Greenhouse effect simulation

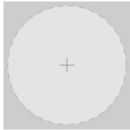
Tutorial for teachers

1. Controls and display

Clicking on the “i” symbol in the top right corner will bring up a quick guide.

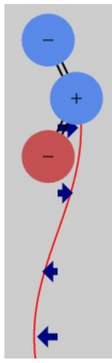
The control buttons are located in the right-hand side menu. If the user needs more space, this menu can be hidden by clicking on .

- Fill in the four circular boxes for the atmosphere: Select a molecule from **Greenhouse gases** (e.g.) or **Non greenhouse gases**, then click on one of the circular boxes in the atmosphere with a + sign in the center to insert it there. Repeat with the three other boxes.



- Choose either **Infrared** or **Visible light**.
⇒ IR thermal radiation is incident from below to reflect its origin from the planet's surface, while shortwave solar radiation centered in the VIS range is incident from above.

- Click **Play** to display the radiation in wave form.
⇒ Greenhouse gas molecules begin to vibrate when they absorb IR radiation. This vibration is represented by a harmonic horizontal movement of the atoms, reproducing both a bending vibration mode (mainly) and a stretching vibration mode.



- **Electric field** displays electric field vectors along the waves (only for IR radiation) in order to study how the incident field dictates the movement of atoms.

- **Sign of charges** displays the sign of the partial charges carried by the atoms of the molecules.

- Click **Pause** to freeze the waves.
Then use the double arrows ◀◀ ▶▶ to move forward or backward step by step in time, in order to study how each atom moves according to the direction of the electric field.

- **Re-emission** shows the IR radiation re-emitted by greenhouse gases as a dashed line. This re-emission is directed both toward space and toward Earth, hence the greenhouse effect. Since the molecules are oriented vertically here, the re-emitted radiation is mainly vertical, although all atmospheric molecules actually re-emit in all directions (see Sect. 5).

- The button resets the simulation.

2. About this simulation

The Greenhouse Effect simulation allows the user to construct a sample atmosphere as an alignment of four molecules in order to visualize how they interact with shortwave solar radiation (VIS for simplicity) or IR thermal radiation emitted by the surface.

Prerequesites

For middle school level, the only prerequisites are the concepts of molecules and atoms. At high school level, the concept of partial charge and an introduction to the concept of electric fields are also necessary in order to study the mechanism of molecular articulation. The concept of wave radiation in different wavelength ranges, in particular IR thermal radiation emitted by the surface, can be explored using the two simulations Oscillating Charge and Thermal Radiation (see next paragraph). All these concepts are reintroduced using images, quizzes, and videos in the interactive activity [Understanding the Greenhouse Effect](#).

Relationship with the other simulations

This simulation is the third 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).

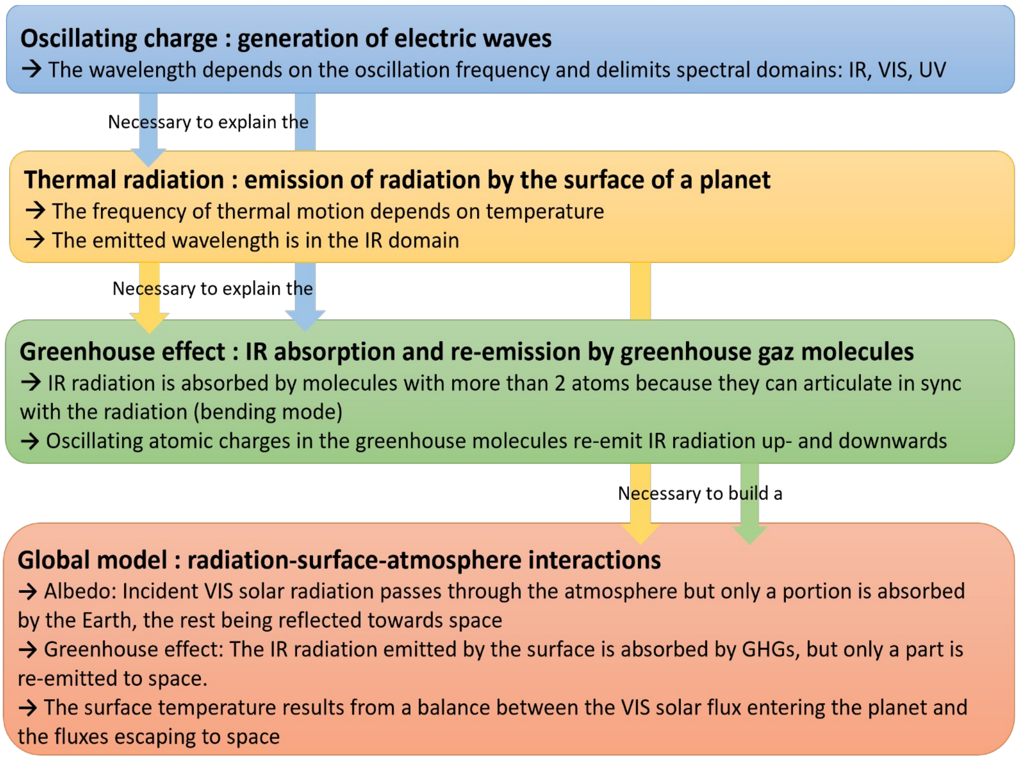


Fig. 1 : Concept map of the four simulations on the causes of global warming. Each simulation targets a category of concepts (highlighted in color), where the main concepts to be discovered are listed by small arrows. The colored arrows between categories illustrate how the concepts discovered in one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

The first two simulations, *Oscillating Charge* and *Thermal Radiation*, allow students to discover the emission of wave radiation in different wavelength ranges (UV, VIS, IR) as well as the emission of IR thermal radiation by the planet's surface, which are necessary concepts for explaining the greenhouse effect.

The *Greenhouse Effect* simulation shows that greenhouse gas (GHG) molecules do not interact with VIS radiation, but absorb IR radiation and re-emit it both into space and back toward Earth. Without this concept of spectral selectivity in the atmosphere, students are led to develop erroneous mental images of the greenhouse effect (see Sect. 3).

The absorption and re-emission of IR radiation by GHGs is a key ingredient in the *Global Model* (fourth simulation) because the IR radiation flux that is evacuated into space contributes to 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

Due to media coverage, students identify carbon dioxide as the main or even the only GHG [1], omitting methane, nitrous oxide, and water vapor [2]. However, water vapor is the most abundant GHG and the most important for climate regulation because it is the source of a positive feedback loop (see tutorial on the Global Model simulation).

The lack of recognition of GHG varieties reveals the absence of an explanatory link between the atomic structure of molecules and their ability to absorb and re-emit IR radiation (GHGs can vibrate in asymmetric modes thanks to a structure with more than two atoms [3]).

Like climate skeptics, students also struggle to conceive that GHGs constitute only a *tiny minority* (< 0.1%) of the molecules in our atmosphere (which is why their concentration is measured in ppm), and that they paradoxically have a significant effect [4]: the “natural” greenhouse effect enables life on Earth, while the “intensification” of this effect through increased concentrations causes global warming. To explain this paradox, students must discover the inability of the main constituents of the atmosphere to absorb IR radiation, making the small fraction of the atmosphere occupied by GHGs sufficient to absorb a significant fraction (on Earth, about 30%) of IR radiation. An absolute change in GHG concentration of 100 ppm therefore corresponds to a significant relative change in concentrations and contributes to a significant change in the greenhouse effect.

Students are generally unaware of the distribution of GHGs throughout the atmosphere, particularly the fact that carbon dioxide, methane, and nitrous oxide are considered to be “well mixed” in the troposphere [5]. Instead, they represent GHGs as a thin layer at the top of the atmosphere [6]. This representation is conveyed in many illustrations found in educational books, the media, and on the internet (see, for example, Fig. 2).

As described in the tutorials on Oscillating Charge and Thermal Radiation simulations, students generally describe radiation as “rays” or “heat,” without any concept of wave or wavelength. Furthermore, they are also unaware of the existence of IR thermal radiation. Without these concepts, students perceive the role of the atmosphere as a “shield” or a “trap” [7]. The role of the “shield” is often attributed to the stratospheric ozone layer, whose growing hole is responsible for letting in more “heat” (see Fig. 3 on the left). Stemming from widespread media coverage of the ozone layer and its absence from school programs, the confusion between its depletion and the intensification of the greenhouse effect is well known and systematic in the literature [1, 2]. In the image of the “trap,” often conveyed in media illustrations of the greenhouse effect (see, for example, Fig. 2), the “sun's rays” enter the atmosphere but cannot escape (the atmosphere would therefore be transparent in one direction but not the other!), bouncing between the Earth's surface and a thin layer of GHGs (see Fig. 3 in the middle).

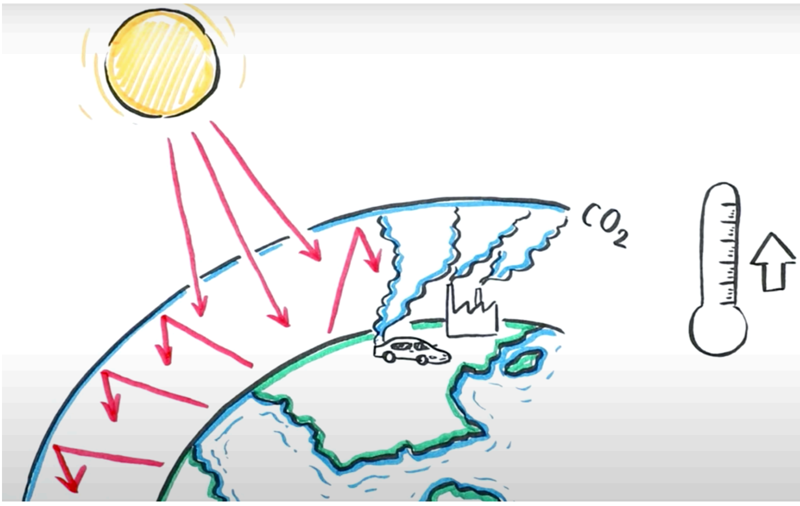


Fig. 2 : Illustration of the greenhouse effect presented during the vote on the Swiss CO_2 Act on June 13, 2021 (source: easyvote.ch). According to the explanation given, “the Sun's rays reach the Earth, but they no longer escape the atmosphere because GHGs trap them like a plastic film.”

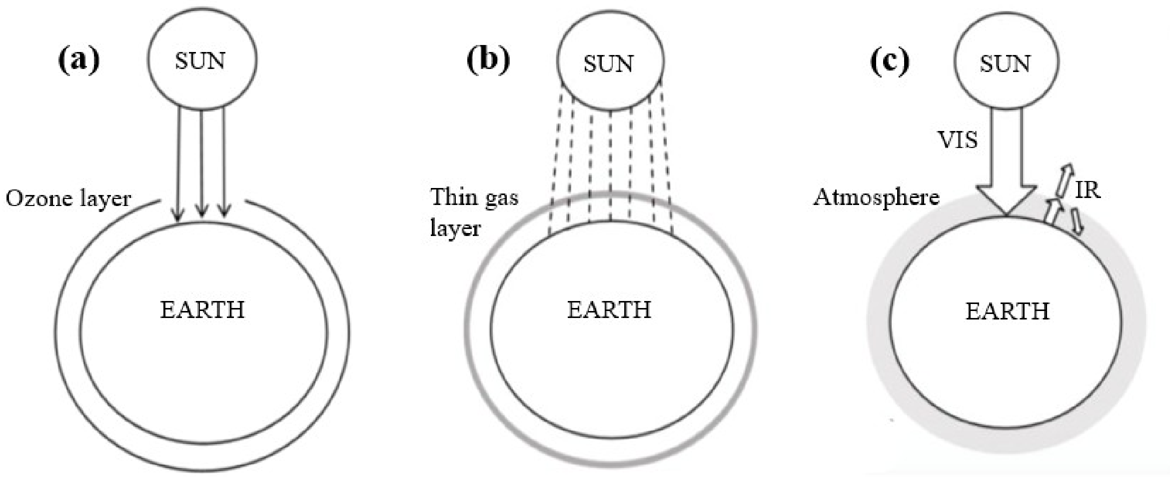


Fig. 3 : The three main mental models of the greenhouse effect identified by Varela et al. [7]. (a) Depletion of the ozone layer “shield,” allowing more solar radiation to enter. (b) Trapping of solar radiation by reflection between the surface and a thin layer of gas. (c) Scientifically correct model where the arrows represent radiative fluxes.

4. For students to discover

Students will discover that molecules do not interact with VIS radiation and that *only greenhouse gas molecules (all containing at least 3 atoms) interact with IR radiation by deforming asymmetrically* (bending vibration mode).

At high school level, they will be able to study the mechanism of molecular deformation based on the partial charges carried by atoms and on electrical force: a molecule consisting of two identical atoms (e.g., N_2), which has no partial charges, is not subjected to any electrical force when immersed in the electric field of radiation. On the contrary, *a molecule with three or more atoms has partial charges of opposite signs and will therefore experience forces in opposite directions*, causing it to deform (according to the relationship $\vec{F}_{el} = q\vec{E}$ between the electric force $\vec{F}_{el}$, the charge $q \lessgtr 0$, and the electric field $\vec{E}$).

For middle school students, we can simplify by noting that a diatomic molecule cannot "bend" (see, for example, this video, which draws an analogy with dancers' legs bending in time to the music).

5. Modeling and didactic choices

We chose to include only four molecules so that they would be large enough for users to visualize their vibrations as oscillations of their atomic constituents. The number four also makes it easy to compare greenhouse molecules side by side with other gases and to order molecules according to their number of atoms (ranging from 1 to 4). In the sidebar, GHG molecules are separated from the other main constituents of the atmosphere (Non greenhouse gases) so that students can easily compare them and recognize their differences in molecular structure (number of atoms). We chose to include both the full names and formulas of the molecules to reinforce their learning.

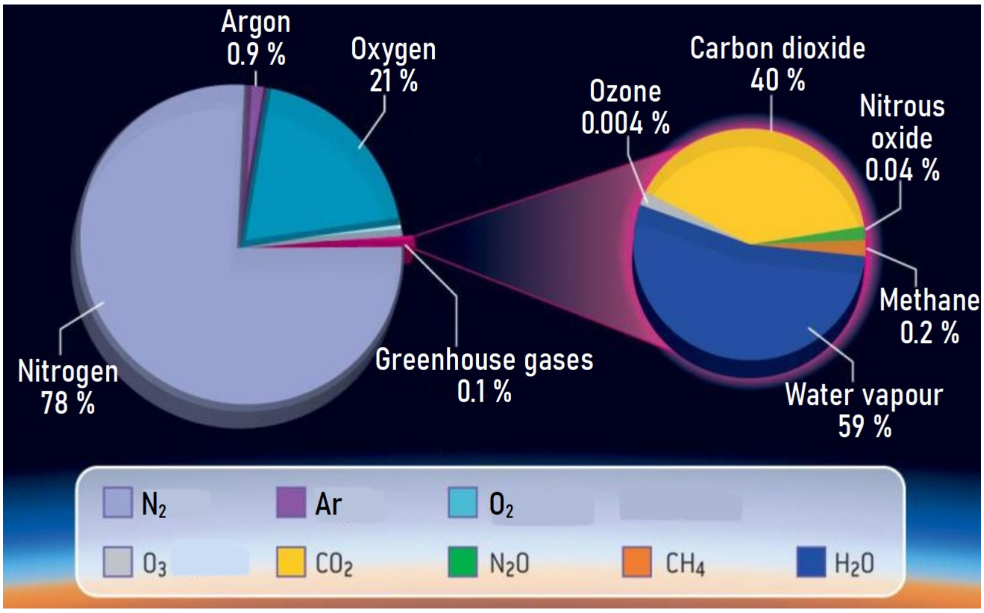


Fig. 4 : (left) Percentages (by volume) of the atmosphere occupied by the main gases and GHGs. (right) Percentage distribution of the various GHGs. Figure adapted using data from the University of Arizona's Atmo336 course.

In the list of GHGs, we have included the GHGs that are most abundant in the atmosphere (see Fig. 4 and Box 1). Note that we have chosen to include ozone in the list of GHGs (since it is one of the main contributors to "radiative forcing" from 1750 to 2019, see Fig. 7.6 of the IPCC's 6th Assessment Report [8]), as this helps to understand that it contributes to the greenhouse effect rather than the opposite (as erroneously suggested by the "shield" model of the ozone layer, see Sect. 3). In particular, students can realize that ozone does not "block" VIS radiation from the Sun. However, further discussion of the stratospheric ozone layer and its interaction with UV radiation is necessary afterwards (see Box 2). This is included in the interactive activity Understanding the Greenhouse Effect.

Box 1 : GHGs contributing to the natural greenhouse effect and its intensification

The greenhouse effect can be quantified as the flow of IR radiation that is absorbed by GHGs and re-emitted toward the surface (and therefore cannot escape into space), in the order of 150 W/m^2. As the most abundant GHGs (see Fig. 4), water vapor contributes about 60% and CO_2 about 20% [9]. These proportions indicate the contributions to the *total* greenhouse effect, including the natural greenhouse effect without anthropogenic intensification.

However, contributions to anthropogenic greenhouse effect *intensification* since 1750 vary, as they depend on changes in emissions, average atmospheric lifetime, and the ability of different GHGs to absorb infrared wavelengths from the Earth's thermal spectrum. In particular, water vapor (tropospheric) plays no role in this, as its concentration in the atmosphere is almost entirely controlled by the water cycle and depends only on the temperature of the atmosphere, which determines the saturated vapor pressure [5, 9]. (the increase in its concentration is therefore the result of warming and in turn has a retroactive effect on the greenhouse effect, known as "water vapor feedback," as described in the Global Model simulation tutorial).

Since CO_2 (along with water vapor) is the main gas regulating the natural greenhouse effect, the CO_2 absorption bands are largely saturated [9], as can be seen in Fig. 5. In contrast, CH_4 and N_2O absorb at wavelengths within the transparency window of the atmosphere. This is why the emission of each ton of CH_4 or N_2O contributes thousands of times more to the intensification of the greenhouse effect than an additional ton of CO_2. However, since the concentration of CO_2 is five orders of magnitude higher than that of CH_4 and N_2O, its contribution to the planet's radiative imbalance since 1750 (or "radiative forcing") remains dominant (Fig. 7.6 of the IPCC's 6th report [8]). Comparing the contributions of different GHGs is beyond the scope of this simulation, and understanding it requires knowledge of spectroscopy that is beyond the students' level.

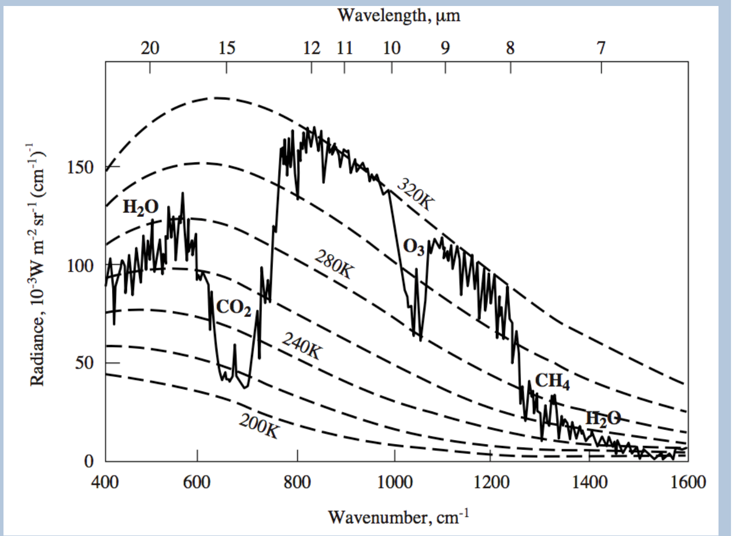


Fig. 5 : Emission spectrum of the Earth's surface (Nigeria) observed by satellite. Planck functions (dashes) indicate that the deeper the absorption bands, the greater the saturation, as re-emission into space occurs at higher altitudes where temperatures are lower [10].

Box 2 : Stratospheric ozone vs. tropospheric ozone

The famous ozone layer located in the stratosphere (at an altitude of over 18 km, see image below) must be distinguished from ozone pollution generated by human activities in the lower atmosphere (troposphere).

The stratospheric “ozone layer,” which formed naturally 50 million years ago [5], is essential for absorbing ultraviolet (UV) radiation from the Sun through the photodissociation of ozone molecules. Although UV radiation does not contribute to atmospheric warming, it can cause damage to living cells. The ozone layer acts as a kind of “sunscreen” for the Earth, protecting it from UV rays without preventing visible radiation from warming it. As it is located in the stratosphere, it does not contribute to the greenhouse effect, which occurs mainly in the troposphere [12].

Tropospheric ozone, on the other hand, is a non-natural product of human activities. In the troposphere, it contributes to the greenhouse effect.

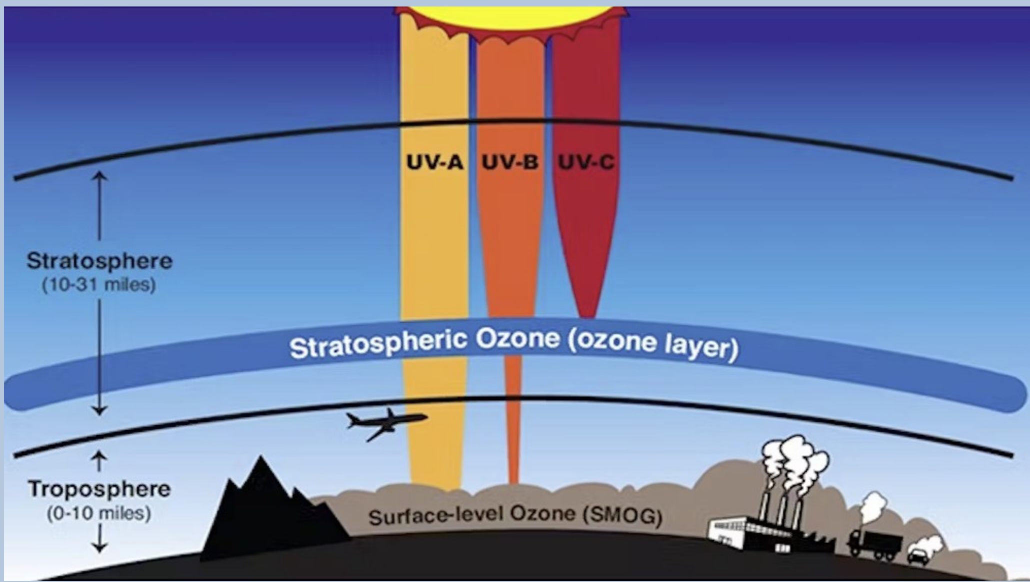


Fig. 6 : Illustration of the different roles of the stratospheric ozone layer (absorbing UV-C rays) and tropospheric ozone [NASA]

As in the Thermal Radiation simulation, incident radiation is represented with a vertical direction and a single wavelength. When the user selects IR radiation, the radiation comes from the bottom of the screen (Earth's surface), and the wavelength represented corresponds to that emitted by the Earth in the Thermal Radiation simulation. VIS radiation, coming from the top of the simulation, represents shortwave solar radiation centered in the VIS. Although the solar spectrum also contains a portion in the UV and IR (see Thermal Radiation simulation tutorial), we have chosen to represent only its VIS portion to simplify and distinguish the effect of thermal IR radiation. Its wavelength is significantly smaller than that of IR radiation, but not to scale (the wavelength of 500 nm corresponding to the peak of the solar spectrum should be 20 times smaller than the 10,000 nm corresponding to the peak of terrestrial thermal radiation), so that it does not appear smaller than the molecules in the simulation. VIS and IR radiation are represented in yellow and red, respectively, consistent with the Global Model simulation (fourth simulation in the series, see Fig. 1).

VIS radiation passes through all molecules, demonstrating the near transparency of the atmosphere in the visible spectrum[1], and IR radiation also passes through the main constituents of the atmosphere that do not produce a greenhouse effect. When IR radiation reaches greenhouse molecules, these molecules begin to vibrate at the same frequency as the radiation [3]. It is then possible to explain to students that the inertia of the atomic constituents does not allow vibration at the higher frequencies of VIS radiation.

To illustrate the absorption of radiation and the conversion of radiant energy into mechanical energy (molecular vibration), radiation does not continue beyond the "point of contact" between the wave and the lower atom of the molecules.

In general, GHG molecules can absorb (and emit) IR radiation at frequencies that cause asymmetric vibration modes to resonate, i.e., producing asymmetry in charge distribution or a "dipole moment" [3]. For simplicity, we have only represented the bending vibration mode (and not other modes such as asymmetric stretching), as students can attribute this mode to the articulation of GHG molecules with more than 2 two atoms [4] (e.g., by analogy with a leg as in this video presented in Section 4). This explanation does not require the concept of dipole moment, which is beyond the scope of high school students' knowledge. The bending mode is also the most important mode for the Earth's greenhouse effect, because the IR intensity emitted by the Earth is much weaker in the absorption band of the asymmetric stretching mode [11].

To represent this bending mode, the molecules are oriented vertically so that the individual atoms oscillate horizontally, parallel to the electric field carried by the radiation. Although this model does not respect the fixed interatomic distances corresponding to a pure bending mode, it allows more advanced students (e.g., at high school) to explain the vibration mechanism by displaying the sign of the partial charges carried by the atoms, as well as the electric field vectors. These students can then attribute the bending to the fact that atoms with a positive partial charge move in the opposite direction to atoms with a negative partial charge (as presented in Section 4). Although strictly speaking, positive atoms accelerate in the direction of the electric field, we chose to represent the oscillation of these atoms in phase with the field so that students can see them moving in the direction of the field, thus avoiding the visual obstacle of "wave detachment" (loss of contact between the wave and atomic oscillation).

For each molecule, we took into account the equilibrium condition of the center of mass to cause atoms with opposite partial charges to oscillate with different amplitudes (see Box 3).

Finally, the last toggle button represents the radiation re-emitted by GHG molecules. The Radiation Re-emission button has been intentionally placed at the bottom to prevent students from activating it before they have been able to predict what the oscillation of GHG atomic charges should generate. Although in reality re-emission occurs statistically in all directions, here it is represented only vertically, both for simplicity and consistency with the orientation of the molecules. The re-emitted waves are represented with the same wavelength as the incident wave, but as a dashed line to avoid confusion with the incident IR radiation. Its amplitude is halved to illustrate energy conservation (half the energy upwards and half downwards).

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1 The main gases in the atmosphere, N_2 and O_2, absorb only a few percent of the solar VIS radiation flux through Rayleigh scattering in the shorter blue wavelengths [5,9]. In reality, the solar spectrum also contains a portion in the IR (not shown in the simulation for simplicity), this is why 5% of solar radiation is absorbed by water vapor and CO2 [5].

Box 3 : Amplitude of oscillations around the center of mass

For an incident electric wave along y, the atoms will begin to oscillate along x, parallel to the field and at the same frequency. The position of the atoms along an x-axis whose origin is placed at the initial rest position of the atoms is then given by:

$$x_\pm(t) = \pm A_\pm \sin(2\pi f t),$$

where f is the frequency of the field and the signs $\pm$ refer to the signs of the partial charges, since atoms with opposite charges will oscillate in opposite directions.

Since the net charge of the molecules is zero, this implies that the vector sum of the electric forces cancels out and that the center of mass of the molecule is in equilibrium. Let m_+ and m_- be the masses of the atoms carrying a partial positive and negative charge, respectively. The equilibrium condition for the center of mass is written as:

$$\sum m_+ x_+(t) + \sum m_- x_-(t) = 0$$

Comme les atomes positifs et négatifs oscillent en antiphase, cette condition est aussi valable lorsque les positions atteignent leurs extrema with amplitudes A_+ and A_- respectively, hence :

$$A_+ \sum m_+ = A_- \sum m_- \Rightarrow \frac{A_+}{A_-} = \frac{\sum m_-}{\sum m_+}$$

On peut alors calculer le rapport des amplitudes à partir des masses atomiques.

For instance, for CO_2 we get $\frac{A_C}{A_O} = \frac{2 \times 16}{12} \simeq 2.7$, so the carbon atom will oscillate with almost three times the amplitude of the oxygen atoms.

For H_2O, we get $\frac{A_H}{A_O} = 8$, for O_3 $\frac{A_{O+}}{A_{O-}} = 2$, for N_2O $\frac{A_N}{A_O} \simeq 0.5$ and for CH_4 $\frac{A_H}{A_C} = 3$.

These amplitude ratios are respected in the simulation.

References

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