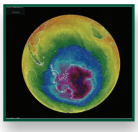
Physical Reasoning about Climate Modeling: A Bridge to Upper-Division Physics



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At Oregon State University, the curriculum for physics majors includes a new course called "Physics of Contemporary Challenges," which serves as a bridge between lower- and upper-division physics at the undergraduate level. The narrative of the course is largely based on climate modeling and sustainable energy issues. We have chosen to emphasize these applied physics topics for three reasons. (1) Urgent real-world problems are a way to connect with students who come from a broad range of backgrounds. (2) The physics that we cover introduces key threads of modern physics (quantum and statistical mechanics) that students will continue to use in upper-division classes. (3) Physical reasoning skills are exciting to learn/practice using compelling real-world examples. Overall, we have found an excellent synergy between our learning objectives (specific physics topics and physical-reasoning skills), and the analysis of real-world challenges associated with climate modeling and sustainable energy.

An interesting side effect of our approach is that we depart from the historical narrative that is typically used to introduce quantum and statistical mechanics. We sacrifice some interesting history, but we also avoid a shortcoming of the historical perspective. The physicists who were celebrated in the early 1900s came from a narrow cross-section of society; therefore, focusing on their stories perpetuates a narrow view of what a physicist looks like. Instead, we focus on the remarkable insights that modern physics brings to contemporary and future challenges.

In this article, I describe parts of our curriculum that pertain to climate modeling, focusing on synergies with fundamental physics and physical reasoning skills. I give examples of active engagement activities we have developed to support student learning of this material. A much larger collection of small-group activities and homework questions, including content about sustainable energy, can be found on the Paradigms in Physics curricular materials website.[1]

Building physical models of Earth's climate

Physical models of the Sun–Earth system are used to estimate the temperature of the planet. These models are based on the balance (or imbalance) of incident sunlight, reflected sunlight, and the blackbody "glow" emitted from Earth (Fig. 1).

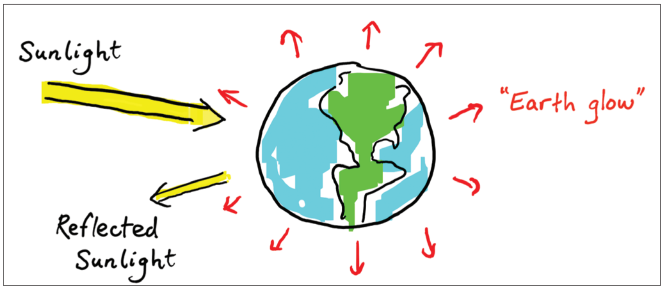

Fig. 1. The balance of energy in and energy out is the starting point for modeling Earth's temperature.

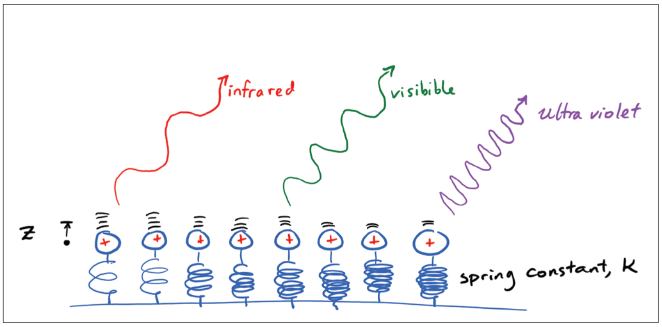

Fig. 2. Thermally activated motion of charged masses on springs is one way to produce a blackbody spectrum.

Planck's law for thermal radiation underpins all climate models, as it describes both sunlight and Earth's infrared glow:

$$S_f(f) = \frac{2hf^3}{c^2}\frac{1}{\exp\left(\frac{hf}{k_B T}\right)-1}, \qquad (1)$$

where S_f is the spectral intensity with respect to frequency, h is Planck's constant, c is the speed of light, k_B is Boltzmann's constant, and T is temperature. To build an understanding of Eq. (1), several classes are spent introducing statistical mechanics and quantum mechanics (including the equipartition theorem, Boltzmann factor, wave functions, and quantized energies of bound electrons). Additionally, we discuss the "classical" theory for the electromagnetic radiation generated by an accelerating charge (power radiated $\propto a^2$, where a is acceleration), noting the correspondence between the classical and quantum description of light emission. We return to these fundamental principles multiple times throughout the course.

Toy models of physical systems can assist with intuition and quantitative reasoning. In the case of Planck's law, we use a toy model consisting of a densely packed array of charged harmonic oscillators, with various natural frequencies that cover a broad band of wavelengths (Fig. 2). When the harmonic oscillators are thermally excited, they emit radiation. For low-frequency oscillators ($f \ll k_B T/h$), classical physics predicts optical power $\propto f^2 T$, consistent with the low-frequency limit of Eq (1). For high-frequency oscillators ($f \gg k_B T/h$), quantized energy levels and statistical mechanics predict an exponential suppression of optical power, $\exp(-hf/k_B T)$, consistent with the high-frequency limit of

DOI: 10.1119/5.0137216

Eq. (1). This toy model gives students a deeper appreciation of the mechanisms that shape the Planck spectrum [Eq. (1)], and a tool to use later when discussing greenhouse gases.

Active engagement is an important pedagogical tool for our class. For example, to get students discussing their understanding of Eq. (1), we ask small groups (3 students per group working together on a shared whiteboard) to produce a sketch of $S_f(f)$ at 300 K and 600 K. Their task is to accurately portray the *relative* size and shape of the two curves using their knowledge of the limiting case behavior and the crossover frequency $f = k_B T/h$. Activities like this are incorporated into every class period, and we follow best practices for maximizing student participation and learning during collaborative group problem solving.[2–4] These best practices include (i) establishing classroom norms for productive/inclusive discussions and (ii) instructional staff visiting individual groups, listening to student reasoning, and offering guidance where needed.

One of the quantitative reasoning skills that we teach is approximation methods for calculating definite integrals. Spectral distributions such as Eq. (1) are ideal for practicing this skill. Definite integrals can be approximated by graphing Eq. (1) and then finding geometric shapes that match the "area" under the curve. We emphasize that the "area" under a graph need not have dimensions of length squared. The total blackbody radiation (across all wavelengths) can be estimated by multiplying the height of the peak by the full width at half maximum. The result can be checked by comparing to the Stefan–Boltzmann law. Similarly, the fraction of optical power in a certain wavelength range can be estimated with rectangles or trapezoids.

Another quantitative reasoning skill we want to share with students is the habit of checking for consistency between measured and/or calculated quantities. For example, satellites orbiting Earth measure the incoming solar intensity to be approximately 1300 W/m^2. Using the Stefan–Boltzmann law, students can check that 1300 W/m^2 is consistent with the temperature of the Sun, the radius of the Sun, and the Sun-to-Earth distance. It is a satisfying back-of-the-envelope calculation, and helps establish expectations for similar back-of-the-envelope exercises throughout the class.

Coarse-grained models of real-world systems (such as a planet bathed in sunlight) allow us to quickly sketch out approximate solutions and/or explore limiting cases. We want students to have experience with this process of coarse-graining a model: smoothing over some details of the system while still reproducing key features and respecting fundamental principles such as conservation of energy. For example, we can describe a planet's surface temperature with a single parameter (average temperature) rather than using a fine-grained temperature map. One limiting case that we analyze with such a coarse-grained model is a spherical planet with no atmosphere. A second limiting case is a planet with an "atmosphere" that is made from a thin material that transmits visible light and absorbs infrared (IR) light. We call this second limiting case the plexiglass model because plexiglass (a transparent plastic) has the required transparency/opacity to visible/IR light. Students enjoy verifying this with a sheet of plexiglass and an IR camera. A small-group activity focused on a "naked" planet (no atmosphere) allows students to discover the important geometric factor ¼ that arises from the ratio of Earth's cross-sectional area (πr^2_{Earth}) and Earth's total surface area ($4\pi r^2_{\text{Earth}}$). The atmosphere-replaced-by-plexiglass model helps students recognize that an atmosphere can act as a ceiling that radiates infrared light onto the planet.

There are additional details about Earth's atmosphere that we incorporate into a more sophisticated model. We ask students to critique the earlier coarse-grained models by comparing the model predictions with experiment. Satellites equipped with IR spectrometers measure the spectrum of light emitted from Earth after sunset.[5] The measured spectrum is not the smooth curve described by Eq. (1). There are sharp dips in spectral intensity, including a prominent dip when wavelength $\lambda \approx 15$ µm. Laboratory measurements of greenhouse gases help us understand these dips. For example, the wavelength-dependent absorption cross-section of CO_2, $\sigma(\lambda)$, has a local maximum when $\lambda \approx 15$ µm.[6] Starting from $\sigma(15\ \mu\text{m}) \approx 10^{-11}\ \mu\text{m}^2$, we calculate the optical depth, L_{opt}, for 15-µm thermal radiation traveling through a simple atmosphere of N_2, O_2, and 400 ppm CO_2:

$$L_{\text{opt}} = \frac{1}{n\sigma(\lambda)}, \tag{2}$$

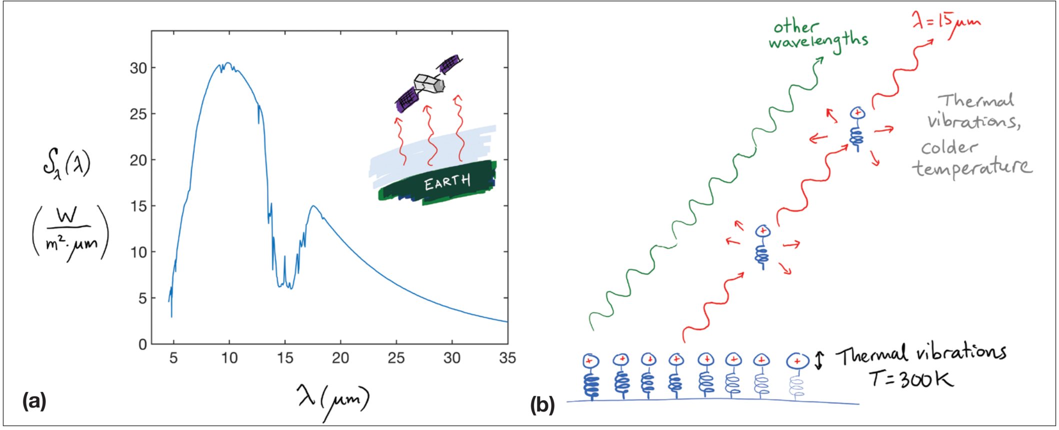

Fig. 3. A satellite with an infrared spectrometer can monitor the radiation that is emitted into deep space. (a) Simulated data from MODTRAN showing the spectral intensity with respect to wavelength of thermal radiation leaving Earth's atmosphere. The ground temperature is 300 K, and the atmosphere consists of N_2, O_2, and 400 ppm CO_2 (other greenhouse gases have been omitted to simplify interpretation of the spectrum). (b) Schematic drawing (not to scale!) showing the short optical path of 15-µm radiation and the long optical path of other wavelengths. CO_2 molecules are represented as harmonic oscillators with resonant frequency corresponding to 15-µm radiation. The air temperature is ~220 K at altitudes where 15-µm radiation can be transmitted directly into deep space.

where n is the number density of CO_2 molecules. Optical depth grows longer at high altitudes, where n is smaller. We find the altitude of "last scattering," and thus find the temperature of the CO_2 molecules in the upper atmosphere that emit 15-μm thermal radiation into deep space (see Fig. 3). The model has enough detail to quantitatively match the dip in the satellite observations. From here, we use a computer program, MODTRAN, to add other greenhouse gas species, adjust gas concentrations, and simulate the total upward flux of infrared light that is emitted into deep space.[7] MODTRAN runs on an internet browser and is freely available. Increasing greenhouse gas concentrations reduces the rate that energy leaves Earth (radiative forcing). Students can use MODTRAN to reproduce the radiative forcing numbers published by the International Panel on Climate Change.

A kinesthetic activity is a fun and engaging way to explain why certain wavelengths of light interact more strongly with CO_2. In a kinesthetic activity, students are asked to move their bodies to act out a physical situation.[8,9] In the CO_2 example, three student volunteers play the role of the three atoms. The students arrange themselves into a molecule and self-identify their partial charge (slightly negative or positive). Then, they respond appropriately to a time-varying electric field. The instructor uses their arm as an electric-field vector, mimicking the oscillating field of incident light. The motion of the three atoms can then be related to the absorption and scattering of the incident light. An accompanying demonstration of a mass hanging on a spring (driven at different frequencies) shows the difference between resonant and nonresonant driving forces. An extension of this activity shows why N_2 and O_2 are not greenhouse gases.

A well-rounded set of quantitative reasoning skills includes sensemaking about differential equations. For this purpose, we analyze the time dependence of Earth's temperature. We ask students to model Earth's oceans and atmosphere using fundamental concepts, back-of-the-envelope estimates, and a differential equation. The heat capacity of the system is dominated by the upper 2000 m of the ocean. Students can estimate the mass of this water by recalling that ~70% of Earth is covered by water. The specific heat capacity of water is predicted by the equipartition theorem (each atom has 6 degrees of freedom). When constructing a differential equation, students must account for the difference between incoming and outgoing radiation, and how this difference changes as the water temperature increases. The model predicts a 30-yr time constant for Earth to respond to a steplike change in CO_2 concentration.

Conclusion

A narrative based on climate modeling incorporates both fundamental physics and physical reasoning skills. This material is suitable for students making the transition from lower-division to upper-division physics; we cover fundamental concepts from quantum and statistical mechanics while also developing a robust set of physical reasoning skills. Our pedagogical strategies include the active engagement techniques of small-group activities, kinesthetic activities, and hands-on demonstrations. After the climate modeling segment of this course, we move on to sustainable energy issues (including fission, fusion, photovoltaics, and wind energy), which are approached with a similar mix of fundamental concepts, physical reasoning, and active engagement.

Acknowledgments

We acknowledge the wonderful textbooks *Six Ideas that Shaped Physics: Unit T—Some Processes Are Irreversible,*[10] *Fundamentals of Atmospheric Radiation*,[6] and *Sustainable Energy Without the Hot Air,*[11] which provided inspiration for curricular material. Valuable discussions with David Roundy, Corinne Manogue, and Liz Gire also inspired this work.

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