Thermal radiation simulation

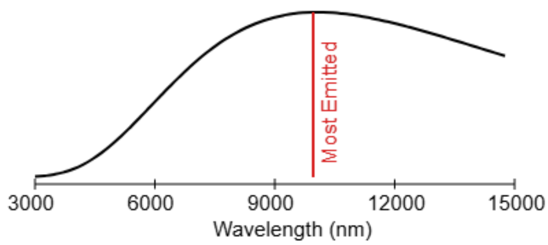
Tutorial for teachers

1. Controls and display

The simulation initializes by showing the planet's surface from a microscopic point of view as a set of atoms arranged in a lattice (cubic for simplicity). The initial temperature of 15°C corresponds to the current average temperature of the Earth's surface.

With the exception of the thermometer on the left of the simulation, the control buttons are located in the right-hand side menu. If the user needs more space, this menu can be hidden by clicking on › .

- **Macroscopic / Microscopic** allows a change of perspective: macro (landscape) or micro (arrangement of positive ions connected by electrons).
- Disable **Electrons** to display only positive ions.
- Click on Play to agitate the ions according to the temperature set on the thermometer.
- **Celsius/Kelvin** toggles the display on the thermometer.
- The slider to the right of the **thermometer** allows you to vary the temperature and the degree of thermal agitation of the ions. The **Mars** and **Venus** indicators allow you to set the temperature to the average value for these planets.
- **Radiation** displays the radiation emitted by the surface in the form of vertical electric (electromagnetic) waves originating from the surface. To avoid overloading the display, only the most emitted wavelength (for which the surface emits the most radiant power, see Sect. 5) is shown.
- Click **Pause** to freeze the ions and the emitted electrical waves in order to measure the wavelength.
- The **Grid** has a spacing of 1000 nm to measure the approximate wavelength of the radiation.
- **Wavelength distribution** displays the distribution of all emitted wavelengths as a normalized Planckian function (the peak amplitude does not vary for scaling reasons, see Sect. 5), indicating the most emitted wavelength in red (corresponding to the displayed waves).



  ⇒ When the temperature varies, the distribution shifts either toward shorter or longer wavelengths depending on whether the temperature increases or decreases.
- The button resets the simulation.

2. About this simulation

This simulation allows us to discover the IR radiation emitted by the planet's surface, by microscopically representing condensed matter as an arrangement of charges (ions or atomic nuclei) in thermal agitation.

Prerequesites

The only prerequisites are the concepts of electrical charge, atoms and the structure of matter as an arrangement of atoms, thermal agitation of the constituents of matter, and wave radiation emitted by an oscillating charge. These concepts are reintroduced through images, quizzes, and videos in the interactive activity Understanding the greenhouse effect.

Relationship with the other simulations

This simulation is the second in a series of four physics and chemistry simulations designed to sequentially introduce the concepts needed to construct a coherent model of the causes of global warming, while dispelling misconceptions reported in the literature (see Sect. 3). Each simulation in the series targets a category of concepts necessary for understanding the subsequent simulations (see Fig. 1).

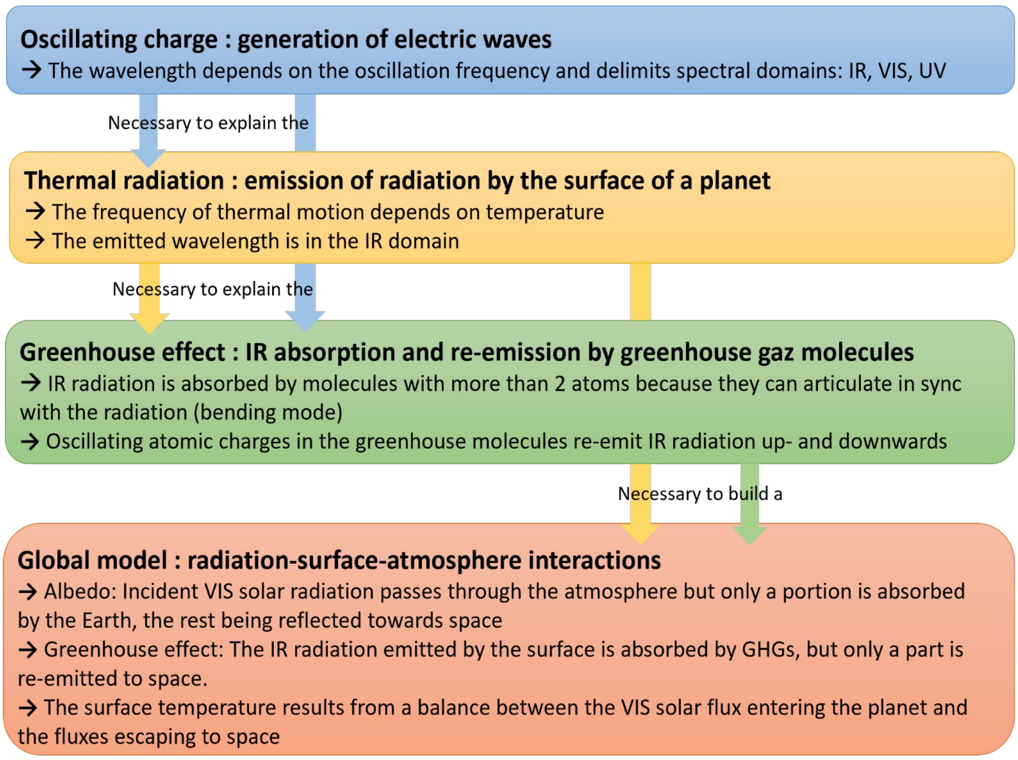


Fig. 1 : Concept map of the four simulations on the causes of global warming. Each simulation targets a category of concepts (highlighted in color), where the main concepts to be discovered are listed by small arrows. The colored arrows between categories illustrate how the concepts discovered in one simulation are necessary for the following simulations.

Following the emission of radiation by a single *Oscillating Charge* (first simulation), the *Thermal Radiation* simulation then reveals the IR radiation emitted by an ensemble of charges (ions) undergoing thermal agitation on the planet's surface.

The emission of long-wavelength thermal radiation by the Earth's surface is a necessary ingredient for understanding the absorption of this radiation by greenhouse gas molecules (third simulation in Fig. 1), because their polyatomic structure can vibrate synchronously with

IR electric field oscillations, but not with VIS solar radiation (wavelengths too short and frequencies too high) [1, 2, 3]. Without this concept of radiation emitted by the planet's surface, students are prone to develop erroneous explanations of the greenhouse effect, such as the rebound of “sunlight” trapped in the atmosphere (see Sect. 3). Furthermore, it is through IR thermal radiation that the planet releases radiant energy into space in order to achieve thermal equilibrium and stabilize its temperature. Thermal radiation is therefore a key ingredient in building a *Global Model* (fourth simulation) and studying the planet's energy balance.

The interactive activity Understanding the Greenhouse Effect includes these four simulations, scaffolded by instructions, images, and quizzes with feedback, to guide students toward constructing a coherent model of global warming.

3. Underlying misconceptions

The concept of thermal radiation is simply absent from the minds of most students of middle and high school [4], partly because they are unfamiliar with the concept of wave radiation of different wavelengths (see the Oscillating charge simulation tutorial), and partly because the concept of thermal radiation is rarely taught at the pre-university level (at the university level, it is conventionally studied through the ideal model of the “black body”, see Box 1).

Without the concept of radiation generation by oscillating charges, students lack an explanatory link between thermal agitation and thermal emission. Students are then led to imagine that the radiation coming from the Earth's surface is nothing more than a reflection of incident solar radiation [4]. This misconception is also found in certain media illustrations and is the source of erroneous mental images of the greenhouse effect, such as that of the “trap” (see Greenhouse Effect simulation tutorial), in which “ the rays of the sun” bounce between the Earth’s surface and a thin layer of greenhouse gases, as in Fig. 2.

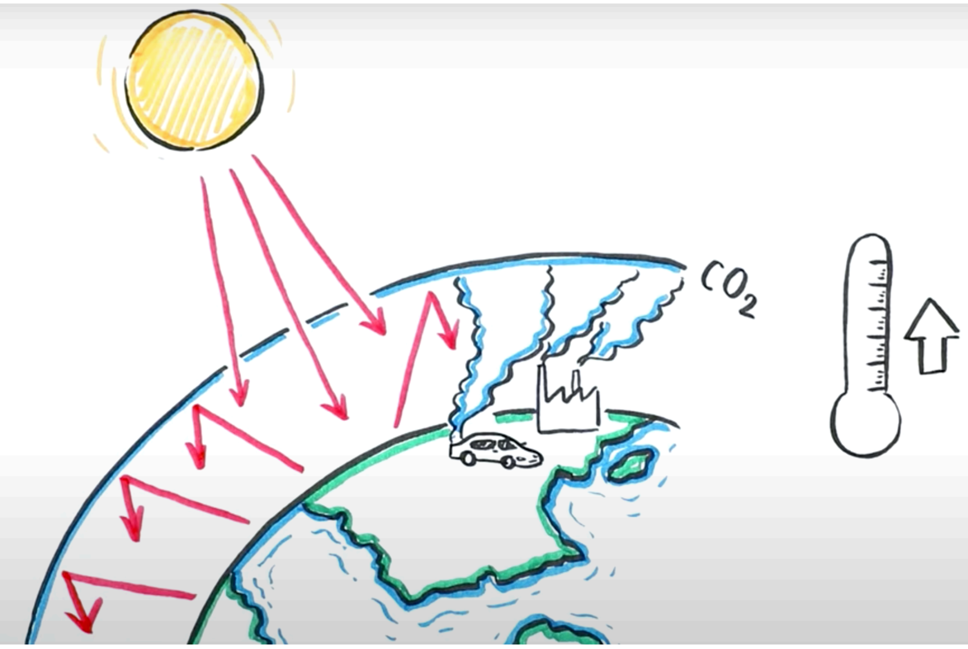


Fig. 2 : Media representation of the greenhouse effect, following the image of the “trap” [easyvote.ch].

4. For students to discover

By observing how the frequency of thermal agitation of atomic nuclei varies with temperature, students will (re)discover the definition of temperature as a measure of the *average* degree of agitation (or frequency of agitation) of the constituents of matter. Students can easily understand that, in reality, not all constituents move synchronously as they do in the simulation. This definition can be (re)established in the classroom, distinguishing it from thermal energy.

The distribution of wavelengths allows students to realize that despite the simplified representation of atomic oscillations at the same frequency and radiation at a single wavelength, ions actually vibrate at varying frequencies, generating a *continuous set of wavelengths characteristic of thermal radiation*.

By varying the temperature while observing the emitted radiation and its wavelength distribution, students will discover that *as the temperature increases, the distribution shifts toward shorter wavelengths* (Wien's law). Students should note that *regardless of the planet, the wavelength distribution always remains in the IR*.

This is why climatologists distinguish between “short wave” solar radiation (centered on the VIS range) and “long wave” terrestrial thermal IR radiation (see Fig. 3).

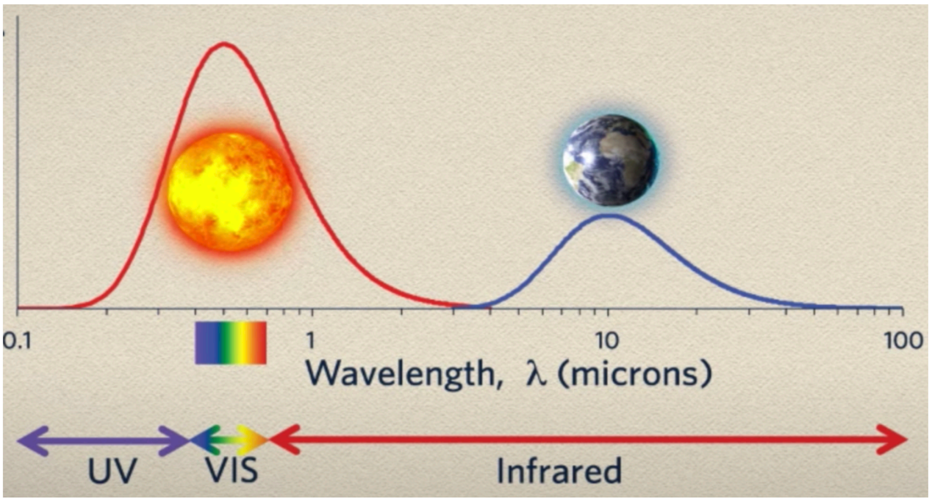


Fig. 3 : Distributions of wavelengths emitted by the Sun and the Earth's surface [5], represented as Planckian functions (not to scale).

5. Modeling and didactic choices

In the simulation, the condensed matter forming the surface of the planets is represented at the microscopic level as a set of independent harmonic oscillators (“Einstein solid”).

When the simulation is in Play mode, the ions in the atomic lattice begin to oscillate harmonically (vertically and horizontally in equal proportions) at the same frequency, which is directly proportional to the temperature in Kelvin (justified if we are far from absolute zero). This single frequency is calculated in a simplified manner as proportional to the temperature (assuming equal energy distribution over three degrees of freedom, i.e. $f = 3kT/h$, where f stands for the frequency, T the temperature in K, h and k the Planck and Boltzmann constants, respectively Boltzmann).

The movement of electrons, on the other hand, is not simulated, as their representation is solely intended to illustrate the neutrality of matter. This is why a toggle button is provided to hide them, so that students can focus their attention on the oscillation of ions. In the simulation, for simplicity's sake, every other ion is shown oscillating vertically and horizontally, all in phase.

We chose not to display radiation when the Play button is clicked, but only when the Radiation button is activated, so that students can predict that the set of agitated charges should emit radiation. When the Radiation button is activated, the user sees sinusoidal waves emerging from the surface vertically upwards, reminiscent of the waves emitted on the horizontal axis by the oscillating charge in the Oscillating Charge simulation. This is again a simplification, as the Earth's surface emits radiation in all directions, but it is consistent with the horizontal oscillation of half of the ions.

Box 1. Black body and thermal radiation emitted by the Earth's surface

The Planck function, or "Planckian," used to represent the distribution of wavelengths, comes from the theoretical "black body" model. This ideal model refers to a perfectly opaque system (with emissivity and absorptivity equal to 1), for which a mathematical expression of the radiant power density as a function of wavelength, i.e., Planck's function, can be derived [6, 7]. It is often used to model the distribution of radiation emitted by relatively opaque bodies at a certain temperature, such as a heating element or the photosphere of a star. [5, 7]. In the case of Earth, although the surface of the planet (with an emissivity of approximately 0.9 [3]) is not a perfect black body, the measured spectrum of its radiation almost follows a Planckian curve (see Fig. 4).

We chose not to refer directly to the black body in the simulation because we felt that this concept was too abstract for secondary school students.

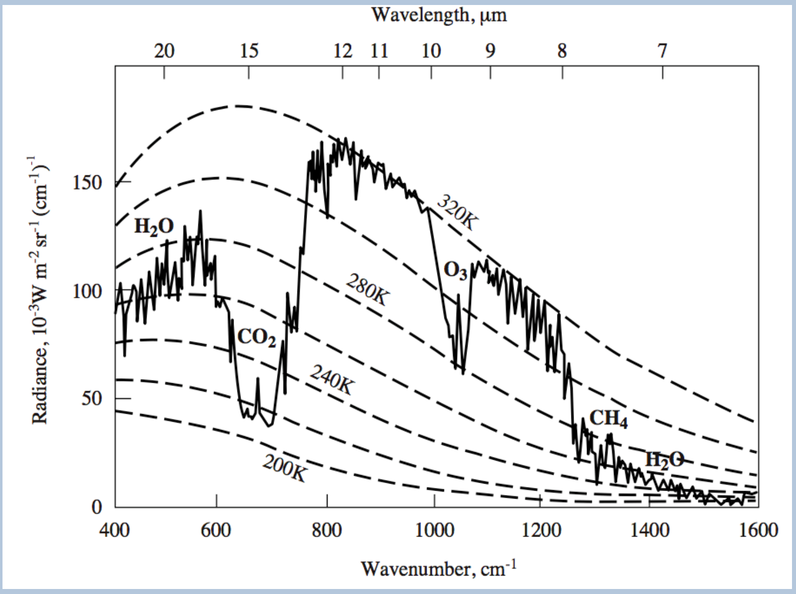


Fig. 4 : Emission spectrum of the Earth's surface (Nigeria) observed by satellite. The parts outside the molecular absorption bands, between 8 and 10 µm and 11 and 12 µm arrpximately, correspond to surface thermal radiation that was able to escape directly into space [9].

All emerging waves have the same wavelength corresponding to the wavelength most emitted by a black body at that temperature (i.e., the wavelength corresponding to the peak of Planck's function, see Box 1), and is inversely proportional to temperature (Wien's law).

The wavelength distribution at a given temperature is represented as a *normalized* Planck function (the amplitude remains the same regardless of temperature, since it is a distribution) for several didactical reasons. This normalization allows students to focus on the wavelength shift in the distribution rather than on the peak amplitude (which varies by four orders of magnitude between Mars and Venus). The vertical axis is therefore purely qualitative, and can be interpreted by students as the “amount of radiation” emitted at different wavelengths. This also avoids the obstacle of units for students (the units on the vertical axis would be W/m^2nm), as the concept of radiative flux and its units (W/m^2) will only be useful and introduced in the Global Model simulation. The most emitted wavelength is shown in red in order to draw students' attention to its correspondence with the wavelength of the radiation represented.

We chose to indicate the temperatures of Mars and Venus on the thermometer so that students could generalize the concept of thermal radiation to bodies other than the Earth's surface (e.g., the surface of the Sun) and conclude that, unlike the Sun, all planets emit in the IR (see Sect. 4). These planets will be included in the Global Model simulation, where students will be able to discover why their temperatures differ based on their albedo and greenhouse effect values.

References

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[2] Salgado D’Arcy, R., youtube channel AllAboutClimate, *Dancing molecules*

[3] Krauss, L. M. (2021), *The physics of climate change,* Post Hill Press

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