Be able to construct a phase diagram & compute heat needed for melting ice. Apply enthalpy, the Clapeyron equation, Raoult's Law & freezing point of sea ice in equilibrium with seawater.	Be aware of Arctic observa-tories and datasets. Understand how climate change affects Arctic ice volume, area, and depth and climate change.	Arctic ice volume, area, and depth
Physics: Permafrost (Python)	Develop skill in analyzing heat flow through a medium, using a numerical derivative technique, as well as heat flux, thermal diffusivity, heat capacity, and thermal conductivity.	Learn what permafrost is, how it responds to a warming climate annually & over multiple years, & consequences for the Arctic.	Temperature profiles through permafrost
Computer Science: Ice Images (Python)	Be able to load, manipulate & plot images, extract RGB components, & apply colormaps. Gain experience with noise removal and edge detection.	Learn about the ice-albedo effect, trends in Arctic sea ice related to climate change, and Earth observing satellites.	Satellite images of the Arctic
Tools in Env Sci[a]: Ice Cores (Python)	Be familiar with Milankovitch Cycles, Dansgaard Oeschger Events, and glacial-interglacial cycles and how they are evinced in ice core data.	Know that polar ice cores record past T & reveal correlations between CO_2 and T over millions of years.	Ice core profiles

[a]Tools in Environmental Science.

downloading and using Python in Jupyter Notebooks (available with the educational materials). Instructors worked through the modules they planned to teach, which were revised based on their feedback. They received training on teaching the modules, beginning with having students do prelab assignments that involve tasks such as downloading the Jupyter Notebook program, watching videos, reading articles, and defining vocabulary. In class, instructors typically give an introductory lecture, and then walk around the room helping students as needed as they work through the module on computers singly or in pairs, with built-in pauses for analysis. Finally, the class typically reunites for a post-module discussion and reflection. (An updated implementation design is provided with each educational module).

Surveys given to instructors after the introductory workshop helped improve alignment with instructor goals and will be used to improve future introductory workshops. After all modules were taught, instructor feedback was solicited in a second workshop and used to improve the modules, including discussing learning goals and how the modules achieved them or needed to be modified. This work was important for forming a set of modules that will be of more widespread interest and are more modular. This included making parts of the modules optional and making simplified versions of the modules for use in lower-level, more general courses.

Table 1 summarizes the modules developed for this work (the Computer Science module was taught in a prior year of the project and is described in the Supplemental). Updated versions of the CGI modules, including solutions and rubrics, are available at the Science Education and Resource Center (SERC) of Carleton College at https://serc.carleton.edu/penguin/.

CGI modules

Modules are discussed in turn below (the full module name is followed by the abbreviation used in figures and tables). These descriptions accompany Table A2, which summarizes the courses, including number of students and amount of time spent on the module, and Table 1, which gives module learning goals and polar research and data used.

Economics: Total economic valuation of the Arctic (Arctic EV)

Students are guided through a partial replication of analysis in a peer reviewed journal article that estimates the total economic value of ecosystem services in the Arctic (∼$800 billion per year). The module begins with a PowerPoint presentation that describes amplified warming in polar regions, a framework for total economic valuation, and methods for gathering data. The students read a journal article about the economics of ecosystem services, minerals and oil in a warming Arctic, on which their partial replication will be based. They start by finding the necessary data from the original sources used in the paper to estimate a variety of ecosystem service values in the Arctic, such as subsistence hunting, climate regulation, and the existence value of polar bears. They then work through an Excel sheet, adjusting the values for purchasing power parity and inflation. Ultimately, students are prompted to identify key assumptions in the analysis and how those assumptions affect the final estimated value. An in-depth description of this module is given by Fortmann et al. (2019).

Economics: Local sea level rise and polar ice melt (Sea level rise)

Students calculate expected marginal damages from sea level rise and flooding linked to polar ice melt in order to estimate how much money should be spent on climate change adaptation. They begin by completing an introduction to the module that discusses ice melt at each pole, watching a video on Antarctic ice melt, and reading an article about Arctic ice melt. The instructor gives a pre-module lecture using prepared slides that connects polar ice melt to sea level rise under different emissions scenarios, such as the possibility of extreme sea level rise given accelerated melting in the Antarctic. The lecture also introduces important concepts such as how to calculate expected damage values based on the probability of different flooding scenarios. Students then investigate various sea level rise scenarios, including one with Antarctic dynamics, and resulting flood levels for a coastal city, using Climate Central's Surging Seas website. Students gather housing data using an online mapping tool to estimate the lost home values associated with different flood levels. They are guided through the module with a series of slides (PowerPoint) that provide examples of how to conduct computations, which the students then do in their own spreadsheets. An in-depth description of this module is given by Fortmann et al. (2019).

Quantum: Rovibrational spectra of the polar atmosphere (Polar spectra)

Students learn about quantum mechanical concepts (population and degeneracy of energy states) and link them to spectral features in atmospheric infrared radiance spectra and the greenhouse effect. The module explains how rotational vibrational transitions link to climate change through the greenhouse effect, and how polar observations are important for climate change, using the example of Greenland ice melt and motivating the use of polar data in the context of climate change as a real-world application to the course topic. Students learn about the greenhouse effect and instruments that are used to measure infrared radiance. They then download and plot a spectrum measured at an Arctic observatory and use a simplified radiative transfer model (within the Jupyter Notebook) to generate a model spectrum, investigating how temperature and gases affect spectra and learning what makes polar regions unique (lower temperatures and water vapor) and the most important greenhouse gases. Students also examine the spectral shapes of emission features. Students next apply quantum mechanical concepts in the context of a South Polar spectrum. This includes modifying the temperature so the R-branches in a simulated spectrum match those in a South Polar spectrum, the result giving an estimate of the atmospheric temperature. They then estimate the near-surface temperature for the same spectra by an alternate method: using the Planck blackbody radiation spectrum. Students learn how spectral saturation can obscure the ro-vibrational structure and how lower temperatures and water vapor concentrations make polar spectra unique.

Thermodynamics: Seasonal Arctic ice melt (Ice melt)

Students learn about thermodynamics topics while calculating how much heat is required to melt Arctic sea ice. Videos are provided about the effect of climate change on Arctic sea ice that professors have the option of having students watch to transition to the topic (Supplemental). Students watch an animation of polar ice extent and download data of Arctic ice extent and volume and derive thickness from it. They integrate the Clapeyron equation to obtain the Clausius-Clapeyron and Thomson Equations, and apply these equations to construct a graphical representation of the phase diagram of water. They then modify this diagram according to Raoult's Law, and use the resulting figures to find the freezing point depression of Arctic sea ice in equilibrium with sea water. Finally, they compute the change in the enthalpy of fusion of water resulting from that temperature depression.

Physics: Heat diffusion through permafrost (Permafrost)

Students learn how to calculate heat diffusion through permafrost. Students prepare for the module by watching videos about thawing permafrost, its link to climate change, and the danger it poses for the Arctic. They review an article about changes in permafrost from Svalbard, in the Arctic. Students then plot and examine a figure from the article showing permafrost temperature with depth and time. Using the figure as a reference, they create their own plots of temperature with depth at three different times and explain how temperature changes with season and depth. They then calculate heat flow through permafrost for these three time periods, and learn how to take a numerical derivative.

Environmental science: Ice cores and climate change (Ice cores)

Students explore the paleoclimate record using ice cores as climate proxies and the role of stable isotopes in recording temperature. The instructor gives students a PowerPoint presentation on climate change on a geologic time scale and how ratios of stable isotopes of oxygen can serve as a temperature proxy. Students learn how ice cores record past temperature and how to recognize Dansgaard Oeschger Events and glacial-interglacial cycles in ice core data. They examine the nature of correlations between carbon dioxide and temperature in the past million years. To prepare for the computational aspect, students complete a tutorial to familiarize themselves with coding in Python. Students then download and work with ice core oxygen isotope ($\delta^{18}O$)

records archived by NOAA, including a 40,000-year record from the Greenland Ice Core Project and a 700,000 composite Antarctic core record. Students use an equation from the literature to convert δ^{18}O values in the 40,000-year record to temperature estimates.

Assessment mechanisms for instructors

Assessment is based on correct completion of tables, graphs, and responses to reflection prompts in the CGI modules. Instructors are provided with the module solution including possible open-ended responses. For this exploratory phase of the project, the suggested rubric was pass/fail (completed or not completed); detailed rubrics are now provided with modules. Since student engagement occurs primarily in class, multiple opportunities exist for an instructor to observe student progress and provide feedback in real time as students work through the modules. Students upload electronic versions of their completed CGI modules, allowing an instructor to further evaluate student work. Many instructors also evaluated student learning of the course topic in their own course-specific way (e.g. homework assignments or exams).

Study population and setting

The CGI modules were taught by nine instructors to 198 students in a variety of courses in four liberal arts colleges and a community college over the academic year 2018/2019 (Table A2). There was a lot of variability among instructors in terms of teaching experience and of teaching the specific course (one to more than 10 years), as well as familiarity with computer coding and python, with some instructors having little to no prior experience with Python.

Demographics of the 136 students who provided feedback on the student survey (Figure A1a-e of the Appendix) are as follows. All respondents were over 18. Fifty-eight percent indicated that they were science, technology, engineering or math (STEM) majors, with 3% indicating they were considering a STEM major ("maybe"), and the remainder indicating they were neither STEM majors nor considering a STEM major. There were equal numbers of students who identified as male (49%) or female (48%); no students selected "other," or "prefer not to say." Students identified as white (77%), Asian (20%), Hispanic/Latino/a (6%), multiple ethnicities (7%), African American/Black (3%), Filipino/a (3%); with the remainder made up of Pacific Islander, Turkish, Black Middle Eastern, and American Indian or Alaska Native and "prefer not to say."

Evaluation

Overall design and strategy

The goals of the evaluation are to collect and analyze feedback from instructors and students in order to assess how well project goals were met, determine challenges and areas for improvement, and potentially reveal unexpected outcomes. To this end, student surveys and instructor interviews were developed by external evaluators at the Social & Economic Sciences Research Center (SESRC) of Washington State University, with input from the project leaders and an undergraduate student.

Student surveys

A retrospective pre-post survey was used to avoid response-shift bias (Howard & Dailey, 1979; Klatt & Taylor-Powell, 2005; Drennan & Hyde, 2008), since evidence of such bias was apparent in pre- and post-intervention surveys administered in the prior year (see Supplemental Materials). The survey was programed into Qualtrics and made available online (by the external evaluators) to students within a few days of completing the module. Surveys were anonymous and included Likert-scale, multiple-choice and open-ended questions. (The student survey is summarized in Table A1 and the complete survey is given in the Supplemental).

Student survey responses were analyzed as follows. For Likert-scale questions, the scale was ranked (see Table S2 in the Supplemental) and medians were determined. A Mann Whitney U test (two-tailed) was used to determine if there were shifts in pre and post responses or differences between groups of respondents. For most survey questions, percentages are reported in terms of number of respondents (n) for that question, with the exception of word selections, which are reported in terms of percent of students who answered at least one question on the survey. For word selections and distributions of race/ethnicity, students could select more than one category, so the total could be over 100%. Open-ended questions on student surveys were analyzed using grounded theory (Charmaz, 2014) and emergent themes were identified and coded.

Instructor interviews

To assess instructor perceptions, instructors were interviewed by the external evaluators after teaching the CGI modules (instructor interview questions are summarized in Table A1 and the complete interview is given in the Supplemental). The external evaluators provided an anonymized written summary of instructor responses, including key points and emergent themes.

Results

Overall student perceptions

Student post-survey responses (medians and modes) from courses taught in 2018/2019 are summarized in Table 2 with distributions shown in Figure 1 and in the Appendix in Figures A1-A2. Results are shown for all survey respondents (overall; dark blue bars in figures) and by module. Numbers in the table correspond to the Likert scale for each question from least (1) to most (5). Most students had little to no exposure to polar data before completing the module (Polar before median of 2, corresponding to "a little" in Table 2;

Table 2. Medians and modes of student survey responses for courses in 2018/2019, where n refers to the number of students who answered the survey item, U is the Mann-Whitney U with associated P, N indicates no, M male, F female, Ex excel, and Py python. Other abbreviations and conversion from Likert scale to rank are described in the text.

	Overall	Econ: Arctic EV	Econ: Sea level rise	Quantum Polar Spectra	Thermo: Ice Melt	Physics: Permafrost	Methods: Ice cores
Python/Excel comfort:							
Before median	3	4	4	3	3	2	1.5
After median	4	4	4	4	4	4	4.0
n	141	31	36	22	19	19	6
U	6509	377	511	134	111 (113)	76 (113)	5.5 (5)
P	<0.01	0.12	0.1	<0.01	0.03	<0.01	0.045
Importance polar:							
Before median	4	4.0	4	4	4	3	3
After median	5	4.5	5	5	4	5	4
n	108	26	26	20	15	16	5
U	3403	249	190	78	69 (64)	22 (75)	5.5 (2)
P	<0.01	0.08	<0.01	<0.01	0.06	<0.01	0.16
Course knowledge:							
Before median	3	3	3	3	3	3	2
After median	4	4	4	4	4	4	3
n	114	28	28	21	15	17	5
U	2298	189	102	101	33 (64)	37 (87)	1.5 (2)
P	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	0.02
Climate knowledge:							
Before median	3	3	3	3	3	3	4
After median	4	4	4	4	3	4	4
n	114	28	28	21	15	17	5
U	3403	274	206	88	59 (64)	33 (87)	11.5 (2)
P	<0.01	0.03	<0.01	<0.01	0.01	<0.01	0.9
Polar before median	2	2	2	2	2	2	2
Learn more polar (%)	60	54	50	62	63	72	100
Module rank median	4	3.5	4	4	4	4	5
First CGI (%)	46	54	55	5	19	88	75
STEM major (%)	58	11	25	100	100	100	40
Female (%)	50	44	57	67	69	18	20
Computational Tool	–	Ex	Ex	Py	Py	Py	Py
Total Students	225	43	63	37	52	20	10
Emergent theme 1	Impacts[a]	Models[d]	Impacts	Course[f]	Urgent	Urgent	Urgent
Emergent theme 2	Urgent[b]	Impacts	Urgent	Action	World	World	Action
Emergent theme 3	World[c]	World	Action[e]	Polar	Polar[g]	Course	Course

[a]Climate change impacts the environment/people on local/global scales.
[b]Evidence indicates that climate is changing/climate change is urgent. [c]The module was relevant to the real world.
[d]Models have uncertainty and must make assumptions/approximations and exclude variables.
[e]There is a need for action/solutions for combatting climate change.
[f]The module was relevant to the course.
[g]Polar regions are unique/important, have local impacts, and impact climate change.

see also Figure A1c). Approximately equal numbers of students reported that it was their first CGI module as reported that they had done a CGI module before (Figure A1a).

Overall, students reported positive increases in learning and viewed the modules favorably (Figure 1a-g; Table 2). There were statistically significant increases in median comfort with the computational tool, course topic knowledge, and climate knowledge (which all increased from "fair" to "good"); and in the median importance placed on polar research in the context of climate change (which increased from "very" to "extremely"). The median module ranking was "good" (4; Table 2) and 96% of respondents ranked the modules as *fair*, *good*, or *excellent* (Figure 1g). Students selected the following words most frequently to describe the modules: *engaging* (51%), *useful* (49%), *helpful* (42%), *fun* (27%), and *challenging* (26%). Sixty percent of respondents reported that they would like to learn more about polar research ("Learn more polar" in Table 2), with another 32% indicating "maybe," (Figure 1h).

The most commonly selected words that indicate room for improvement of the modules were *confusing* (13%) and *boring* (11%) (Figure A2d). These were reflected in some student responses to open-ended survey questions, such as "Maybe giving a little bit more background to some of the formulas and other very detailed aspects of the module that made it a little confusing to get through."

Although over a third of students indicated they had no exposure to polar data prior to the module and 20% ranked themselves as "very uncomfortable" with the computational tool before the module, no student indicated that the computational element was too hard, although a few students requested more support for coding.

No statistically significant differences were found between responses in upper-level and lower-level courses. Comparing STEM and non-STEM majors, only minor differences were found. Non-STEM majors placed a higher importance on polar research in the context of climate change before the module (medians of 3.5 and 4.0 and n of 64 and 45 for STEM and non-STEM, $U = 1101$, $P = 0.03$), and STEM majors were more interested in learning more polar research after the module (medians of 3 and 2 and n of 67 and 49

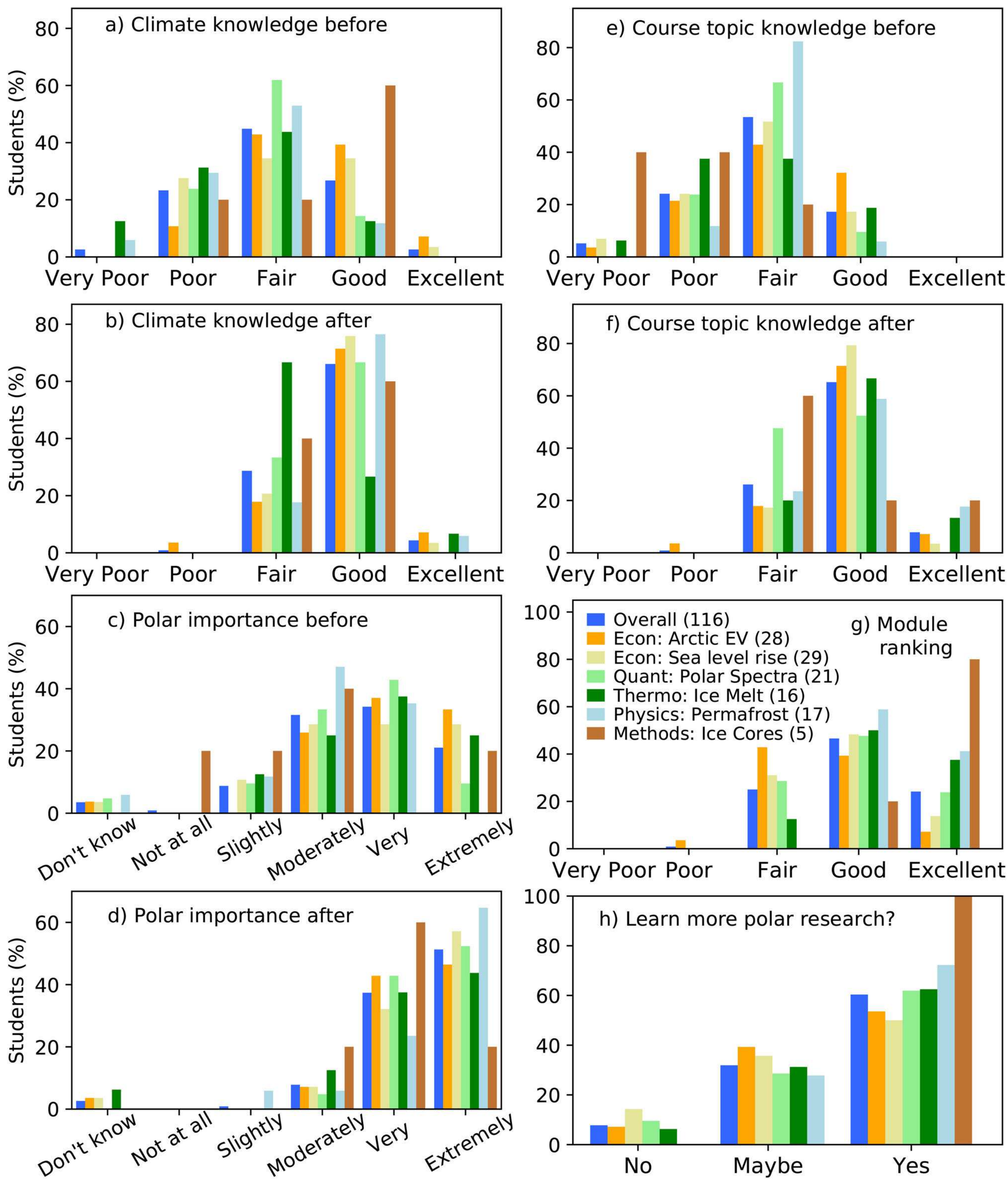

Figure 1. Student self-assessment of (a) climate knowledge before taking the module, (b) climate knowledge after taking the module; important placed on polar research in the context of climate change (c) before taking the module and (d) after taking the module; course topic knowledge (e) before taking the module, and (f) after taking the module; as well as responses regarding (g) student ranking of module, and (h) Student response to question, "Would you like to learn more about polar research?" The legend in panel (g) gives module names, which correspond to all panels, and the approximate number of survey respondents.

for STEM and non-STEM majors, Mann-Whitney $U = 2043$, $P < 0.01$).

Student perceptions by module

Median student perceptions were fairly similar across modules; differences are discussed below.

Economics: Arctic EV and Sea level rise

The Economics modules have a variety of differences from the other modules. One major difference is that the computational tool used was Excel rather than Python. Students generally reported greater comfort with the computational tool before the module relative to other modules (median of 4 or "somewhat comfortable" rather than "neutral" or "somewhat uncomfortable"). This is unsurprising given the prevalence of Excel use compared to Python at the undergraduate level and below. The after-module median was the same as for the other modules ("somewhat comfortable)."

Another major difference is that the Economics modules have the highest percentages of non-STEM majors (72 and 90% for Sea Level Rise and Arctic EV). Thus these classes represent a unique opportunity to bring polar research to students who may be unlikely to otherwise experience it. At the same time, it was expected that including geophysical research and computational tools in a primarily non-STEM major classes would introduce additional challenges. Despite this expectation, the economics modules were overall received very positively. Median responses were similar to those from other modules (Table 2). The median ranking for the importance of polar research in the context of climate change increased from 4 to 5 (from "very important" to "extremely important") for the Sea level rise module. The most-frequently selected positive words to describe the modules were "useful" and "engaging," (more than 35% of respondents selected each; Figure A2c), while about 30% selected "helpful."

The Arctic EV module received a lower overall ranking than other modules, with a median of 3.5 compared to 4 ($P < 0.01$, $U = 671.5$, $n = 26$ for Arctic EV, $n = 85$ for other modules). This is not attributable to the low percentage of STEM majors (10%), given that module rankings between STEM and non-STEM majors as a whole did not differ. Over a third of respondents who selected words to describe the module chose "confusing." This was also echoed in the comments. However, there is evidence that these differences may be due to year-to-year variability (See Supplemental Material).

Quantum: Polar spectra and Thermodynamics: Ice melt

The quantum mechanics and thermodynamics modules had similar student compositions and results (see Table 2). The quantum students reported perhaps the largest gains in climate knowledge. This could be due to the fact that the polar spectra CGI included a student-directed investigation of the greenhouse effect's impact on spectra. These modules received the highest frequency of students selecting the words "engaging," and, for the polar spectra CGI, "helpful," (Figure A2c). Twenty-four to 38% of respondents gave these modules a ranking of "excellent," with close to half ranking them as good (Figure 1g). The quantum students ranked their polar knowledge prior to the module the highest compared to other modules (with almost 20% saying "a fair amount"). Student survey respondents for these modules were all STEM majors. Compared to other modules, they had the most prior experience with CGIs, and the highest proportion of women.

Physics: Permafrost

Students who completed the permafrost module also completed a simplified version of the ice melt module and had the option of completing a simplified version of the polar spectra module as extra credit. Therefore, student survey results may relate to any of these modules. The physics class (Engineering Physics) was a lower level course taught at a community college. Student surveys included the highest word selections of "fun," "exciting," and "motivating" compared to other modules, and also scored highly in "useful" and "helpful." All respondents ranked the module as "Good" or "Excellent." This set of students reported being all STEM majors, with the largest proportion of men (82%) and the most racial/ethnic diversity (Figure A1b-d).

Climate literacy and the importance of polar regions

The following emergent themes were identified in student open-ended responses (Figure A1f; keywords used in the figure follow each theme): climate change impacts the environment and people locally and globally (CC impacts); the student recognized evidence that climate is changing or the need to respond to climate change is urgent (CC urgency); the module was relevant to the real world (World relevance); the module was relevant to the course (Course relevance); polar regions are unique, important, have local impacts, or impact climate change (Polar regions); models must make assumptions or approximations, exclude variables, and have uncertainty (Assumptions); there is a need for action and solutions for combatting climate change (Action); climate change is complex (CC complex); and polar and climate research and data are readily available (Data).

As an example, the following quote contains a number of themes, indicated in brackets: "I learned how significant what goes on in the poles is to the rest of the world [World relevance]; even though they seem distant and not related, the amount of ice we have, permafrost, etc. is rapidly diminishing [Polar regions; CC urgency], but if we take action it's still not too late to change [Action]. I also learned how to analyze polar data and research how the physics being learned in class relates to what is going on in the poles [Course Relevance]." The theme that climate change is complex was indicated in responses such as, "A lot of the time since we're using real data the relationships are very complex and allow you to apply what you're learning to model real world situations." Themes related to assumptions and data were expressed in comments like, "Much of the data gathered during this module was heavily reliant on making educated assumptions, which surprised me," and "I learned that the data and research regarding polar regions is extensive and is always ongoing." (See the Supplemental for other examples).

Instructor perceptions

Instructor interview responses, summarized by the external evaluator (see Supplemental), demonstrate that many project objectives were met (Table A2). Instructors found that modules met course learning objectives and helped students effectively learn course content. They reported that students found the modules to be fun and engaging and that the climate change application motivated them to learn course content, resulting in an overall positive experience. Instructors further indicated that students improved critical thinking skills and computational literacy and gained comfort and hands-on experiences with Excel and Python. Finally, most instructors reported that participating in the project changed their thinking about teaching.

Instructors also reported a variety of indirect benefits of teaching the modules. For example, prior to teaching the module, instructor goals included becoming part of a community of educators, having more fun and variety in class, improving computational fluency, staying current in the field, becoming reconnected with current research, and improving as an educator. After the module many instructors realized these gains, reporting enjoying the interdisciplinary aspects and networking afforded by working with other instructors, gaining a new perspective on their discipline, learning programing skills, gaining topical knowledge, applying what they learned to other courses, and gaining an appreciation of active learning or using real-world data. Most instructors reported that they will continue to use the modules in their courses.

Efficiency and effectiveness

An important goal was that the modules would allow instructors to efficiently teach course topics without taking up too much additional class time (Table A1). One instructor indicated that they were "choosing to make the tradeoff, where I spent more time teaching students about polar science, or polar data, or climate change." Instructors overall found this tradeoff worthwhile, in part because they thought the modules were effective in enhancing student learning. One offered that students attained "a more sophisticated understanding of the concepts." In response to a question asking whether students learned course content "better, the same, or worse" with CGI modules, six of the nine instructors interviewed gave an unqualified response of "better," two assumed it was better, though it was difficult to say, and one indicated that student learning was similar. No interviewed instructor indicated that the CGI modules hindered student learning.

Free-form responses by students reinforce this interpretation. While a few students indicated that the modules were too long ("I didn't really feel that the takeaways from this module justified the amount of time spent on it." "I was engaged for 2 hours, but after that point, I stopped making meaningful connections and just focused on completing the CGI"), a greater number felt the approach was a good use of their time, as evinced by comments such as: "it was a great way to learn," "the topic was pretty interesting and relevant so I stayed focused on the topic," "It was engaging and very educational!" and "The ideas rose naturally and was clear and concise."

Discussion

Benefits of linking the course topic to the real world

We believe the positive reception on the part of students and instructors derives from their recognition that the modules related course content to the real world, especially polar regions, in the context of climate change (meeting a project objective; Table A1). This interpretation hinges on the fact that the most prominent themes manifested by analysis of open-ended student responses are that climate change is impacting the world, the module was relevant to the real world and to the course, and that polar regions are unique and important. Student open-ended responses reinforce these themes. In addition, a variety of student responses cite the complexity inherent in real-world data and relationships as a contributing factor in the development of skills resulting from engagement in the modules. Taken together, these data suggest that the application of disciplinary content in a real-world (polar) setting influenced by climate change promotes key components of critical thinking, including critical analysis of assumptions and discernment among diverse sources of information (Paul & Elder, 2009; Nelson & Crow, 2014).

Climate literacy and the importance of polar regions

A number of student free-form responses and the emergent themes that derive from them are consistent with increases in climate literacy, understanding of the role of polar regions, and value placed on the importance of polar regions for climate change. Furthermore, students reported learning concepts that are part of the climate literacy principles (USGCRP, 2009) used in developing the CGI modules, suggesting that these principles were implemented successfully. This is apparent by comparing emergent themes to the climate literacy principles. For example, the theme that climate change impacts the environment and people locally and globally links to the climate literacy principles "climate affects life," and "climate change has consequences." (Other examples are given in the Supplemental).

Limitations and challenges

An important constraint on adopting the methodology presented here is that Guided Inquiry requires an active-learning classroom setting, with instructors accustomed to providing feedback and help as needed. However, several considerations mitigate this constraint. Because most modules presented here can be taught in discrete units (usually one multi-hour lab period or several shorter class sessions), their adoption is compatible with a variety of existing teaching environments, including lecture-based ones, as long as instructors are willing to transition to an active-learning mode during the CGI exercise itself.

Another requirement is that students must have in-class access to computers with the necessary program installed (via a campus computer lab or personal laptop). This was not found to be an obstacle for the relatively small classes taught in this project, but might present a challenge for large classes at state universities. Moreover, instructors and students must be willing and able to acquire basic Excel or Python/Jupyter Notebook skills. The level of skill required in terms of Python coding was found to be readily achievable even to novices. The instructors without prior experience with Python were able to successfully teach the modules after completing a brief tutorial on python and working through the modules. In general, lack of prior coding experience on the part of students was not found to be an obstacle to successful engagement. For example, overall module rankings, comfort with the computational tool after completing the module, and negative experiences with coding were not found to be correlated with whether the students were STEM majors or in upper vs. lower-level classes. However, there was variability in computational fluency with some students requesting more help with coding, and others requesting greater computational challenge.

A technical challenge relates to changes in repositories where polar research datasets are stored. Over the time span of the project, some repositories were reorganized or removed altogether. This necessitates periodic checks to ensure that data remain available online, modifying modules to use alternative data when previously-used data is removed, and making available digital back-ups. This challenge would seem to be an inescapable feature of digital repositories for the foreseeable future.

We recognize important limitations in our assessment methodology. It does not quantitatively demonstrate student learning, but rather gauges student reflections on learning and engagement and instructor perceptions of learning. Moving forward, we hope to address this challenge through pre/post survey quizzes and module assessments. Additionally, the number of student surveys is fairly small, with only 114 students completing most or all of the survey and between 5 and 36 respondents per module. Finally, racial diversity in the student study group is limited, with a low proportion of students who identify as persons of color. We hope to increase diversity through expanding the types of modules and including additional institutions.

Implications

Lessons learned

The most important lesson learned in this project relates to proof of concept: instructors from a wide variety of disciplines are willing to bring polar data and research into their courses, providing students meaningful hands-on access to data and research they otherwise may not have known existed.

A number of other lessons were learned as well. We found that a well-designed array of support mechanisms greatly improves the likelihood of a successful teaching outcome. This includes not just educational materials, tutorials, and instructor versions of CGI modules, but also (ideally) real-time access to a polar scientist or climate expert, even if only remotely. And while we have found that these resources can usually be assembled with sufficient advance planning, we are also convinced that more formal mechanisms for supplying such expertise would be desirable, e.g., through partnerships with outreach organizations like Skype a Scientist.

Another lesson concerned the need for mechanisms that give meaning and context to classroom transitions between normal disciplinary-focused teaching and CGI activities. To facilitate the transition to a CGI activity, we found that vetted videos on climate change (e.g. the National Academies of Science series on climate change) often served well as introductions to topics that instructors had inadequate training in. We also realized the importance of methods to aid in the reverse transition, i.e., from CGI engagement back to regular coursework.

Summary

We have described how we have introduced undergraduates to polar research by incorporating polar-themed CGI modules into a variety of courses and disciplines. These modules are designed to enhance student learning of preexisting disciplinary course objectives, while at the same time introducing students to polar-specific data or processes and principles of climate literacy. Qualitative assessment suggests this is an efficient approach that students and instructors find leads to student learning of disciplinary content, with added bonuses of heightened critical thinking and engagement, computational confidence, and climate literacy.

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Appendix

Table A1. Objectives for Computational Guided Inquiry (CGI) Modules addressed through student surveys (first six objectives) and instructor interviews (last 3 objectives).

Objective	Evaluation instrument: Question or Topic
Increase student confidence in computational tools.	How comfortable were you with Excel / the Python programing language before this module, and how comfortable are you now?
Develop student appreciation of the importance of polar research in the context of climate change.	Before this module, how much exposure did you have to polar research? How important did you think polar research was in the context of climate change before this module and how important do you think it is now? Describe what you learned in this module about polar regions, data, or research. Would you like to learn more about polar data?
Improve student perceptions of climate literacy.	How would you rate your climate knowledge before this module and now? Describe what you learned in this module about climate or climate change.
Provide students an engaging, useful, and fun way to learn actively by analyzing real-world polar research and data.	Doing this module was a _________ way to learn about a topic in your course. Choose from the list below to fill in the blank. (Check all that apply) Overall, how would you rate the polar data module you just completed?
Increase perceived course topical knowledge.	How would you rate your knowledge on the course topic before this module and now? Describe what you learned in this module relating to your course topic.
Solicit additional feedback.	Add other words to describe the module. Why did you give the polar data module this rating? Do you have any suggestions for improving this polar data module? Do you have any other comments about the polar data module?
Provide instructors an educational module that they feel allows them to efficiently teach course topics without using more class time than desired.	How was your experience implementing the modules in your course? What were the principal hurdles to implementing the modules? How did you transition from the course topic to the module? What was effective and how could the transition be more effective? If you will be teaching the same class in the future, do you plan to continue to use the modules? If not, why not?
Provide instructors with a tool that they believe is fun and engaging for students and that allows them to help guide students in learning actively by analyzing real-world polar research and data	To what extent were the modules fun and engaging for the students? Did providing the context of climate change motivate students to learn? Did the modules you implemented substitute for preexisting course objectives? How effective were the modules in helping your students meet the course learning objectives? Would you say that your students learned the course content better, the same, or worse with the modules than with the original classroom pedagogy?
Solicit additional feedback.	Did the students gain anything else from the modules? What have you taken away from your participation in the project? Has your involvement in the project changed how you think about teaching? If so, how? Is there anything else you'd like to share about your experience in this project?

Table A2. Course descriptions for Computational Guided Inquiry (CGI) Modules, including course names, educational setting (CC, PLA, and State indicate community college, private liberal arts, and state schools, respectively, and Econ stands for economics), course level, time taken to complete the modules, number of students in the course (N) and number of students who completed the survey (n). Long names for modules are given in the main text.

Module	Course	Setting	Level	Time (h)	N	n
Arctic EV	Environmental Econ	PLA	Lower	2	24	19
	Climate Change Econ	PLA	Upper	2	19	12
Sea level	Sci & Econ of Clim Chng	PLA	Upper	1.5	44	19
rise	Climate Change Econ	PLA	Upper	2	19	17
	Regional & Urban Econ	PLA	Upper	1.5	35	0
Polar	Physical Chemistry	PLA	Upper	5	11	9
Spectra	Physical Chemistry	PLA	Upper	4	5	2
	Physical Chemistry	PLA	Upper	3	4	4
	Quantum Chemistry	PLA	Upper	3.5	10	7
	Engineering Physics[a,b]	CC	Lower	3	8	–
Ice Melt	Physical Chemistry	PLA	Upper	5	20	15
	Physical Chemistry	PLA	Upper	4	11	0
	Physical Chemistry	PLA	Upper	5	5	0
	Chemical Thermodynamics[a]	PLA	Upper	5	10	5
	Engineering Physics	CC	Lower	3	20	–
Permafrost	Engineering Physics	CC	Lower	3	20	21
Ice Cores	Tools in Env. Sci.[c]	PLA	Lower	4.5	10	6
Total				–	275	136
Total Unique[d]				–	198	–

[a]These modules were simplified for the lower-level class. Student surveys for these modules are only counted once, under Permafrost.
[b]This module was given as extra credit.
[c]Tools in Environmental Science.
[d]Estimated total number of (unique) students who completed one or more modules.

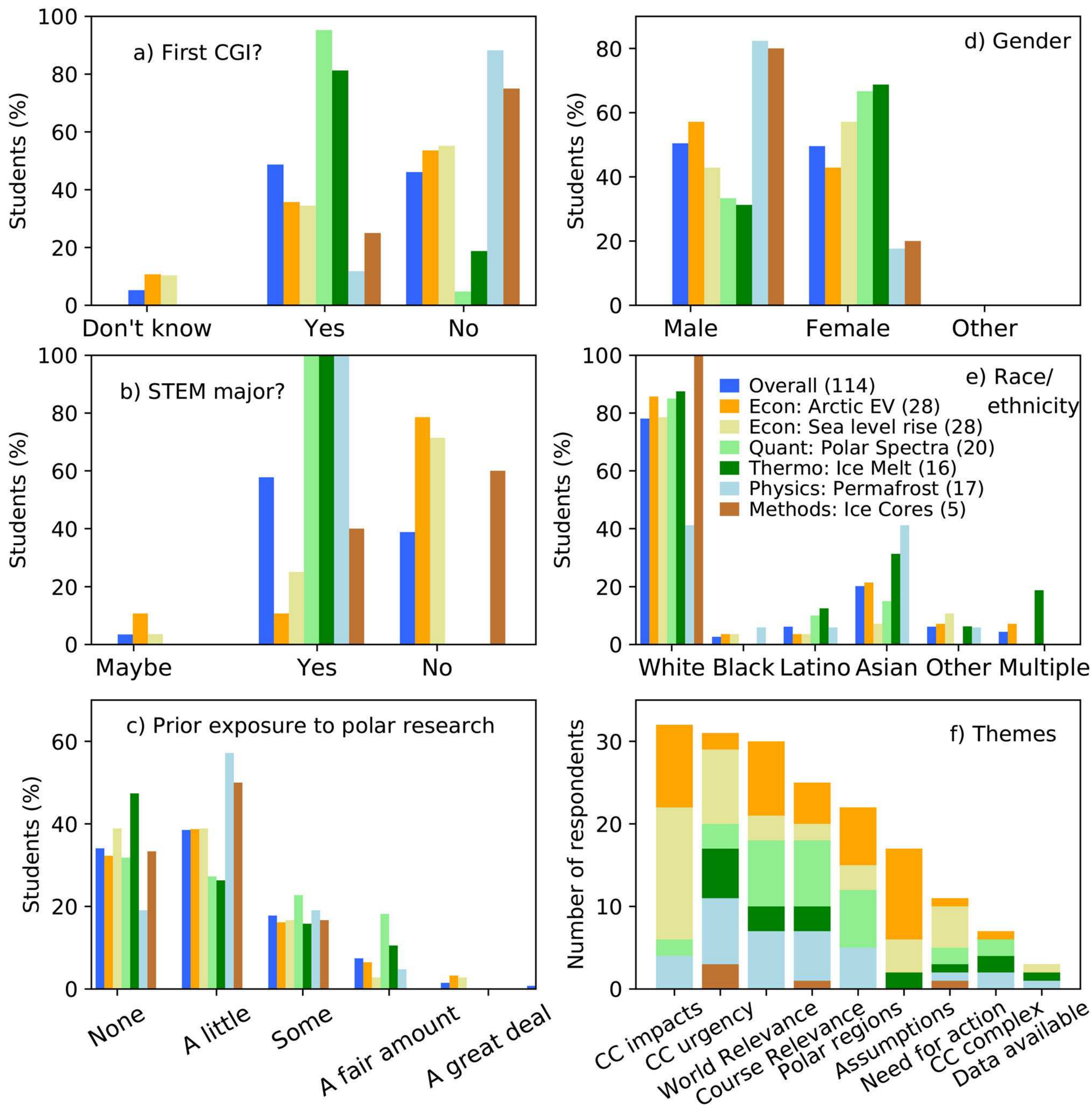

Figure A1. Student demographics, including student-reported answers to the questions (a) "Is this the first CGI you have done?" and (b) "Are you a STEM major?" as well as student self-assessment of (c) exposure to polar data and research before taking the module, (d) gender identity, and (e) race/ethnic identity (other is described in the text). Also shown are (f) Emergent themes identified in student open-ended responses (see text). The legend in panel (e) gives module names, which correspond to all panels, and the approximate number of survey respondents.

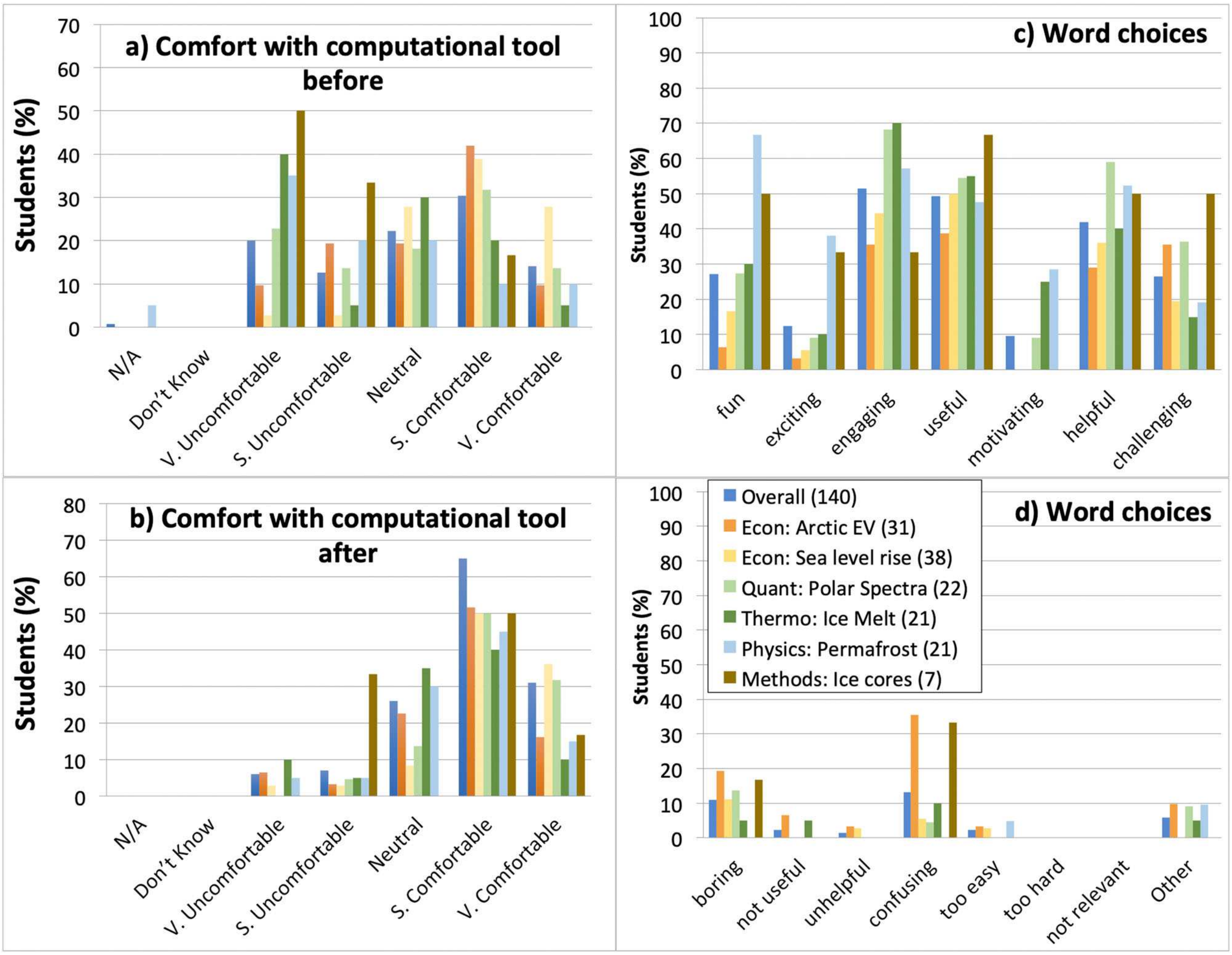

Figure A2. Comfort with computational tool (a) before the module and (b) after the module. Economics (Econ) modules use Excel; other modules use Python. (c,d) Words selected by students to describe the module they completed. The legend in panel (d) gives module names, which correspond to all panels, and the approximate number of survey respondents.