Tutorials in climate modeling[a)]

Special Collection: Teaching about the environment, sustainability, and climate change

Lane H. Seeley

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Tutorials in climate modeling[a)]

Lane H. Seeley[b)]
Department of Physics, Seattle Pacific University, Seattle, Washington 98119

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This article describes a learner-centered, tutorial-based approach to climate modeling. Using these tutorials, students in a general education course in global climate change taught in the physics department engaged with compelling, "real-world" questions by drawing on foundational physics concepts along with their prior experiences and conceptual resources in the process of knowledge construction. Students used simulations, energy tracking diagrams, and algebraic analysis to construct climate models that address challenging quantitative questions and reveal key concepts in climate science. Special emphasis was given to the learning goals, pre-requisite knowledge, and conceptual challenges associated with these activities. Instructional materials are provided for educators who wish to adapt these tutorials for use in their own educational context. The supplementary materials are appropriate for both non-science majors and upper-level physics majors.

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I. INTRODUCTION

Global climate change is perhaps the single most important scientific issue of our time. The current generation of students will be called upon to act decisively to limit the extent of human-caused climate change. They will also be asked to respond equitably and adapt strategically to the impact of a changing climate. To meet these challenges, students should be empowered with a basic conceptual and quantitative understanding of the underlying physics of Earth's changing climate. There are many excellent educational resources that have been designed to help students understand the physics of Earth's climate.[1,2] This article will describe a learner-centered, tutorial-based approach to climate science in which students construct and adapt their own climate models. The unit described here was developed for a physics course on global climate change at a small, private, liberal arts university. This course is open to students from all majors, has no pre-requisites, and uses Andrew Dessler's *Introduction to Modern Climate Change* as a primary textbook.[3] In the activities presented here, students engage with compelling, "real-world" questions as they draw on foundational physics concepts along with their prior experiences and conceptual resources in the process of knowledge construction. Students use simulations, energy tracking diagrams,[4] and algebraic analysis to construct climate models that address challenging quantitative questions and reveal key concepts in climate science. Throughout this article, I will reference tutorials and other instructional resources which are included as the supplementary material for instructors to adapt for their instructional context.

The primary learning goals of this unit are as follows:

(1) Students learn to use simple climate models as tools to engage with significant questions about Earth's changing climate.
(2) Students recognize that climate change can be reasonably approximated as a shift from one state of dynamic equilibrium to an altered state of dynamic equilibrium.
(3) Students realize that the greenhouse effect warms Earth's surface through absorption and emission of infrared radiation in the atmosphere and which is essential for a habitable planet.
(4) Students determine that the release of thermal energy from fossil fuel combustion can only account for a small fraction of the recently observed increase in global surface temperature.

II. PRE-REQUISITE PHYSICS IDEAS FOR CLIMATE MODELING

Climate change is a critical socio-political issue, but it also provides an exciting context for exploring and applying fundamental physics concepts. For students to understand and construct climate models, they will need a robust understanding of electromagnetic radiation and energy flow. Here is a brief list of concepts that students will need to construct, understand, and apply the basic climate models:

- Students recognize that electromagnetic radiation comes in a wide spectrum of wavelengths, and only a very small portion of the electromagnetic spectrum is visible to humans.
- Students differentiate transmission, reflection, absorption, and emission of radiation with a particular emphasis on what happens to energy in each of these processes.
- Students recognize that the amount and wavelength of radiation emitted from an object depends on its temperature and that all objects above zero kelvin radiate energy.
- Students understand the concept of electromagnetic energy flux and why it is measured in units of W/m^2.
- Students can relate these ideas to the Stefan–Boltzmann law and Wien's displacement law.

There are many resources for teaching the preceding ideas about electromagnetic radiation such as the PhET blackbody spectrum simulation.[5]

III. ASSESSING STUDENT UNDERSTANDING OF SHIFTS BETWEEN EQUILIBRIUM STATES

Figure 1 illustrates a simplified, single-layer atmosphere model for a hypothetical Earth-like planet. In this model, various energy flows in the planet's atmosphere are represented by arrows that represent the energy flux averaged over an annual cycle and the entire surface of the planet. In this model, arrow A shows that the globally and annually averaged solar energy absorbed at the surface of the planet is 238 W/m^2. This value is approximately consistent with the actual average rate of solar energy absorption at Earth's surface and is described in greater detail in Sec. V. Arrows B through F represent infrared radiation emitted from the planet surface (B), infrared radiation that transmits through the atmosphere (C), infrared radiation absorbed by the atmosphere (D), infrared radiation emitted upward from the atmosphere (E), and infrared radiation emitted downward from the atmosphere (F). For simplicity, this model does not include incoming solar energy that is reflected by the planet or absorbed by the atmosphere. Understanding climate modeling requires that students are comfortable using systems-based reasoning to differentiate equilibrium and non-equilibrium conditions. Simple climate models often use an equilibrium approximation in which the energy inputs and outputs to Earth are in balance. Therefore, students need to recognize that when system properties change, Earth's climate system can shift from one equilibrium state to a different equilibrium state.

I conducted a pre-assessment of student understanding after they had read a textbook chapter on climate modeling, but before they had completed our tutorials. In our climate modeling pre-assessment, we posed a scenario in which the amount of greenhouse gases in a planet's atmosphere increases suddenly from a volcanic eruption and the planet then reaches a new equilibrium state with a higher surface temperature. Students were asked, "Once the surface temperature has stabilized at a higher level would the rate at which energy is leaving the top of the planet's atmosphere (**C** + **E**) be greater than, less than, or equal to the rate prior to the eruption?" Of 31 students in this course, 23 of them expected that there would now be less total energy leaving the top of the planet's atmosphere. The reasoning students used to explain this answer was consistent, with most of them arguing that the increased greenhouse gases would "trap more energy" and allow less energy to leave the atmosphere. Seven students expected that the total rate of energy leaving the top of the atmosphere would be equal to the rate prior to the eruption. These students also had consistent reasoning, with most of them arguing that once the surface temperature is stable the energy flows into and out of the planet must be in balance. These results are consistent with prior studies and suggest that the critical concept of shifts in equilibrium is challenging for many students and may not be resolved through textbook reading or lectures alone.[6]

IV. USING FLUID FLOW TO EXPLORE DYNAMIC EQUILIBRIUM

To help students gain confidence with complex system analysis, we introduce a water flow system as an analog to Earth's climate system. A *climate water analogy tutorial* is included in the supplementary material.[7] In this activity, students observe a large, graduated cylinder, which is initially in dynamic equilibrium with a constant inflow from a faucet and a constant outflow from two holes near the bottom of the cylinder as shown in Fig. 2. Students make detailed predictions for how the water height will change over time when one of the holes is suddenly plugged. Many students expect that the water flow from the remaining unblocked hole will increase as the water level rises. Students often predict this result based on experience and/or reasoning about water

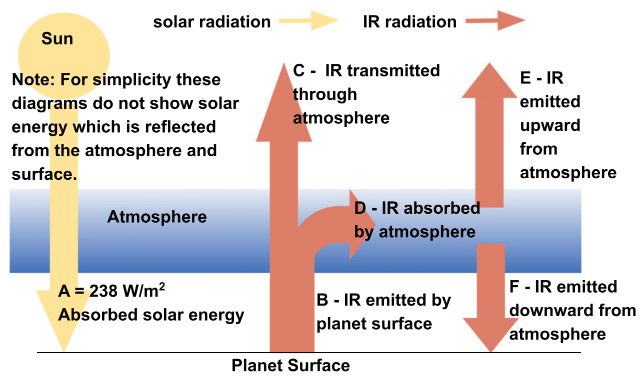

Fig. 1. Single-layer atmosphere climate model.

pressure and depth. Students discuss their predictions with peers and then observe a demonstration or video in which the water level rises quickly and then stabilizes at a new, equilibrium height. With careful observation many students recognize that the outgoing water stream rises slightly as the water level rises indicative of a greater flow rate. Videos and data are provided in the supplementary material, but the experiment can also be easily demonstrated if your classroom has a water faucet. Students can also conduct their own investigations if time permits. This tangible example helps students recognize that when the water level has stabilized the inflow and outflow must be back in balance. We have found that students are able to use this water flow experiment to construct an analogy for energy flow in Earth's climate system. Here is a typical example of a student working out this analogy for themselves:

> "Energy (water) enters the earth (the cylinder) and gets re-emitted through our atmosphere back into space. The surface temperature (height of the water) of the planet sits at an equilibrium point with the current amount of greenhouse gasses, but if we were to increase the amount of greenhouse gases and block more energy from emitting

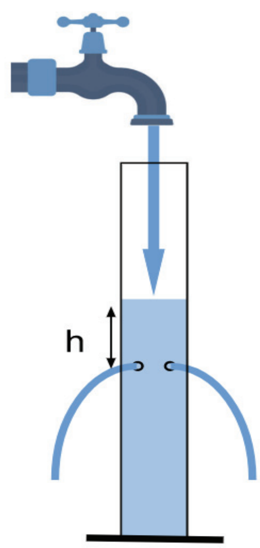

Fig. 2. Students make graphical predictions for how the water level will change over time when one of the holes in a graduated cylinder is suddenly closed.

through our atmosphere then the surface temperature would rise to a new equilibrium point."

V. MODELING EARTH WITHOUT A GREENHOUSE EFFECT

It is both pedagogically appropriate and enlightening for students to begin by constructing a climate model for Earth without a greenhouse effect. This model describes a hypothetical situation in which Earth's atmosphere is entirely composed of gases like N_2 and O_2, which do not absorb in the infrared portion of the electromagnetic spectrum. Students can draw upon the climate water analogy tutorial to recognize that if Earth's temperature is stable, the energy inflow and outflow must be in balance. We have included a short *Modeling Earth Without a Greenhouse Effect Tutorial* in which students estimate the average surface temperature of Earth without a greenhouse effect.[7] This well-known calculation depends on the following: the solar constant at Earth's distance from the Sun, $S = 1360$ W/m^2, the average albedo(reflectivity) of Earth's surface in the solar spectrum, $\alpha = 0.30$, and the Stefan–Boltzmann approximation for infrared emissions from Earth's surface. Upon reflection, most students recognize that the result of this calculation, $T = 255$ K or $-18\,^\circ$C, is much lower than the actual average surface temperature of Earth. In fact, at this temperature, Earth would be completely covered by ice, the albedo would be about 0.75, and the average surface temperature would be close to $-70\,^\circ$C. This calculation provides students with a first step in quantitatively modeling Earth's climate. It also highlights some of the most important and uncontroversial scientific facts about our climate. Without a greenhouse effect, our planet would be covered in ice and inhospitable for most life as we know it. The greenhouse effect is responsible for raising the surface temperature of Earth by approximately $85\,^\circ$C. Humans have significantly increased the concentration of two of the most significant greenhouse gases.[8] It would be very surprising if these increases in greenhouse gas concentrations did not have a significant impact on Earth's climate.

VI. MODELING THE GREENHOUSE EFFECT

Once students have studied a climate model for Earth without a greenhouse effect, they are ready to consider how the greenhouse effect influences energy flow. Simulations can provide an excellent way for students to explore dynamic energy processes within Earth's atmosphere. We have included a set of interactive slides which can be used to provide guidance to students as they use the PhET Molecules and Light simulation to study how visible and infrared photons interact with gas molecules in Earth's atmosphere.[7] Students recognize that greenhouse gas molecules (CO_2, CH_4, CO, H_2O, NO_2, and O_3) absorb infrared photons and emit them in random directions. They also realize that neither of the most prevalent atmospheric gases, N_2 and O_2, interact with infrared photons and none of these atmospheric gas molecules interact with visible light photons.

We have also developed a set of interactive slides that can be used to guide students as they use a *PhET greenhouse effect* simulation to study the role of greenhouse gases on energy flows in Earth's atmosphere.[7] Using this simulation, students can observe that when they add greenhouse gases to the atmosphere, there is a transient period during which less energy is leaving the top of the atmosphere than entering. Once the surface temperature stabilizes, the energy leaving the atmosphere is balanced with the energy entering. This second point is surprising for many students who expect that when greenhouse gases "trap energy," there will be less energy leaving than arriving. This simulation along with ideas developed from the water flow experiment help students recognize that Earth's climate system can shift from one equilibrium state to a different equilibrium state with a higher average surface temperature.

VII. A BALANCED CLIMATE MODEL FOR A CHANGING CLIMATE?

Once students have a basic qualitative understanding of the greenhouse effect, they are ready to begin quantitative analysis using simple climate models. Modeling Earth's climate is simpler if we assume that the energy flows into and out of the Earth system are in balance. Is this a reasonable approximation during in a changing climate? We typically have students explore this question individually or in groups using online resources before we discuss the question as a whole class. Earth's oceans can store a lot of thermal energy. According to a 2020 report by the National Oceanic and Atmospheric Administration, more than 90% of the climate related increase in thermal energy that happened on Earth between 1971 and 2010 occurred in the ocean.[9] This report also states that, "Averaged over the full depth of the ocean, the 1993–2019 heat-gain rates are 0.55–0.79 W per square meter." The surface area of the ocean is 362 million square kilometers or 3.62×10^{14} square meters. This means that the oceans have gained thermal energy at a rate of approximately 2.4×10^{14} W. This is a huge amount of thermal energy, but it is still only about 0.1% of the rate at which Earth is receiving energy from the Sun. Put another way, for every 1000 units of energy that arrive from the Sun only about one unit warms up the oceans. The remaining 999 units are either reflected from Earth or were emitted back into space as infrared radiation.[10] Even during the current era of relatively rapid climate change, a balanced Earth remains a fairly accurate approximation.

VIII. A BASELINE MODEL FOR EARTH'S PRE-INDUSTRIAL CLIMATE

The Intergovernmental Panel on Climate Change uses the period from 1850 to 1900 as a pre-industrial baseline climate prior to significant anthropogenic, or human caused, climate change. During this period, the average global surface temperature was approximately $14\,^\circ$C. If the solar constant over Earth's cross-sectional area (πR_E^2) is $S = 1360$ W/m^2 and the average albedo is $\alpha = 0.30$, students calculate in our *modeling earth without a greenhouse effect tutorial* that the average rate at which solar energy is absorbed over Earth's entire surface area ($4\,\pi R_E^2$) is approximately 238 W/m^2. For comparison, this means that on average each square meter of Earth's surface absorbs a power equivalent to six old-fashioned 40-W incandescent light bulbs. This scenario provides a first climate modeling puzzle for the students as they work through our climate modeling tutorial. Their task is to determine the energy flows in arrows B through F that will result in a balanced climate model according to the following model assumptions. They assume that the emissivity of Earth's surface in the infrared is approximately 1. For simplicity, they also use a single-layer model for Earth's atmosphere in which a percentage

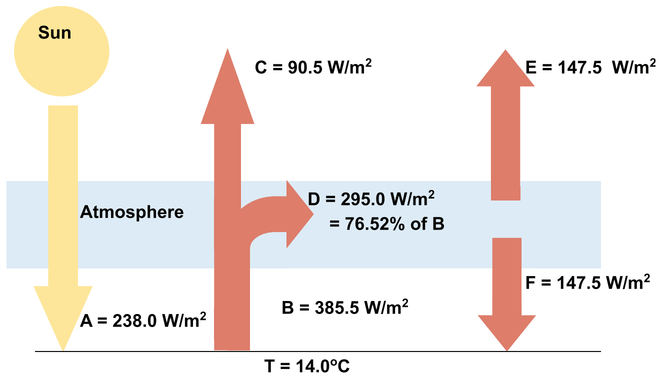

Fig. 3. A baseline model for Earth's pre-industrial climate. Students determine the energy flows in arrows B through F, which balance this climate model.

of the infrared radiation emitted by Earth's surface is absorbed by the atmosphere. In this simplified model, half of the infrared radiation absorbed by Earth's atmosphere is emitted back down toward the surface, and half is emitted into space.[11]

Figure 3 shows a solution to a baseline, pre-industrial climate model in which the surface temperature is 14.0 °C. To construct this model, students first use the Stefan–Boltzmann law to determine that the surface emits 385.5 W/m^2 of infrared radiation.[12] In order to balance energy flows to the surface, the atmosphere must absorb 295.0 W/m^2 of the outgoing infrared radiation and emit half of it back to the surface. This produces a state of dynamic equilibrium in which the energy flows are balanced at the surface and at the top of the atmosphere. Students also find that for this model 76.52% of the infrared radiation emitted by Earth's surface is absorbed by the atmosphere with the remainder transmitting directly through the atmosphere to space.[13]

IX. TWO POSSIBLE MODELS TO EXPLAIN CLIMATE CHANGE

Quantitative climate modeling is challenging and can be frustrating. Nevertheless, quantitative climate models are critical for understanding how our human actions impact global climate. Some of the most fundamental questions about anthropogenic climate change can only be addressed with quantitative models. Consider the elicitation question shown in Fig. 4, which proposes two plausible models to explain the rise in global temperature over the past 100 years. Both models described in Fig. 4 can qualitatively explain some amount of global temperature increase. Therefore, answering this question requires rigorous quantitative climate modeling. We have developed a *Climate Modeling Tutorial* that guides students through a process of constructing and quantitatively analyzing three different climate models: The baseline pre-industrial climate model shown in Fig. 3, a model for a 1.0 °C increase in surface temperature caused by release of thermal energy (Fig. 5(a)) and a model for a 1.0 °C increase caused by increased infrared absorption in the atmosphere (Fig. 5(b)).[7]

A. Modeling climate change from thermal energy or greenhouse gases

If the Earth's average surface temperature increases 1.0 °C to 15.0 °C, the surface will emit 390.9 W/m^2 of infrared radiation. The model in Fig. 5(a) depicts a hypothetical scenario in which this increase in surface temperature is entirely caused by the release of thermal energy at Earth's surface. In this model, the fraction of infrared radiation absorbed by the atmosphere would remain at 76.52% as in the baseline model. Balancing energy flows to the surface would require an input of thermal energy of approximately 3.3 W/m^2 at the surface from the combustion of fossil fuels. In this model, both the atmosphere and Earth's surface are in dynamic equilibrium, but there is net outflow of 3.3 W/m^2 at the top of the atmosphere from the fossil fuel energy which is extracted from below Earth's surface. Alternatively, the model in Fig. 5(b) depicts the hypothetical scenario in which the entire increase in surface temperature is caused by an increase in the percentage of infrared radiation absorbed by the atmosphere. In this simplified model, an increase in atmospheric absorption from 76.52% to 78.23% is sufficient to cause an increase in global surface temperature of 1.0 °C.

To decide which of these later two models provides a quantitatively reasonable explanation for a 1.0 °C rise in average surface temperature, students are encouraged to search online for an estimate of the current rate at which fossil fuel combustion is releasing thermal energy at Earth's surface.[14] The rate at which humans are releasing energy per square meter of Earth's surface is called the *anthropogenic heat flux*. While the anthropogenic heat flux can have a significant impact on the surface temperature in densely populated areas, globally averaged, it is only about 0.03 W/m^2.[15] Therefore, the release of thermal energy at the surface can only explain about 1% of the observed rise in global surface temperature.

When students have completed our climate modeling tutorial, they next complete homework in which they synthesize the results of their analysis in the tutorial. On this homework assignment, we found that all 31 students described a shift to a new equilibrium state. Furthermore, most students were able to use their climate modeling to argue that the thermal energy model is quantitatively insufficient to explain the observed increase we have seen in global surface temperature. A typical example of student reasoning was, "If the Earth's surface were at 15 °C and the percentage of infrared energy absorbed by the atmosphere remained the same as at 14 °C (meaning no increase in greenhouse gas effect), then

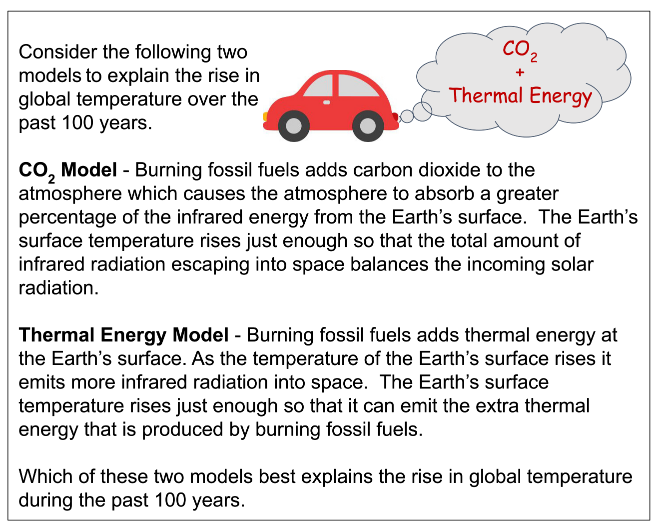

Fig. 4. A challenging question to motivate student curiosity and engagement with quantitative climate modeling.

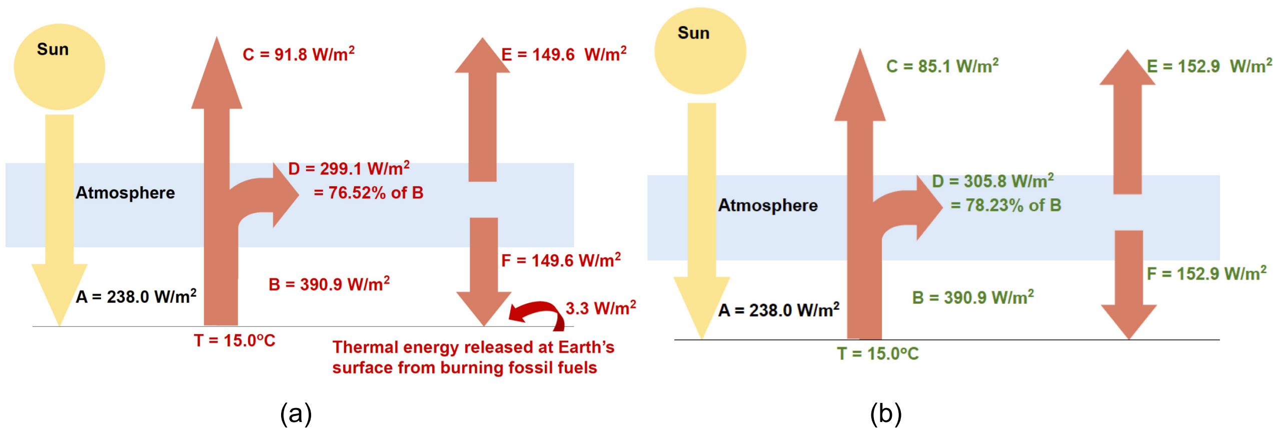

Fig. 5. (a) A hypothetic model in which a 1.0 °C rise in average surface temperature is entirely caused by thermal energy released at the surface. (b) A different, hypothetical model in which a 1.0 °C rise in average surface temperature is entirely caused by an increase in absorption of infrared radiation by Earth's atmosphere.

we would need to be adding 3.05 W/m^2 of thermal energy to the surface to maintain this temperature. This value is much greater than the amount of thermal energy we are actually adding (0.028 W/m^2)."

B. Going further: Modeling forcing, feedback, and climate sensitivity

The preceding analysis demonstrates that anthropogenic heat flux cannot be the primary cause of climate change. It is more difficult to quantitatively evaluate the role of anthropogenic carbon dioxide as a driver of climate change. Since pre-industrial times, the amount of carbon dioxide in Earth's atmosphere has increased by about 50%. Yet, the climactic impact of this additional atmospheric CO_2 is complicated for several reasons. Greenhouse gases absorb infrared radiation at all altitudes, so a single-layer model for Earth's atmosphere is a fairly limited approximation. In addition, there are several other greenhouse gases (CH_4, CO, NO_2, etc.), and water vapor is responsible for about half of Earth's greenhouse effect.[16] For courses with sufficient time and student interest to pursue climate modeling further, we have developed an activity in which students model a climate in which atmospheric carbon dioxide has doubled.[7] This activity develops the important climate modeling ideas of forcings, feedbacks, and climate sensitivity. We begin by introducing students to the idea of radiative forcing. Radiative forcing describes a method of quantifying a change to the climate system according to an equivalent change in absorbed solar energy. For example, doubling atmospheric CO_2 is estimated to produce a forcing equivalent to an increase in solar absorption of approximately 4 W/m^2 according an estimate provided on page 96 of Ref. 3. In other words, it is estimated that doubling carbon dioxide would have approximately the same impact on global climate as increasing the amount of absorbed solar energy by 4 W/m^2. This estimate is widely accepted by climate scientists because it does not depend on feedbacks, which are the most challenging aspects of global climate to accurately model. In this activity, students can refine their climate model to show that a forcing of 4.0 W/m^2 would require an increase in atmospheric absorption of approximately 2%, from 76.52% in Fig. 4 to 78.60% in Fig. 6(a). Notice that if the atmospheric absorption increases to 78.60% and the surface temperature initially remains at 14.0 °C, the total rate at which infrared energy is leaving the planet, C + E, decreases by 4.0 W/m^2. For the planet to get back into energy balance, the average rate of infrared emissions from the surface would need to increase to 392.1 W/m^2 as shown in Fig. 6(b). According to the Stefan–Boltzmann law, this would require an increase in global surface temperature of approximately 1.2 °C before feedbacks are considered.

Climate scientists use a climate *feedback parameter* to quantitatively relate the Earth's surface temperature change after feedbacks to the temperature change without feedbacks according to the following equation:

$$\Delta T_f = \frac{\Delta T_i}{(1-g)}.$$

Here, ΔT_i is the average surface temperature increase without feedbacks, ΔT_f is the average surface temperature change after feedbacks, and g is the feedback parameter. When we use an initial temperature change of 1.2 °C and a reasonable estimate for the feedback parameter of $g = 0.6$, we get a final temperature change estimate with feedback of 3 °C. These values are based on estimates provided on pages 104 and 105 of Ref. 3. For comparison, the Intergovernmental Panel on Climate Change (IPCC) estimates that when feedbacks are included the impact of doubling atmospheric carbon dioxide on global surface temperature would be an increase of between 2 °C and 5 °C.[17] It is empowering for students to see that a simple climate model can provide estimates that are in rough agreement with the most sophisticated climate science estimates.

X. CONCLUSIONS

Understanding Earth's changing climate is sociopolitically relevant and can be intellectually engaging for all students. In this article, we have described a sequence of tutorials that are designed to provide scaffolding as students construct and refine their own climate models. We believe that supporting students in constructing climate understanding will cultivate a deeper and more flexible understanding of Earth's climate. It is also possible that this constructivist approach to climate learning will result in greater self-efficacy as students confront the many challenges associated with climate change. We have found that these tutorials are accessible to non-science majors but are also challenging for

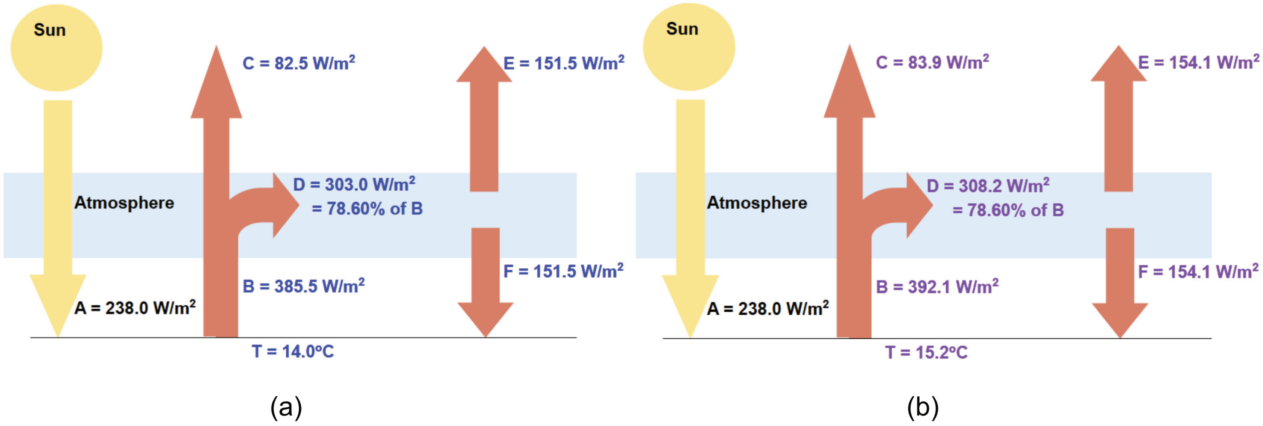

Fig. 6. (a) A model showing how it is possible to produce a radiative forcing of 4 W/m^2 by increasing the percentage of infrared radiation absorbed by Earth's atmosphere from 76.52% to 78.60%. To re-balance the climate model, as shown in (b), the outgoing infrared radiation must increase to 392.1 W/m^2, which requires an increase in average surface temperature to 15.2 °C.

upper-level physics and engineering students. We have included these tutorials as a supplementary material for instructors who wish to adapt them to best fit their learning goals and instructional context.

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AUTHOR DECLARATIONS

Conflict of Interest

The author has no conflicts to disclose.

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[b)]ORCID: 0000-0002-3044-6359.

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[6]J. M. Keller, *Development of a Concept Inventory Addressing Students' Beliefs and Reasoning Difficulties regarding the Greenhouse Effect, Part II. Distribution of Chlorine Measured by the Mars Odyssey Gamma Ray Spectrometer* (The University of Arizona Press, Tuscon, 2006).

[7]See supplementary material at https://www.scitation.org/doi/suppl/10.1119/5.0134144 for the details of climate water analogy tutorial, modeling earth without a greenhouse effect tutorial, PhET molecules and light interactive slides, PhET greenhouse effect interactive slides, climate modeling tutorial, and forcing and feedback tutorial.

[8]Water vapor is the most important greenhouse gas, but the concentration of water vapor in Earth's atmosphere is largely controlled by the ocean surface temperature.

[9]R. Lindsey and L. Dahlman, "Climate change: Ocean heat content," <https://www.climate.gov/news-features/understanding-climate/climate-change-ocean-heat-content>.

[10]J. Donev, "Earth's energy flow," University of Calgary, <https://energyeducation.ca/encyclopedia/Earth%27s_energy_flow>.

[11]We encourage students to calculate energy flows to at least one decimal place to avoid significant and confusing rounding errors.

[12]This assumes an emissivity for the Earth's surface of 1.0 in the infrared for simplicity.

[13]We encourage students to calculate the atmospheric absorption to four significant figures to avoid significant and confusing rounding errors.

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