10-1-2023

Teaching the Global Energy Balance: A Complementary Computational and Hands-On Gamified Activity

Danielle M. Schmitt

Robert Nazarian
Fairfield University, rnazarian@fairfield.edu

Peer Reviewed

Repository Citation

Schmitt, Danielle M. and Nazarian, Robert, "Teaching the Global Energy Balance: A Complementary Computational and Hands-On Gamified Activity" (2023). *Physics Faculty Publications*. 180.
https://digitalcommons.fairfield.edu/physics-facultypubs/180

Published Citation

Schmitt, Danielle M, and Robert H Nazarian. "Teaching the Global Energy Balance: A Complementary Computational and Hands-On Gamified Activity." The Physics Teacher 61, no. 7 (2023): 584–87. https://doi.org/10.1119/5.0136931.

Teaching the Global Energy Balance: A Complementary Computational and Hands-On Gamified Activity

This image signals that this contribution is a featured part of the special collection on "Climate Change and Sustainability in Intro Physics."

Danielle M. Schmitt, Princeton University, Princeton, NJ
Robert H. Nazarian, Fairfield University, Fairfield, CT

Over the past several decades, secondary schools and institutions of higher education have increased the number of and frequency with which they offer climate change and sustainability-themed courses[1,2] and research opportunities[3] driven by growing student interest.[4,5] In the secondary education setting, only a third of the instructors teaching these classes have any formal training in this discipline,[6] while some university science faculty have expressed varying degrees of comfort with teaching this subject.[7] Here, we propose a new, easily adaptable class activity for both high school and college-level instructors to teach one of the most fundamental topics in climate science: the global energy balance and how it affects Earth's average global temperature.[8] This highly interactive activity has been implemented in both lecture- and lab-based settings at two different universities over the past six years and refined, based on student feedback, with each iteration. The complementary approach of this activity, which uses both a simple computer model and an experimental game, makes it appropriate for students who do not have a background in the sciences (particularly physics), which is the primary demographic of high school and intro-level college courses.

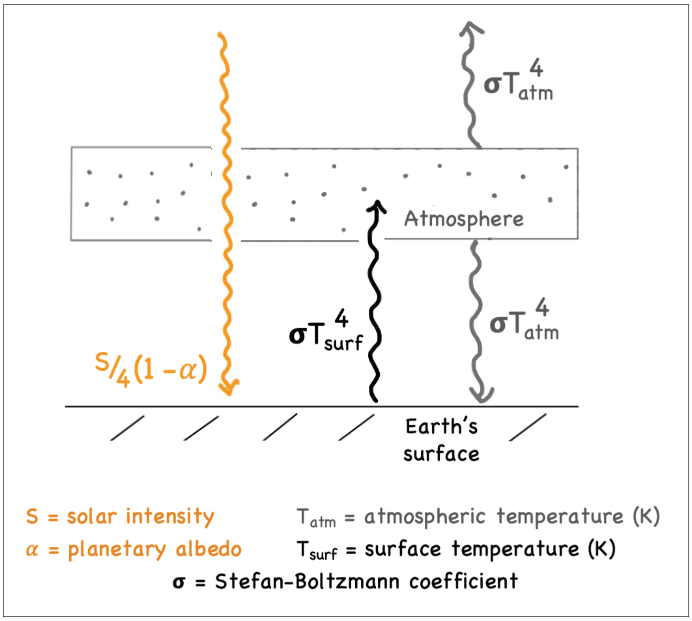
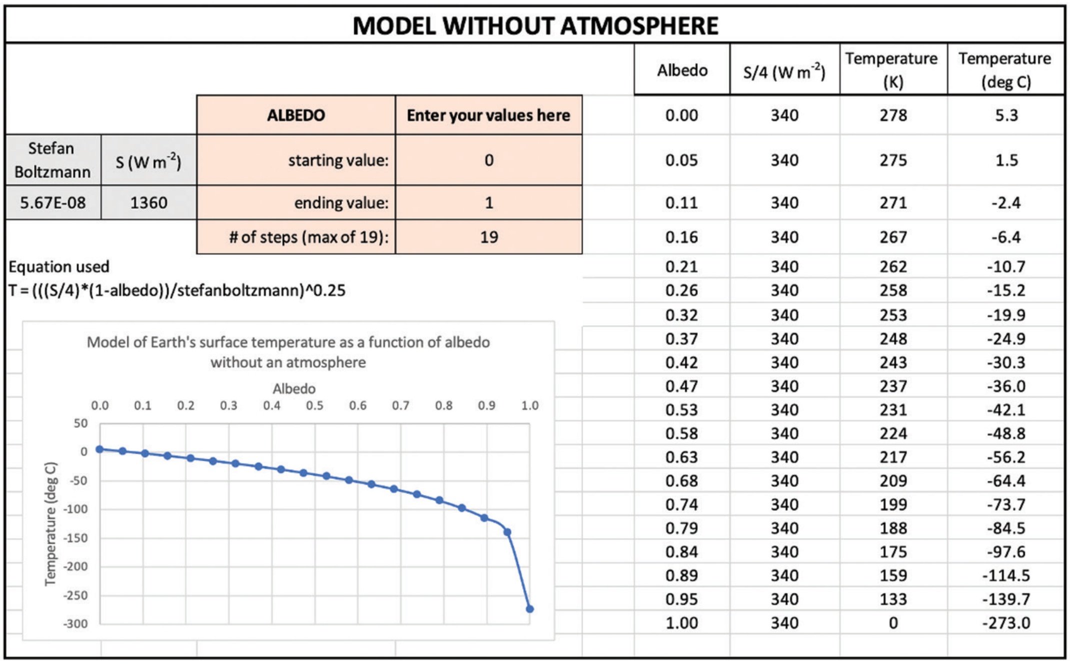


Fig. 1. Cartoon of Earth's energy budget explored in this activity, including solar radiation and radiation from Earth's surface and atmosphere. Notes: 1. α includes solar radiation reflected from both the atmosphere (e.g., clouds) and Earth's surface. 2. *S* is divided by 4 because of the geometric relationship between solar radiation intercepted by Earth's surface and the area over which this radiation is spread. For more information, refer to the instructor version of the model (available in the supplementary materials).[9]

While climate courses at the high school and introductory college level may be interdisciplinary in scope, approximately one-third of instructors surveyed report teaching physical climatology, thereby exposing students to the fundamental physics that governs our climate system.[2] One of the most fundamental and important concepts in physical climatology, and taught in almost all climate courses, is the global energy balance.[2] Using simple concepts from modern physics, an algebra-based model can be constructed to calculate the global mean surface temperature with reasonable accuracy; namely, the incoming shortwave radiation from the Sun must be balanced by Earth's longwave radiation to space (see Fig. 1).[2,8,10] Despite the relative simplicity of this model, it is still one of the most difficult topics covered in introductory climate courses, especially for students who have limited science backgrounds; students who have never taken an earth science or physics course before report more difficulty in learning about the global energy balance.[11] Furthermore, students enter these classes with a variety of backgrounds/prior courses and may respond to learning new material in different ways.[11,12] Given the importance of this topic to studying the climate system, the difficulty with which students report learning this topic, and the variety of student backgrounds, we have developed a two-pronged, complementary approach that conveys the relevant concepts using both a simple computational model and a hands-on experimental game. After completing these activities, students should be able to describe how solar intensity, albedo, and the presence or absence of atmospheric greenhouse gases affect Earth's temperature.

This activity begins with the use of simple models in Excel that allow students to explore the role of two variables [average planetary albedo, α (the reflectivity); and solar constant, S (the radiation from the Sun reaching Earth)] that are fundamental to setting Earth's globally averaged surface temperature (full Excel models, as well as instructor materials that include descriptions of the equations used to calculate temperature, are provided in the supplementary material; see Fig. 2 for layout).[9] Students investigate how changes in α and S affect Earth's surface temperature for two scenarios. In the first, and simplest, scenario, students analyze an Earth-like world with no atmosphere and in the second, more realistic scenario, students analyze a world in which there is a "one-layer" atmosphere that is transparent to solar radiation and absorbs all infrared radiation emitted by Earth's surface (i.e., the incorporation of the greenhouse effect).



MODEL WITHOUT ATMOSPHERE

		ALBEDO	Enter your values here
Stefan Boltzmann	S (W m^{-2})	starting value:	0
5.67E-08	1360	ending value:	1
		# of steps (max of 19):	19

Equation used
T = (((S/4)*(1-albedo))/stefanboltzmann)^0.25

Albedo	S/4 (W m^{-2})	Temperature (K)	Temperature (deg C)
0.00	340	278	5.3
0.05	340	275	1.5
0.11	340	271	-2.4
0.16	340	267	-6.4
0.21	340	262	-10.7
0.26	340	258	-15.2
0.32	340	253	-19.9
0.37	340	248	-24.9
0.42	340	243	-30.3
0.47	340	237	-36.0
0.53	340	231	-42.1
0.58	340	224	-48.8
0.63	340	217	-56.2
0.68	340	209	-64.4
0.74	340	199	-73.7
0.79	340	188	-84.5
0.84	340	175	-97.6
0.89	340	159	-114.5
0.95	340	133	-139.7
1.00	340	0	-273.0

Fig. 2. Screenshot of the first model used. Students insert values in the gray and peach cells, and the graph and the cells in the Albedo, *S*/4, and both temperature columns automatically populate. This example uses the approximate magnitude of the present solar constant (1360 W m^{-2}) for *S* and the full range of albedo (0 to 1). The model is available in the supplementary material.[9]

One of our goals is for students to become comfortable using Excel as a tool for analyzing and presenting data. To accomplish this, the instructor leads the students as they follow along, step by step, showing them how to set the value of S (incoming radiation from the Sun), the minimum and maximum value of α (planetary albedo), and the number of steps between the minimum and maximum values of α. Next, they are shown how to copy, paste, and edit the model to investigate the effects of changing S while α is held constant (all of the requisite steps are provided in the instructor spreadsheet in the supplementary material).[9] The class then performs these same investigations for the second scenario, in which the presence of an atmosphere incorporates the greenhouse effect into the model. After the students create and explore the two scenarios, they are prompted to consider the results of their investigations, including comparing the ranges of Earth's surface temperature for a world with versus without an atmosphere while S is held constant and α varies and vice versa. Students are then provided with a worksheet containing questions related to each model so as to express their understanding of the model and associated physics (these, and the answers, are located in the student and instructor worksheets located in the supplementary material).[9]

While the learning goals of our courses include a mastery of Excel, we recognize that these goals may not be shared among all high school and college classrooms. If this is the case, we encourage pairing a student that is proficient with the software with a student that has less experience so as to provide more opportunity for discourse between the students than would happen if they worked individually. Furthermore, the instructor should roam around the classroom during this interactive modeling activity to ensure that students or student pairs do not fall behind.

In this two-scenario approach, students incorporate new physical processes through a scaffolded scheme, with the goal of gradually mastering new concepts. Additionally, the combination of group work with the instructor (Excel activity) and the accompanying worksheet allows students multiple opportunities to engage with the material. Furthermore, this particular component of the activity uses quantitative and/or computational analyses, in contrast to the second part of the activity, to investigate Earth's energy balance. The iterative process of students making modifications to the model provides them with the opportunity to visualize and contextual-

Fig. 3. Household items provided to the students in one iteration of the activity. In addition to these suggested items, other materials provided are at the instructor's discretion (additional recommendations are included in the supplementary material).[9]

ize how changing each of the parameters impacts the globally averaged temperature.

The second part of this activity complements the first; students work in small groups and use their creative skills to create a box (solar oven) that achieves the greatest increase in internal temperature after being exposed to sunlight. An assortment of common household materials is provided (see Fig. 3 for a picture of common items and the instructor version of the worksheet for a corresponding table of items used), as are a few simple rules:

- All of the groups' boxes should be of similar size (i.e., a comparable volume of air to be heated).
- The only energy source that can be applied is visible light.
- There must be a way to insert a thermometer to measure the temperature.

Students are additionally instructed to keep notes on how they constructed their ovens so that they can present their approach to the rest of the class. This activity is then conducted as a game in which the students compete to build a solar oven with the largest possible increase in temperature (see example solar ovens in Fig. 4).[13]

As the students construct their solar ovens, the instructor ensures that all ovens are of similar size, but otherwise provides minimal guidance regarding the physics; students are meant to be applying what they have learned from the model component of the activity and will later have an opportunity to revise their ovens. Once constructed, the groups go outside to place their boxes in the sun (in the case of poor weather, the ovens are placed under lamps fitted with LED bulbs that produce similar radiative effects). Initial temperatures of the ovens are simultaneously recorded for all groups, and students spend the next 10 minutes describing their ovens and the physics-based rationale for their designs. During these presentations, the instructor emphasizes connections between design features and variables such as albedo, sunlight intensity, and greenhouse effect resulting from the composition of the air in the box (all previously explored in the modeling component of the activity). If none of the groups change the composition of the air in the boxes, the instructor prompts them to consider which aspect investigated in the models wasn't incorporated into their designs and to consider how they could include it. Such repetition of important content has been shown to be effective in the STEM classroom.[14] When time is up, all groups record their final temperature and calculate the change from the initial temperature.

Groups then have the option to adapt their boxes or to create new ones that take into account their results, the results of other groups, and the discussion of each of the different oven designs and physical basis for such designs. At the conclusion of the revision time, students repeat the process of measuring initial and final temperatures and discussion of the strategy of their redesigns. A prize is presented to the group(s) with the greatest temperature change (the prize and how it is determined [e.g., largest increase overall, greatest improvement] is left to the instructor). A more detailed example of how this activity was implemented, including a list of suggested materials and additional tips for implementation, is included in the instructor version of the worksheet, which can be found in the supplementary materials.[9]

The use of two different modes of investigating the energy balance is purposeful and driven by earlier results from the peer-reviewed literature. Specifically, providing students with the opportunity to engage with the concepts in multiple ways leverages students' unique academic backgrounds and effectively supports a diverse group of learners, which is particularly important since such a course is generally taken by non-STEM majors.[15] On their own, computational models have been shown to be remarkably useful STEM teaching tools for building understanding of physical processes and applying such understanding.[16] Separately, the building of the solar ovens provides a creative and experiential learning activity that may serve as a tool to empower and engage students historically underrepresented in STEM.[17] Finally, we expect the student engagement and, perhaps, learning gains from this experiential component to be even greater since we have introduced it in a gamified environment.[13]

Performing the computational activity first, followed by the solar oven experiential "game," is recommended. The computer model reinforces and allows students to apply the concepts they previously learned in class (energy balance, the role of albedo and solar radiation, etc.) while exploring the magnitudes of temperature changes that could occur by changing the different parameters. A benefit of the subsequent game is the presentation of their design, which serves as an opportunity for formative assessment, with the instructor immediately addressing any misconceptions. Even if there aren't any misconceptions, the instructor can emphasize how their strategy relates to the variables investigated in the computer model.

In the multiple iterations of this activity, we have noticed that students who were previously quiet or nonparticipatory in class were much more engaged with this activity, even volunteering to be the spokesperson for the informal design strategy presentation. In addition to the high student engagement and buy-in that has been observed, students have explicitly stated that they enjoyed the competition in conversations and end-of-semester evaluations. Explaining that the hands-on nature

Fig. 4. Three example solar ovens from one iteration of this activity. All solar ovens are subjected to similar conditions (surface, incoming sunlight, etc.).

resulted in their group getting "really into it," students noted that they will remember the concepts more than if they had performed the numerical model alone. While student evaluations have been shown to contain bias,[18] these anecdotal observations and conversations point to this activity being broadly applicable in a variety of introductory college courses in which students come from a variety of non-STEM backgrounds.

Since the initial design of this activity, it has been implemented and further improved in three separate introductory courses at two universities (an R1 institution and a primarily undergraduate institution). Despite the differences in the types of universities, student makeup, size of the courses, classroom materials, and instructional techniques, we have found that students have responded overwhelmingly positively to this interactive activity. Furthermore, the time and resources required to include this activity in a lecture- or lab-based course are low; the Excel model and instructor resources are freely available (see supplementary material[9]), and the disparate household objects used for the solar oven should be exactly that—disparate and common. The ease with which this activity has been integrated into existing courses at unique universities suggests that it is generalizable enough to be adapted in a host of advanced high school and introductory college courses that teach the physics of the climate system. Furthermore, with the rise of the hybrid teaching landscape, this activity presents an exciting and equitable opportunity to engage remote students; most students have access to Excel through university subscriptions and a host of household items that can be temporarily repurposed for the solar oven.[19] Given the importance of teaching the relevant physics in a variety of increasingly popular high school and college climate courses, this interactive activity may fill a crucial hole in conveying the importance of and essential physical processes underpinning the global energy balance and global mean temperature.

References

1. K. Coleman et al., "Students' understanding of sustainability and climate change across linked service-learning courses," *J. Geosci. Educ.* **65**, 158–167 (2016).
2. W. L. Filho et al., "Handling climate change education at universities: An overview," *Environ. Sci. Eur.* **33**, 109 (2021).
3. R. H. Nazarian, "The use of model intercomparison projects in engaging undergraduates in climate change research," *Schol. Pract. Undergrad. Res.* **5**, 27–28 (2021).
4. C. Gayford, "The perspectives of science teachers in relation to current thinking about environmental education," *Res. Sci. Technol. Educ.* **16**, 101–113 (1998).
5. C. Gayford, "Biodiversity education: A teacher's perspective," *Environ. Educ. Res.* **6** 347–361 (2000).
6. S. Buhr Sullivan et al., "Navigating climate science in the classroom: Teacher preparation, perceptions and practices," *J. Geosci. Educ.* **64**, 550–559 (2014).
7. A. Beck et al., "Leveraging higher-education instructors in the climate literacy effort: Factors related to university faculty's propensity to teach climate change," *Int. J. Clim. Change: Impacts Responses* **4**, 4 (2013).
8. M. Wild et al., "The global energy balance from a surface perspective," *Clim. Dyn.* **40**, 3107–3134 (2013).
9. Readers can access the Appendix at *TPT Online* at https://doi.org/10.1119/5.0136931, in the "Supplementary Material" section.
10. A. Dessler, *Introduction to Modern Climate Change*, 2nd ed. (Cambridge University Press, 2016), pp. 52–58.
11. L.-A. L. Dupigny-Giroux, "Exploring the challenges of climate science literacy: Lessons from students, teachers and lifelong learners," *Geogr. Compass* **4**, 1203–1217 (2010).
12. A. L. Franzoni et al., "Student learning styles adaptation method based on teaching strategies and electronic media," in *2008 Eighth IEEE International Conference on Advanced Learning Technologies*, Santander, Spain (2008), pp. 778–782.
13. R. Kumar and R. Lightner, "Games as an interactive classroom technique: Perceptions of corporate trainers, college instructors and students," *Int. J. Teach. Learn. High. Educ.* **19,** 53–63 (2007).
14. A. Voice and A. Stirton, "Spaced repetition: Towards more effective learning in STEM," *New Dir. Teach. Phys. Sci.* **15** (2020).
15. J. A. Anderson and M. Adams, "Acknowledging the learning styles of diverse student populations: Implications for instructional design," *New Dir. Teach. Learn.* **49**, 19 (1992).
16. R. K. Coll et al., "The role of models/and analogies in science education: Implications from research," *Int. J. Sci. Educ.* **27**, 183–198 (2011).
17. M. R. Goldberg et al., "Using experiential learning to inspire, educate, and empower underrepresented undergraduates in STEM," Paper presented at 2011 ASEE Annual Conference & Exposition, Vancouver, BC. 10.18260/1-2--18451.
18. P. Spooren et al., "On the validity of student evaluation of teaching: The state of the art," *Rev. Educ. Res.* **83**, 598–642 (2013).
19. K. D. Smith, "Is it face time or structure and accountability that matter? Moving from a flipped to a flipped/hybrid classroom," *J. Appl. Res. Higher Educ.* **42**, 609–621 (2021).

Danielle Schmitt *is an academic laboratory manager in the Department of Geosciences at Princeton University. Her primary focus is on the development of curricula, laboratory activities, lecture demos, and field trips for introductory-level courses related to the ocean and the atmosphere. To foster geoscience literacy, she leads public outreach initiatives and professional development workshops for K–12 teachers.*
dschmitt@princeton.edu

Rob Nazarian *is an associate professor of physics at Fairfield University. In addition to his work in the scholarship of teaching and learning, Rob actively conducts research in the area of ocean, atmosphere, and climate physics. He holds a PhD in atmospheric and oceanic sciences from Princeton University.*