Global Model simulation

Tutorial for teachers

1. Controls and display

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

The simulation has two modes (see Sections 1.2 and 1.3): the *Waves* mode, which displays radiation in wave form for an initial qualitative study, and the *Fluxes* mode, which displays radiative fluxes with their values in W/m^2.

Regardless of the mode selected, shortwave solar radiation centered on the visible range (VIS) is represented in yellow, while infrared (IR) radiation is represented in red.

Because this simulation is designed to study radiation entering and leaving the “Earth system” at the top of the atmosphere, the boundary between the atmosphere (sky blue) and space (black) is shown to separate this system from space.

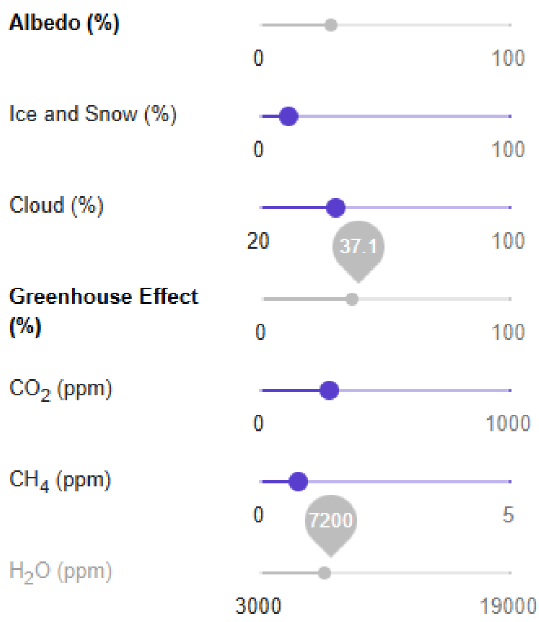
The thermometer indicates the average *surface* temperature of the planet.

Moving the mouse to any point in the atmosphere (the pointer turns into a magnifying glass) and clicking displays a microscopic view showing the greenhouse gas (GHG) molecules included in this simulation, CO_2, CH_4, and H_2O, with concentrations adjusting according to the values of the sliders in ppm.

1.1 The climatic variables

The simulation includes four independent climate variables, which can be modified using the sliders under Albedo and Greenhouse Effect:

- Ice and snow (%) = Percentage of surface area covered by the cryosphere
- Nuages (%) = Percentage of the sky covered by low-altitude clouds[1]
- CO_2, CH_4 (ppm) = Average concentrations of CO_2 and CH_4 in the troposphere in parts per million (ppm)



About water vapor: The slider is grayed out because the H_2O concentration remains constant unless the user activates the Water Vapor feedback (see Sections 1.4 and 5.6), in which case it will depend on the temperature.

1 It is mainly these clouds, located at an altitude of 1 to 2 km, that contribute to the Earth's albedo (see Box 1 for contributions to albedo).

Albedo and Greenhouse effect:

Albedo is defined as the ratio between the sum of reflected VIS fluxes and solar flux.

The greenhouse effect is defined as the ratio between the IR flux re-emitted toward Earth by GHGs and the thermal IR flux emitted by the surface (see Sect. 5.3 for more details).

These two parameters cannot be modified directly by the user (the sliders are grayed out) because their values are functions of the climatic variables via parameterizations (see Sect. 4 Boxes 1 and 2). Their values are therefore automatically adjusted when the above climatic variables change.

1.2 Waves mode

The simulation initializes by default in the Waves mode in **1850** (pre-industrial era when the planet was in thermal equilibrium). It is recommended to begin studying the simulation in this qualitative mode and to **remain in 1850 to study this mode** (because the temperature remains stable when you click Play for the first time, unlike in 2020). The wave representation will facilitate the identification of the different types of radiation and the qualitative study of the effect of variables on these types of radiation. This is because the amplitude of the waves represented is proportional to the radiative flux values (Sect. 1.3). The wavelength of IR waves is qualitatively greater than that of short-wavelength radiation, consistent with the Thermal Radiation and Greenhouse Effect simulations.

- Click **Play** to display the radiation in wave form.
  The first time, the radiation is displayed sequentially to make it easier for students to identify.

To perturb the equilibrium and alter the Earth's temperature:

- Click on **Pause** to freeze the waves. Climate variables can only be modified when the simulation is paused (because the Earth system is no longer in thermal equilibrium when variables are modified).

- Alter one or more **climate variables** (see Section 1.1) using the sliders **under Albedo or Greenhouse Effect**.
  ⇒ While modifying a slider, the amplitude of the waves directly affected is adjusted. For example, if you increase the percentage of ice and snow, the VIS wave reflected by the surface increases in amplitude.
  ⇒ The Start Period (here 1850) will appear deselected, as the new variable values will no longer strictly correspond to this period.

- Click on Play to let the planet's temperature evolve.

- You can click on the Rewind button (next to Play) to return to the situation just before Play and play it again.

1.3 Fluxes mode

In Fluxes mode, radiation is represented by arrows indicating *radiative flux* values (i.e., radiant power density) in [W/m2]. This allows the user to quantitatively study the effect of variables on fluxes and to deduce, through an *energy budget* (net sum of fluxes at the top of the atmosphere), whether the Earth is in a state of equilibrium (stable temperature) or radiative imbalance (temperature subject to variation).

In order for students to deduce the concept of thermal equilibrium on their own, it is recommended to begin by studying the period 1850, when the planet was in equilibrium.

- Click **Play** : the first time, the flux arrows are displayed sequentially as in Wave mode.
  ⇒ The width of the arrows is proportional to the flux values shown.
- The ⇌ icon at the top of the atmosphere indicates that the planet is in equilibrium: you can deactivate it by clicking on the button in the top right-hand corner (Hide net flux).

To perturb the equilibrium and alter the Earth's temperature:

- Change the model variables (listed in Section 1.1) using the sliders (no need to click Pause as in Waves mode, because in Fluxes mode, the simulation automatically pauses once the fluxes are displayed).
  ⇒ When adjusting a slider, the width of the arrows and the values of the directly affected fluxes are adjusted. For example, if the concentration of CO_2 or CH_4 is increased, the IR flux escaping into space decreases while the flux re-emitted towards the surface increases.
  ⇒ Immediately after a variable change, IR fluxes begin to blink, indicating that their values will vary (the IR flux emitted by the surface will vary with temperature until equilibrium is restored, which will also cause the IR fluxes escaping into space and the flux re-emitted by GHGs toward the surface to vary).
- Click **Play** : The thermometer and IR flows (values and arrow widths) gradually adjust until a new radiative equilibrium is reached.

Switch the period to 2020 to study the current situation:

- IR fluxes blink, indicating that the planet is no longer in equilibrium
- Click on **Show net flux** at the top right.
  ⇒ The net flux value corresponds to the solar flux value minus the sum of the VIS and IR fluxes leaving the planet.
- Without changing any variables, click **Play** to see the temperature evolution until a new equilibrium is reached.

This means that even if all emissions were stopped immediately and atmospheric GHG concentrations remained at current levels, the temperature would still rise slightly to reach thermal equilibrium.

1.4 Feedbacks

The concentration of water vapor in the atmosphere and the coverage of snow and ice (cryosphere) are functions of temperature, causing two main feedbacks in the Earth's climate system: the “water vapor” feedback and the “ice-albedo” feedback (see Sect. 5.6 and Box 3 for more details). The simulation allows these two feedbacks to be investigated *separately*.

The effect of feedbacks is only visible when climate variables are modified to force the system *out of equilibrium at a given period* (note the period 2020, for which equilibrium is not the initial state), because feedbacks will then amplify the increase or decrease in temperature (see Sect. 5.6). To study the effect of a feedback, we can either (A) compare its effect (change in temperature, water vapor concentration, or cryosphere cover) to the case without feedback following a change in variables, or (B) activate it from an equilibrium temperature reached without feedback and see how this feedback would change this state.

- Make a variable change that causes an imbalance (e.g., by increasing CO_2 values to 500 ppm and CH_4 to 2 ppm to simulate a possible situation in 2050).
- Click **Play** to see what temperature the planet is adjusting to *without feedback.*

(A) Comparison of the case without and with feedback:

- Click **Rewind** to return to the situation just before Play.
- Enable **Water Vapor or Ice and Snow** at the bottom of the side menu.
  ⇒ If the Net Flux indicator is activated, students may notice that it is greater than in the case without feedback.
- Click **Play** again to observe the feedback effect..
  ⇒ The Ice and Snow (%) slider or the H_2O (ppm) slider (which are no longer grayed out) adjusts along with the temperature until a new equilibrium is reached. This simultaneously changes the greenhouse effect or albedo slider, which now also depend on the concentration of water vapor and the cryosphere cover, respectively.

(B) Activation from an equilibrium temperature:

After reaching, without feedback, a state of equilibrium that is not the equilibrium corresponding to the chosen period:

- Enable **Water Vapor or Ice and Snow** at the bottom of the side menu.
  ⇒ The water vapor concentration slider or ice and snow cover adjust automatically based on the equilibrium temperature. The same applies to the greenhouse effect or albedo slider.
  ⇒ The IR fluxes blink and the Net Flux indicator shows a thermal imbalance, prompting students to predict how the temperature and fluxes will change. If the Ice and Snow feedback is enabled, then the flux reflected by the surface also blinks, as its value will also change.
- Click **Play** to obseve the evolution.

If the radiative imbalance is too great before a feedback is activated, the temperature may no longer converge towards equilibrium. In the case of the greenhouse effect, this is known as "runaway greenhouse effect".

1.5 *Ice age and planets*

These situations will enable students to transfer their new knowledge to explain the climate during an ice age, or on the planets Mars and Venus.

By selecting **Ice Age** under Periods or Planets, the temperature indicated on the thermometer and the GHG concentrations correspond to the last glacial maximum that occurred 18,000 years ago [1].

When selecting **Mars** or **Venus**, all climate variable sliders appear grayed out, as humans cannot alter the climate of these planets. As for the Earth. The temperatures of these planets can be explained by their values of albedo and greenhouse effect (see Sect. 4 for more details).

2. About this simulation

This simulation represents a global model (zero-dimensional [1, 2]) of the planet, including IR radiation and its interaction with GHGs, as well as shortwave solar radiation (VIS for simplicity) and its interaction with ice, snow (cryosphere), and low-altitude clouds in the troposphere.

2.1 *Prerequesites*

All the knowledge needed to understand the simulation in Wave mode (emission of wave radiation in different wavelength ranges, IR thermal radiation emitted by the surface, absorption and re-emission by GHGs) can be acquired through the Oscillating Charge, Thermal Radiation, and Greenhouse Effect simulations. To guide students in discovering these concepts, these three simulations are integrated into the interactive activity Understanding the Climatic Greenhouse Effect, scaffolded by images, quizzes with feedback, and videos.

The Fluxes mode also requires prior understanding of the concepts of energy and radiant power. The concept of radiative flux can then be deduced from power, as introduced in the interactive activity Towards a global climate model.

2.2 Relationship with the other simulations

This simulation is the last 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).

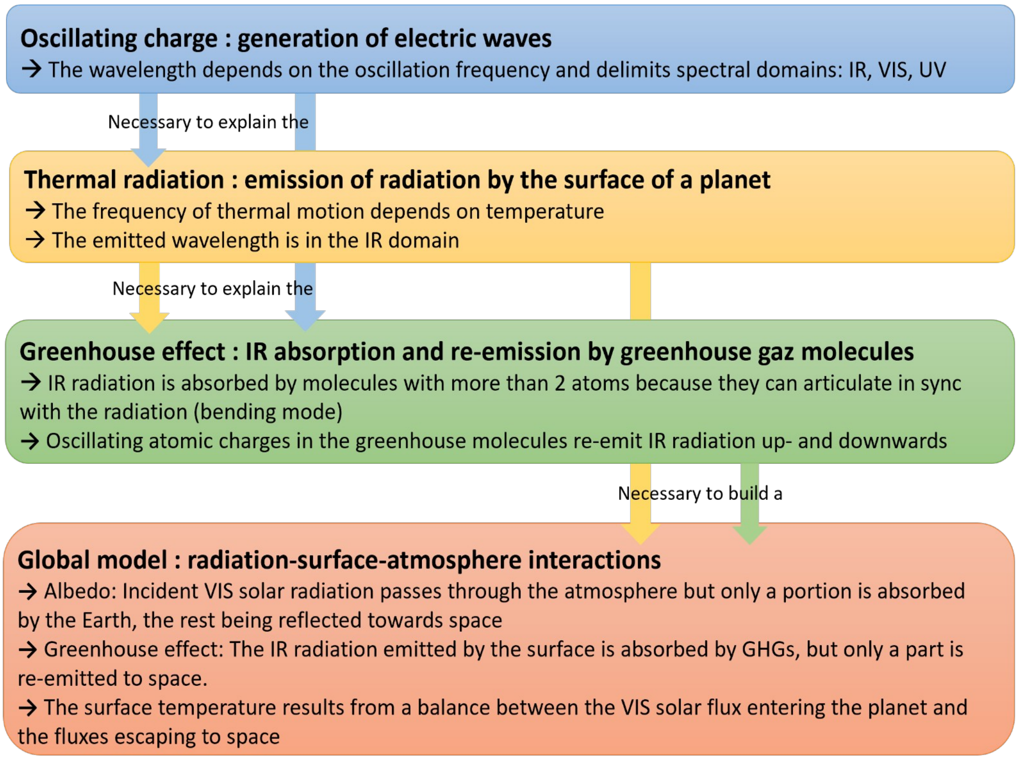


Fig. 1 : Concept map of the four simulations on the causes of global warming. Each simulation targets a category of concepts (highlighted in color), where the main concepts to be discovered are listed by small arrows. The colored arrows between categories illustrate how the concepts discovered in one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

The first three simulations focused on a wave description of radiation using a microscopic approach to matter. They successively reveal the emission of electric waves and wavelength ranges (first simulation in Fig. 1), the emission of thermal IR radiation by the ensemble of charges on the planet's surface, and the absorption-re-emission of this IR radiation by GHG molecules.

Although the first three simulations would suffice to provide the fundamental ingredients for understanding the mechanism of the greenhouse effect, a fourth simulation is justified in order to integrate the concepts previously discovered into a macroscopic rather than microscopic view. To make the connection, the Wave mode uses a wave description of radiation consistent with the first three simulations. In addition, a global model is necessary to understand radiative equilibrium (a concept that students lack, see Sect. 3), in particular the role of the greenhouse effect and albedo in this equilibrium.

3. Underlying misconceptions

As the construction of a coherent global model is based on several categories of underlying concepts like pieces of a puzzle (ideally acquired through previous simulations, see Sect. 2.2), any missing or erroneous concept in these categories will lead to an erroneous model (see Sect. 3 of the previous simulation tutorials for an inventory).

As explained in the Greenhouse Effect simulation tutorial, there are two recurring erroneous global models (see Fig. 2): the ozone shield layer and the GHG layer trapping solar radiation [3]. These models stem, among other things, from the absence of a wave description of radiation, leading to the omission of IR thermal radiation emitted by the Earth.

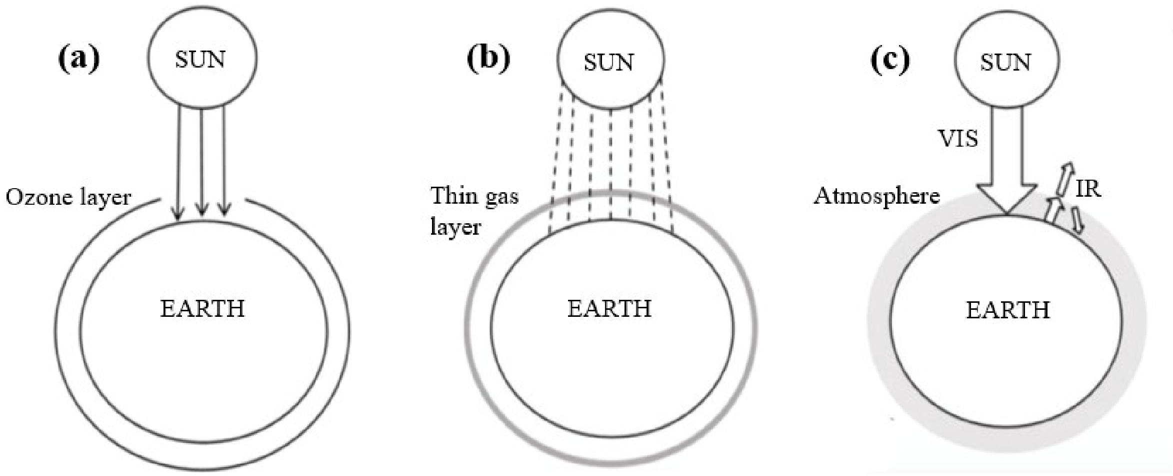


Fig. 2 : The three main mental models of the greenhouse effect identified by Varela et al. [7]. (a) Depletion of the ozone layer "shield," allowing more solar radiation to enter. (b) Trapping of solar radiation by reflection between the surface and a thin layer of gas. (c) Scientifically correct model where the arrows represent radiative fluxes.

These erroneous mental models also reveal a lack of understanding of the concept of thermal equilibrium, or a difficulty in transposing this concept to a global scale [4]. This missing concept leads to the perception that the Earth's warming is solely due to solar radiation, without taking into account the thermal radiation emitted by the surface, the IR radiation re-emitted by GHGs toward the surface, or the solar radiation reflected back into space. The Earth should therefore be constantly heating up.

Not using thermal equilibrium could also lead to another misconception, not reported in the literature to our knowledge, namely that the thermal IR radiation emitted by the surface is solely a consequence of the Earth's temperature without contributing to thermal equilibrium. In reality, the temperature of the planet (of its surface, for example) itself depends on the energy fluxes entering and leaving the planet. In other words, the temperature depends on the solar flux, but also on the part of this flux reflected back into space (the planet's albedo) and the part of the thermal IR flux evacuated into space (not absorbed by GHGs).

Finally, the general focus of the media on CO_2 leads students to overlook water vapor as a GHG, even though it is the most abundant GHG [5]. As detailed in Section 4.6, the temperature dependence of water vapor concentration is essential for climate regulation because it is the source of positive feedback.

4. For students to discover

The Waves mode allows students to identify the different types of radiation that play a role in the model. They can also familiarize themselves with the different variables in the model by observing their qualitative effect on radiation.

Students will notice that *the amount of thermal IR radiation emitted by the surface increases with temperature*. To observe this clearly, large temperature variations are required, e.g., by significantly varying cloud cover.

By comparing the flux values at the top of the atmosphere through addition and subtraction, students will be able to deduce the concept of thermal (radiative) equilibrium and imbalance: *When the fluxes leaving the atmosphere are lower than/equal to/higher than the incoming solar flux, the temperature increases/remains constant/decreases*.

Having observed that the thermal IR flux depends on temperature, they will also understand that *the thermal flux varies with temperature until it reaches a new state of thermal equilibrium*.

Using the displayed flux values, students will be able to find out the definitions of the greenhouse effect and albedo parameters by performing the correct calculation. With a little guidance, they will realize that the planet's energy balance depends solely on these two parameters, since they determine the amount of VIS and IR flux leaving the planet (on Earth, solar flux is virtually constant, varying by only 0.1% during the 11-year solar cycle [1], but on other planets, solar flux also plays a role).

Through the greenhouse effect simulation, students had already discovered that water vapor is a GHG. They can then make the connection with water vapor feedback.

Students should discover that *regardless of the feedback* (water vapor or ice-albedo), *it amplifies the temperature variation caused by any change in the variables* (which is why they are called “positive” feedback loops).

By comparing the state of the planet during the last glacial maximum (Ice Age) and in 2020, students will notice that the difference between the global temperature during that period and the current temperature is only 6°C! By comparing this difference with the temperature increase between 1850 and the present day, they will be able to realize the significance of a temperature increase of just over 1°C.

By studying the cases of Venus and Mars, they will realize that, just like Earth, the average temperature of other planets is dictated by the values of the albedo and greenhouse effect parameters (as well as solar fluxes). At first glance, students may believe that the difference in temperature is due to the different distances from the Sun (and therefore to the different solar flux values, 147 and 650 W/m^2 respectively). But since Venus is covered in clouds (albedo of about 77%), only a visible flux of 150 W/m^2 passes through these clouds, comparable to the 147 W/m^2 on Mars. *The difference in temperature must therefore be explained by a difference in the greenhouse effect*. When observing CO_2 concentrations, students will be surprised by their similarity. The greenhouse effect depends not only on GHG concentrations, but also on the density of the atmosphere (which is very thin on Mars)!

The interactive activity [Towards a global climate model] guides students toward these discoveries by scaffolding the simulation with instructions and quizzes with feedback.

5. Modeling and didactic choices

5.1 Zero-dimensional model

The simulation is based on a zero-dimensional (0D) model of the Earth system (surface and atmosphere), i.e., all values are planetary averages without dependence on latitude or longitude and without vertical stratification [1]. It cannot therefore simulate any phenomena related to atmospheric stratification or atmospheric currents. The following are therefore excluded from the simulation: the different layers of the atmosphere, the greater warming of lower latitudes compared to higher latitudes [5], greater warming of the oceans compared to land masses [5, 6], energy exchanges between the surface and the atmosphere, such as turbulent convection, evaporation, and thermal radiation from the atmosphere [1, 5], as well as the cooling of the stratosphere and the rise in the upper limit of the troposphere [5]. These elements can be discussed with students, but are not included in the learning objectives (see Sect. 4).

Since it does not include stratification and does not simulate internal energy flows within the system (e.g., surface-atmosphere exchanges), *this model only allows for the study of the energy balance at the boundary of the Earth system, i.e., at the "top of the atmosphere"* (TOA). Furthermore, at the TOA, the planet's thermal equilibrium boils is purely radiative, which is easier for students to understand and consistent with the study of radiation in simulations. Unlike the TOA, the thermal equilibrium of the planet's surface is not purely radiative, as energy transport by evaporation and turbulent convection must be taken into account, as well as the total IR flux to the surface, as shown in Fig. 3 (which would require a 1D model, see paragraph above).

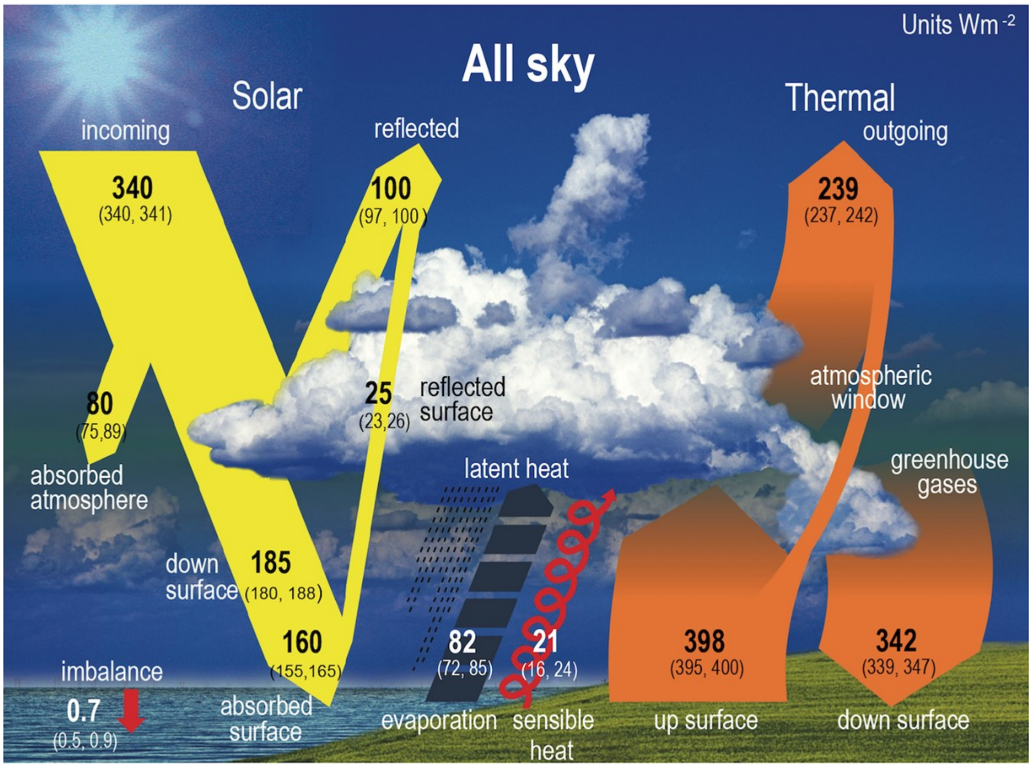


Fig. 3 : Global averages of energy fluxes at the TOA and at the Earth's surface in the current situation, from the IPCC 2021 report [7]. Shortwave radiation fluxes are shown in yellow and IR fluxes in red.

From a situation of thermal equilibrium at the TOA, it is possible to determine the equilibrium temperature of the surface given the values of the greenhouse effect and albedo parameters (see Sect. 5.4). However, due to the simplifications mentioned above, this simulation can only be used to study qualitatively the impact of albedo and the greenhouse effect on temperature change, and not to make quantitative predictions about future climate change.

5.2 Radiation and radiative fluxes simulated

As in the Waves mode of the simulation, the amplitude of the radiation is directly proportional to the values of the radiation fluxes, we will directly present the radiation in Fluxes mode. Fig. 4 shows an excerpt from the simulation in Fluxes mode for the 2020 period (non-equilibrium situation corresponding to Fig. 3 provided by the IPCC), where symbols have been assigned to the different simulated fluxes. The flux values are rounded to integers to make it easier for students to identify the thermal equilibrium condition at the TOA by comparing incoming and outgoing fluxes.

Like the other fluxes in this 0D model, the solar flux F_{Sol} entering the top of the atmosphere corresponds to a global average. It is obtained by multiplying the "solar constant" $S \simeq 1460\mathrm{W/m^2}$ by the cross-sectional area of the Earth (of radius R) to obtain the power received by the entire globe, then dividing by the surface area of the globe: $F_{Sol} = \frac{S\pi R^2}{4\pi R^2} = S/4$ (see the interactive activity Towards a global climate model).

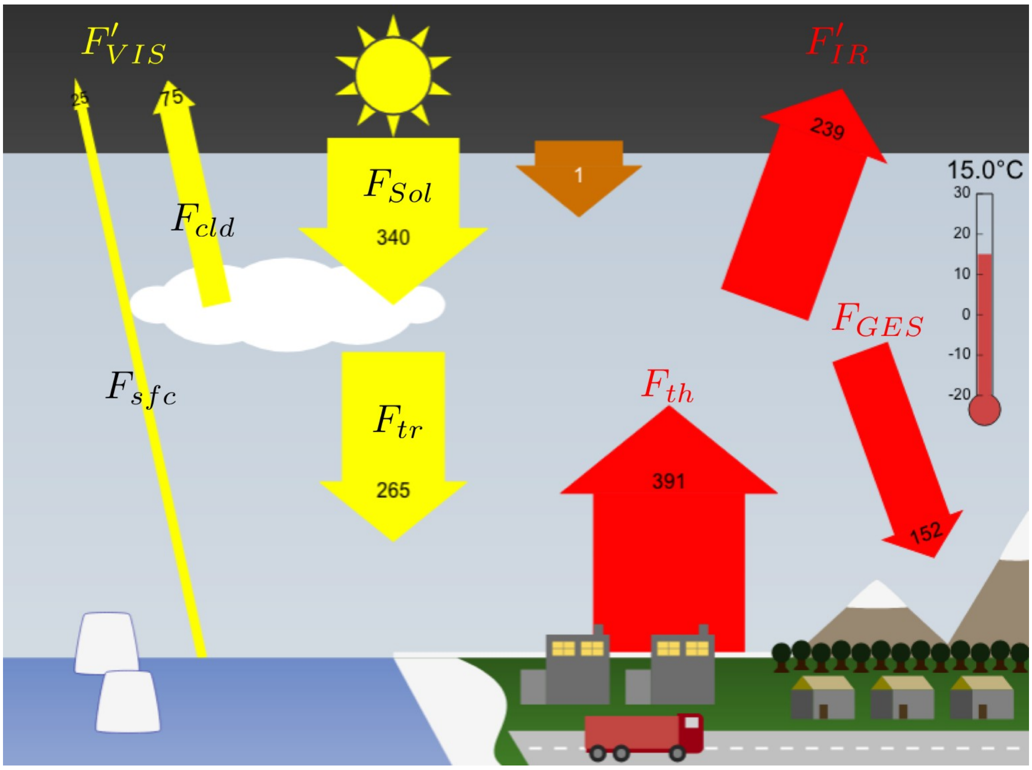


Fig. 4 : Excerpt from the simulation in Flux mode in Period 2020, where the planet is not in thermal equilibrium.

The total flux reflected into space will be denoted F'_{VIS} and its value depends on the Earth's albedo. It consists of a part reflected by clouds, F_{cld}, and a part reflected by the *entire surface* (land and oceans), F_{sfc}, even though the flux arrow had to be placed over the ocean in the simulation. These two fluxes depend on the fraction of the sky covered by clouds and the fraction of the surface covered by the cryosphere, which can be modified by the sliders (see Box 1 for the calculation of albedo and these fluxes).

The transmitted radiation and its flux F_{tr} are only represented to satisfy energy conservation ($F_{tr} = F_{Sol} - F_{cld}$), but this flux is not needed to establish a radiative budget at the TOA.

Its flux arrow (the same applies to the wave in Waves mode) is shortened before the surface, as it does not represent the actual flux value reaching the surface (which is lower due to atmospheric absorption, see Fig. 3).

The thermal radiation emitted by the surface is modeled assuming a perfect black body (see tutorial on Thermal Radiation simulation) whose thermal flux F_{th} is given by Stefan-Boltzmann's law:

$$F_{th} = \sigma T^4 \quad (1)$$

, where σ is the Stefan-Boltzmann constant and T is the temperature in Kelvin.

The IR flux escaping into space, F_{IR}, corresponds to the integral of the IR spectrum observed from space (see Fig. 5). It includes the portion of thermal radiation emitted by the surface whose wavelengths have not been absorbed by GHGs (the “atmospheric window” in Fig. 3), as well as the radiation re-emitted by GHGs into space (absorption bands in Fig. 5).

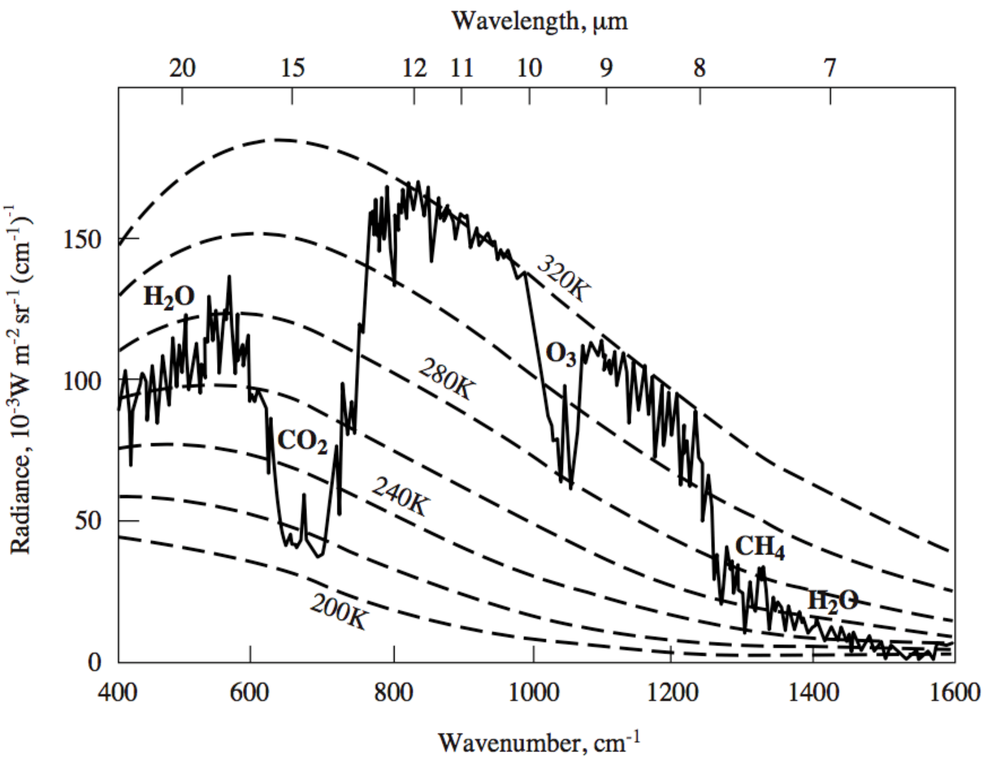


Fig. 5 : Emission spectrum of the Earth's surface (Nigeria) observed by satellite. Surface thermal radiation corresponds to Planckian radiation (dashed line) at 320 K. The parts of the spectrum outside the molecular absorption bands, between 10 and 12 um and 9 and 8 um, correspond to surface thermal radiation that was able to escape directly into space, i.e., the “atmospheric window” [8]. The absorption bands correspond to radiation re-emitted by GHGs into space; the deeper the band, the higher the altitude at which re-emission into space occurs, where temperatures are low [5].

Finally, F_{GES} refers to the flux re-emitted by GHGs *toward the surface*, which therefore could not escape into space:

$$F_{GES} = F_{th} - F'_{IR} \quad (2)$$

Note that the F_{GES} value is lower than the total IR flux to the surface (see Fig. 3). This is because the former only represents the contribution of GHGs to the IR flux re-emitted to the surface, while the total IR flux to the surface takes into account the thermal emission from the troposphere linked to its temperature gradient.

5.3 Modification of the greenhouse effect and albedo by variables

Albedo is defined as the fraction of shortwave solar radiation that is reflected back into space by the planet (by the surface, low-altitude clouds, and aerosols [1]):

$$\alpha = \frac{F'_{VIS}}{F_{Sol}} \tag{3}$$

The greenhouse effect (sometimes referred to as "normalized" to differentiate it from the greenhouse effect phenomenon in general [1]) is defined as the fraction of IR heat flux that is re-emitted by GHGs toward the surface, or equivalently (see Eq. 2), that is *not* evacuated into space:

$$\varepsilon = \frac{F_{GES}}{F_{th}} = 1 - \frac{F'_{IR}}{F_{th}} \tag{4}$$

The albedo α and the greenhouse effect (normalized) ε are therefore the two *parameters* that control the amount of radiative flux that can escape from our atmosphere. The equilibrium temperature can therefore be calculated from these two parameters: $T = T(\alpha, \varepsilon)$ (see Sect. 5.4).

In order to adapt the values of these parameters to any choice of climate variables, we used parameterizations where ε is a function of CO_2 and CH_4 concentrations (and indirectly of H_2O concentration via temperature, see Sect. 5.6) and α is a function of the fraction of cryosphere and cloud cover. The parameterization of α takes into account multiple surface-cloud reflections, and the parameterization of ε was derived from a 1D model of atmospheric IR opacity (see Boxes 1 and 2 for details).

To simplify the simulation and parameterization of ε, only the concentrations of the two GHGs causing the most significant anthropogenic forcings [7] can be modified, namely CO_2 and CH_4. The parameterization of ε therefore does not take into account high-altitude clouds that contribute to the greenhouse effect (which are difficult to model because they also depend on temperature) [1]. It is therefore possible that our parameterization overestimates the influence of the concentrations of these two GHGs on the greenhouse effect. As for the parameterization of α, it does not take aerosols into account.

Immediately after a change in climate variables (simulation still paused), the albedo and greenhouse effect sliders automatically adjust to the values calculated by the parameterizations. However, since the flux values displayed are rounded to the nearest integer, students may not be able to recalculate the precise values displayed on the Albedo (%) and Greenhouse effect (%) sliders (this is the case, for example, in 1850).

5.4 Calculation of temperature and fluxes

Knowing the values of the albedo α and greenhouse effect ε parameters (either at the start of a period or after a change in climate variables), the equilibrium temperature can be calculated by assuming that the system reaches thermal equilibrium (purely radiative) at the TOA. In this case, the solar flux entering the system balances the sum of the outgoing VIS and IR fluxes:

$$F_{Sol} = F'_{VIS} + F'_{IR} \tag{5}$$

Inserting equ. (1), (3) and (4) in equ. (5) yields :

$$F_{Sol} = \alpha F_{Sol} + (1-\varepsilon)\sigma T^4 \Rightarrow T = \sqrt[4]{\frac{(1-\alpha)F_{Sol}}{(1-\varepsilon)\sigma}} \qquad (6)$$

Knowing the equilibrium temperature T via equ. (6), the equilibrium thermal flux value F_{th} can be calculated by equ. (1) and the flux values F_{GES} and F'_{IR} by equ. (4)

Frame 1: Parameterization of terrestrial albedo and calculation of reflected fluxes

The variables affecting albedo in the simulation are the fraction of clouds (low-altitude) f_{cld} and the fraction of surface f_{cry} covered by the cryosphere. We have applied the following parameterization to calculate the contributions to albedo by the surface, α_{sfc}, clouds, α_{cld}, as well as the Earth's global albedo α [18]:

$$\alpha_{sfc} = f_{cry}\alpha_{cry} + (1-\alpha_{cry})\alpha_0 \qquad (7)$$

$$\alpha_{cld} = f_{cld}\alpha_c \qquad (8)$$

$$\alpha = \alpha_{cld} + \frac{(1-\alpha_{cld}^2)\alpha_{sfc}}{1-\alpha_{cld}\alpha_{sfc}} \qquad (9)$$

, where α_{cry}, α_0 and α_c denote the intrinsic mean reflectivities of the cryosphere, non-cryospheric surface and clouds, respectively. Equation (9) takes into account multiple reflections between surface and clouds, otherwise the albedo would be overestimated.

The fluxes reflected by the clouds F_{cld} and by the surface F_{sfc}, as well as the flux transmitted through the clouds, F_{tr}, can then be calculated as follows by adapting equ. (1):

$$F_{cld} = \alpha_{cld}F_{Sol} \qquad (10)$$

$$F_{tr} = (1-\alpha_{cld})F_{Sol} \qquad (11)$$

$$F_{sfc} = (\alpha-\alpha_{cld})F_{Sol} \qquad (12)$$

The values of α_{cry}, α_0 and α_c were adjusted so thtat with $f_{cry} = 0.1$ and $f_{cld} = 0.45$ (see Sect. 4.3), equ. (9) reproduces the Earth's albedo and the reflected flux values in 2020 (see Fig. 3). To reproduce the equilibrium temperature of 13.8°C in 1850, we had to reduce α_0 to obtain an albedo lower than that of 2020, as a result of deforestation and desertification [18]. During the ice age, we also had to adjust $f_{cld} = 0.42$ to reproduce the radiative equilibrium at a temperature of 9°C.

In this parameterization, the cloud fraction f_{cld} corresponds to low clouds, at a typical altitude of 1-2 km, since it is mainly this type of cloud that affects the earth's albedo. High-altitude clouds also have an impact on the greenhouse effect, but are not taken into account in this simulation [19]. Nor does this parameterization include the effect of aerosols, which can act as condensation nuclei for cloud production.

If a change in climatic variables has been made and the simulation is still on Pause, the directly affected fluxes change value and arrow width (respectively amplitude in Waves mode) to show the effect of the variables on radiation. If the fraction of cryosphere or clouds has been changed, the fluxes F_{cld} and F_{sfc} are adapted accordingly. If GHG concentrations have changed, F_{GES} and F'_{IR} are adapted according to equ. (4) and the new value of ε. Before the user clicks Play, we have chosen to blink the IR fluxes (as well as the flux reflected by the surface if the Ice and Snow feedback is activated, as this flux will change according to the evolution of the cryosphere cover) to indicate that these fluxes will evolve, and to encourage students to make a prediction about the Earth's response.

When Play is clicked, the simulation displays a progressive evolution of the thermometer and IR fluxes to their new equilibrium values. As the simulation only solves the equilibrium equation (6) and not a time evolution equation (which should take into account the heat capacity of the system [9]), this display gives no indication of the actual time scales.

Box 2: Parameterization of the terrestrial greenhouse effect

The value of the normalized greenhouse parameter ε as a function of CO_2 and CO_4 concentrations and temperature were obtained using the 1D Rapid Radiative Transfer Model (RRTM) used in state-of-the-art climate modelling [19, 20]. From the interface of this model, the value of ε was calculated by equation (4), comparing the IR flux evacuated to space and the thermal flux emitted by the surface. We applied a separative method to arrive at the following parameterization:

$$\varepsilon = A\,[CO_2]^a + B\,[CH_4]^b + c(T) \qquad (13)$$

The first two terms were obtained by setting all other variables to 0 and adjusting the variation of ε according to power laws (see Fig. 6a). For example, the first term was obtained by setting $[CH_4] = 0$, with no clouds and a relative humidity of 0. The shape of the power laws in (due to exponent values less than 1) reflects the progressive saturation of the CO_2 and CH_4 absorption bands [5, 19].

The term $c(T) = CT + D$, was found by varying the surface temperature while keeping GHG concentrations equal to 0 and a tropospheric mean relative humidity of 45% constant (as often assumed in climate models and corroborated by observations [21]). This relative humidity value (which lies somewhere between the values reported in the literature [22, 23]) was adjusted to reproduce the 2020 value of ε. We then performed a linear regression over a reasonable temperature range 10° < T < 20°.

As long as the user does not activate the water vapour feedback in the simulation, the term $c(T)$ retains a constant value $c(T_0)$, where T_0 is the equilibrium temperature of the chosen period: 2020, 1850 and the Ice age (see Box 3 for water vapour feedback calculation).

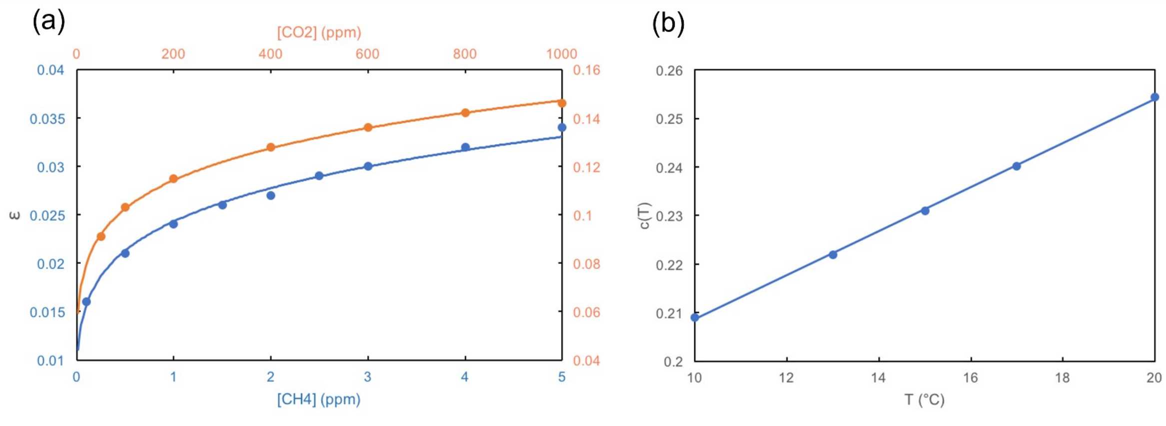


Fig. 6 : (a) Variation of the greenhouse effect parameter ε obtained with the RRTM model as a function of CO_2 concentration only (red) or CH_4 concentration only (blue). Power-type trend curves correspond to the first two terms of equation (13). (b) Variation of the c(T) term of equation 13 by varying temperature in RRTM.

5.5 Periods and planets

For each period (1850, 2020, or Ice Age), the initial values of the climate variables (GHG concentrations, cryospheric cover and cloud cover) are hard-coded (see Table 1 for values and references). Knowing the values of these variables, the parameters ε and α are calculated using their parameterization equations (9, 13), and the equilibrium temperature for this period is calculated using equation (6). The displayed H_2O concentration depends on this temperature and is calculated as described in Box 3.

For the period 1850, the equilibrium temperature calculated and displayed is 13.8°C, which is consistent with the 14°C estimated for the period 1951-1980 [10] and the temperature difference between 1850 and this period. The cryosphere coverage at this period was deduced from the linear regression between cryosphere fraction and temperature (see Fig. 7, Box 3).

The 2020 period is the only one not to initialize in a state of equilibrium, as the radiation balance is unbalanced at the SDA (see Figs. 3 and 4). The temperature displayed at initialization, 15°C, is consistent with a temperature anomaly of 1.2°C since the reference period 1850-1900 [5, 6]. Click on Play to see the temperature evolve towards equilibrium.

The ice age of the simulation corresponds to the last glacial maximum (ca. -18000). Assuming that the total extent of the cryosphere was twice as large as today, i.e. 20% [2], the cloud fraction was adjusted to 42% in order to reproduce an equilibrium temperature of 9°C, consistent with a cooling of -6°C [11].

As our parametrization equations are not valid on Mars and Venus (the density of the atmosphere and the composition of the surface being too different from Earth), the values of ε and α are also hard-coded for these planets. Thus, when the user selects Venus or Mars, the Greenhouse Effect (%) and Albedo (%) sliders are automatically adjusted to these values, regardless of the GHG concentrations displayed. As the climatic variables cannot be modified on Venus and Mars, all sliders appear grayed out. Solar flux on Mars and Venus has been adjusted to 147 W/m^2 and 650 W/m^2 respectively, according to their distances from the Sun.

Table 1 summarizes the various predefined values of the variables for the different periods with their bibliographic references.

Table 1 : Initial values of climate variables for different periods and planets.

Periods or Planets	[CO_2] (ppm)	[CO_4] (ppm)	[H_2O] (ppm)	Clouds (%)	Ice and snow (%)	α (%)	ε (%)
1850	285 [12]	0.8 [12]	calculated	45 [13]	12	calculated	calculated
2020	413.2 [14]	1.9 [14]	calculated	45 [13]	10 [15]	calculated	calculated
Ice Age	200 [16]	0.4 [16]	calculated	42	20	calculated	calculated
Mars	950000 [17]	0	200 [17]	0	0	25 [17]	0 [17]
Venus	965000[17]	0	0	100 [17]	0	76.9 [17]	99.1 [17]

2 This cryospheric cover was estimated using a pseudo-1D model resolving the meridional profile of the variables, adjusting a cryosphere threshold to -10°C, according to our scientific advisor Dr. Stéphane Goyette, Climate and nonlinearity group, University of Geneva.

5.6 Feedbacks

The simulation takes into account only two feedback mechanisms: the "ice-albedo" feedback and the "water vapour" feedback. The ice-albedo feedback varies the albedo as a function of temperature through the variation of the cryosphere (increase or melting of the cryosphere), while the water vapour feedback varies the greenhouse effect by taking into account evaporation as a function of temperature (saturation vapour pressure depending exponentially on temperature, see Box 3, equ. 14).

We have chosen to include these two feedbacks for the following reasons. The ice-albedo feedback is often discussed in the media and is therefore familiar to some students. As for the water vapour feedback, it serves to reinforce in students the role of water vapour as the most important GHG in our atmosphere (they discovered that it is a GHG by studying the Greenhouse Effect simulation), even though its concentration is not directly dependent on human activities but on the water cycle.

The methane feedback, although particularly threatening and described in the media, is not included because it is difficult to predict using equations. The same applies to other complex feedbacks, such as clouds [7].

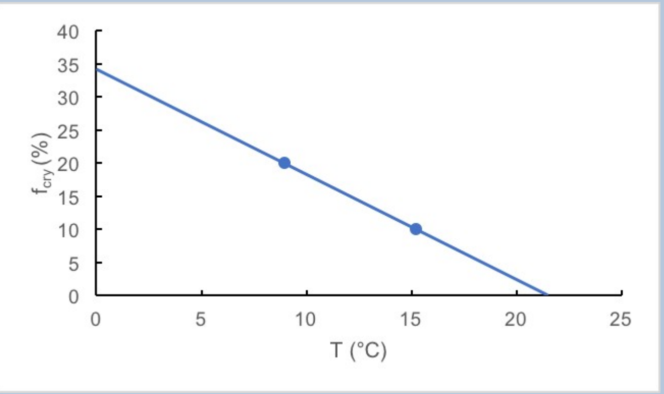
The ice-albedo and water vapour feedbacks are referred to as "positive" because they tend to amplify the temperature variation resulting from a change in climatic variables. This is why the effect of these feedbacks is only visible when the user makes a variable change that forces the system *out of equilibrium* (see Box 3).

As the calculation of these feedbacks (see Box 3) is performed by a succession of equilibrium states, the simulation tends to exaggerate the effect of feedbacks on temperature. That iswhy we have left the choice of activating only one feedback at a time, to avoid runaway effects (and also not to scare the students!).

Box 3. Feedback loops

The greenhouse effect ε depends on temperature through the function $c(T)$ (see equation 13). As for albedo, it depends indirectly on temperature through the cryosphere fraction. To determine $f_{cry}(T)$, we performed a linear regression using the values for 2020 and the glacial period (see Fig. 7). The regression reaches $f_{cry} = 0$ for $T \sim 21°C$, which is consistent with paleoclimatic results indicating an ice-cap-free Earth during the Eocene [25].

Fig. 7 : Dependence of cryospheric cover fraction f_{cry} on temperature. The two points correspond to the 2020 and Glacial periods, for which the values were known.



Box 3. Feedback loops (suite)

When the "Water vapour" or "Ice and snow" feedback buttons are checked, ε or α change iteratively, as shown in Fig. 8. Initially, the equilibrium temperature T_0 is calculated from the initial greenhouse effect ε_0 and albedo α_0. After a change in the variables producing α_1, ε_1, the equilibrium temperature changes to T_1 (blue in Fig. 8) and the feedback loops can be calculated (red in Fig. 8). If, for example, the water vapour feedback is activated, a new greenhouse effect is calculated as a function of T_1 via the function $c(T), \varepsilon_2 = \varepsilon(c(T_1))$, and we enter the first iteration of the loop. The new temperature T_2 can then be calculated according to equation 6. As T has changed, the next iteration where $\varepsilon_3 = \varepsilon(c(T_2))$ can be calculated, etc. The WHILE conditional loop stops when the convergence criterion $T_{i+1} - T_i < 0.01°\mathrm{C}$ is reached.

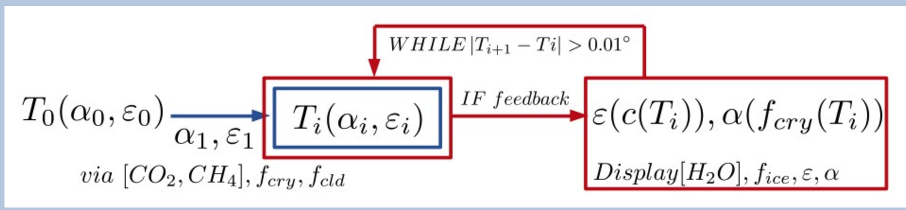


Fig. 8 : Feedback loop calculation diagram.

So that the user can "see" that temperature affects water vapor concentration $[H_2O]$, we display the latter by calculating the saturated water vapor pressure as a function of temperature in K using the following equation, derived from the Tetens equation [24] converted to ppm for a relative humidity of 45%:

$$[H_2O](\mathrm{ppm}) = 2.78 \times 10^3 \exp(\frac{17.27T}{T + 237.3}) \quad (14)$$

References

[1] Kandel, R. (2019), *Le réchauffement climatique*. Que sais-je?

[2] Goyette, S, *The physics of the greenhouse effect*, UNIGE Téléchargeable sur archive-ouverte.unige.ch

[3] Varela, B., Sesto, V., García-Rodeja, I. (2020), *An investigation of secondary students ? mental models of climate change and the greenhouse effect*, Research in Science Education, 50, 599–624

[4] Jarrett, L., Takacs, G. (2020), *Secondary students ? ideas about scientific concepts underlying climate change*, Environmental Education Research, 26, 400–420

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

[6] Berkeley Earth, *Global temperature report for 2024*

[7] Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., ... & Zhou, B. (2021), Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change, *Climate change 2021 : the Physical Science Basis, Chap. 7*

[8] Jacob, D. J. (1999), *Introduction to atmospheric chemistry*, Chap. 7, Harvard university

[9] Flath, D., Kaper, H. G., Wattenberg, F., & Widiasih, E. (2012), *Energy Balance Models*.

[10] Hansen, J., Ruedy, R., Sato, M., & Lo, K. (2010), *Global surface temperature change,* Reviews of geophysics, 48, 4.

[11] Tierney, J. E., Zhu, J., King, J., Malevich, S. B., Hakim, G. J., & Poulsen, C. J. (2020). *Glacial cooling and climate sensitivity revisited*. *Nature*, *584*, 569-573.

[12] Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., ... & Zhou, B. (2021), *Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change, Climate change 2021 : the Physical Science Basis, Chap. 2*

[13] Stanfield, R. E., Dong, X., Xi, B., Del Genio, A. D., Minnis, P., Doelling, D., & Loeb, N. G. (2011), *Comparison of Global Cloud Fraction and TOA Radiation Budgets between the NASA GISS AR5 GCM Simulations and CERES-MODIS Observations*. In *AGU Fall Meeting Abstracts* (Vol. 2011, pp. GC43A-0883).

[14] World Meteorological Organization (2021), *State of the global climate 2020*, Geneva, Switzerland: WMO.

[15] Ohmura, A. (2021), *Snow and ice in the climate system*. In *Snow and Ice-Related Hazards, Risks, and Disasters* (pp. 73-92). Elsevier.

[16] Petit, J. R., Jouzel, J., Raynaud, D., Barkov, N. I., Barnola, J. M., Basile, I., ... & Stiévenard, M. (1999), *Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica*. *Nature, 399(6735)*, 429-436.

[17] NASA National Space Science Data Center *Planetary Fact Sheet*

[18] Sagan, C., Toon, O. B., & Pollack, J. B. (1979), *Anthropogenic albedo changes and the earth's climate*. *Science*, *206*(4425), 1363-1368.

[19] Archer, D. (2009), *Global Warming I: The Science and Modeling of Climate Change*, MOOC de l'Université de Chicago sur Coursera

[20] Mlawer, E. J., Taubman, S. J., Brown, P. D., Iacono, M. J., Clough, S. A. (1997), *Radiative transfer for inhomogeneous atmospheres : RRTM, a validated correlated-k model for the longwave*, Journal of Geophysical Research : Atmospheres, 102, 16

[21] Dessler, A. E., Zhang, Z., & Yang, P. (2008), *Water‐vapor climate feedback inferred from climate fluctuations, 2003–2008*. Geophysical Research Letters, 35(20).

[22] Rieckh, T., Anthes, R., Randel, W., Ho, S. P., & Foelsche, U. (2018), *Evaluating tropospheric humidity from GPS radio occultation, radiosonde, and AIRS from high-resolution time series*. Atmospheric Measurement Techniques, 11(5), 3091-3109.

[23] Sivira, R. G., Brogniez, H., Mallet, C., & Oussar, Y. (2015), *A layer-averaged relative humidity profile retrieval for microwave observations: design and results for the Megha-Tropiques payload*. Atmospheric Measurement Techniques, 8(3), 1055-1071.

[24] Alduchov, O. A., & Eskridge, R. E. (1996), *Improved Magnus form approximation of saturation vapor pressure*. Journal of Applied Meteorology (1988-2005), 601-609.

[25] McInerney, F. A., & Wing, S. L. (2011), *The Paleocene-Eocene Thermal Maximum: A perturbation of carbon cycle, climate, and biosphere with implications for the future*. *Annual Review of Earth and Planetary Sciences, 39(1)*, 489-516.