

# SimClimat documentation

Camille Risi

November 2019

A web version of this documentation is on [http://www.lmd.jussieu.fr/~crlmd/simclimat/documentation\\_2019](http://www.lmd.jussieu.fr/~crlmd/simclimat/documentation_2019)

The SimClimat software is an educational software for climate simulations ([Risi, 2015]). Through a user-friendly interface, it allows to run climate simulations at different time scales. The results pertaining to global surface temperature, sea level, ice sheet extent and atmospheric composition are displayed as curves and drawings. The user can test the influence of various parameters influencing the climate, such as astronomical parameters or the composition of the atmosphere, and can plug or unplug some climate feedbacks.

SimClimat is composed of a graphical interface coupled to a physical climate model. This documentation first describes the graphical interface (section 1) and then the physical model (section 2). This documentation also presents how to implement the experimental method with SimClimat in a classroom (section 3). The physical content and results of SimClimat are compared to the "true" climate models used in the IPCC reports (section 4).

## Contents

<b>1</b>	<b>Graphical interface</b>	<b>2</b>
1.1	Supported platforms	2
1.2	Inputs	2
1.2.1	Initial state	2
1.2.2	Duration	3
1.2.3	Color and name	3
1.2.4	Parameters	4
1.3	Outputs	5
1.3.1	Curves	5
1.3.2	Drawings	6
1.3.3	Export in .csv format	6
1.4	Small user's guide	6
<b>2</b>	<b>The physical model of SimClimat</b>	<b>7</b>
2.1	Observational constraints on the model	7
2.2	Temporal integration	7
2.3	Global radiative equilibrium model	8
2.3.1	Absorbed solar flux	8
2.3.2	Infrared radiation emitted by the Earth	8
2.3.3	Equilibrium temperature	9
2.4	Coupling the radiative equilibrium model with the other components	9
2.4.1	Greenhouse effect	9
2.4.2	Albedo	11
2.4.3	Sea level	11
<b>3</b>	<b>Implementing the experimental method with SimClimat</b>	<b>11</b>
3.1	Why do we need numerical modeling?	11
3.2	Implementing the experimental method with SimClimat: examples	11
3.2.1	Role of human activities in the observed recent global warming	11
3.2.2	Climate feedbacks at play in the recent global warming	12
3.2.3	Mechanisms at play in glacial-interglacial variations	12

<b>4</b>	<b>Comparing SimClimat to climate models used in IPCC reports</b>	<b>17</b>
4.1	What kind of models are used for climate projections in IPCC reports?	17
4.2	How does a climate model work?	17
4.3	Comparing the physical content	17
4.4	Comparing climate projections by SimClimat and climate models	19
4.5	Climate feedbacks involved in global warming	19
4.6	Role of human activities in current global warming	19
<b>5</b>	<b>Updates and known bugs</b>	<b>19</b>
5.1	Updates in May 2024	19
<b>6</b>	<b>Appendix: equation details for the physical model</b>	<b>23</b>
6.1	Evolution of global temperature	23
6.2	The greenhouse effect	23
6.2.1	The two components of the greenhouse effect	23
6.2.2	The greenhouse effect related to $CO_2$ as a function of $CO_2$ concentration	23
6.2.3	The greenhouse effect related to water vapor as a function of the water vapor concentration	23
6.2.4	The water vapor concentration as a function of temperature	24
6.3	The carbon cycle	24
6.3.1	Biological storage and continental alteration	24
6.3.2	$CO_2$ solubility in the ocean	25
6.3.3	Absorption of part of $CO_2$ emissions by the ocean and the vegetation	25
6.4	Albedo and ice sheets	25
6.4.1	Albedo as a function of ice sheet extension	25
6.4.2	Ice sheet extent as a function of temperature and of summer insolation at $65^\circ N$	25
6.4.3	Summer insolation at $65^\circ N$	25
6.5	Sea level	26

# 1 Graphical interface

## 1.1 Supported platforms

SimClimat works on personal computers with Windows and on smart-phones with Android or Mac-OS. The interface automatically adapts to the screen.

## 1.2 Inputs

A simulation is defined by:

1. An **initial state**: initial values for temperature,  $CO_2$  concentration, sea level and ice sheet extent;
2. A **duration**: number of years of simulation;
3. A simulation **name** and its color;
4. **Parameters** determining the behavior of the model during the simulation.

### 1.2.1 Initial state

In the interface, the initial state can be chosen in the page following the home page (figures 1,2). The possible initial states are:

1. "Today's world": The temperature is  $15.3^\circ C$ , the  $CO_2$  concentration is 405 ppm,  $CO_2$  emissions are 8 GtC/year, the sea level is 0 m.
2. "The pre-industrial world": The climatic variables are those of the pre-industrial era: the temperature is  $14.4^\circ C$ , the  $CO_2$  concentration is 280 ppm, the sea level of -0.2m ,  $CO_2$  emissions are null.
3. "The final state of the previous simulation": This allows to continue the previous simulation.



Figure 1: Screenshot of the home page of SimClimat with Windows.

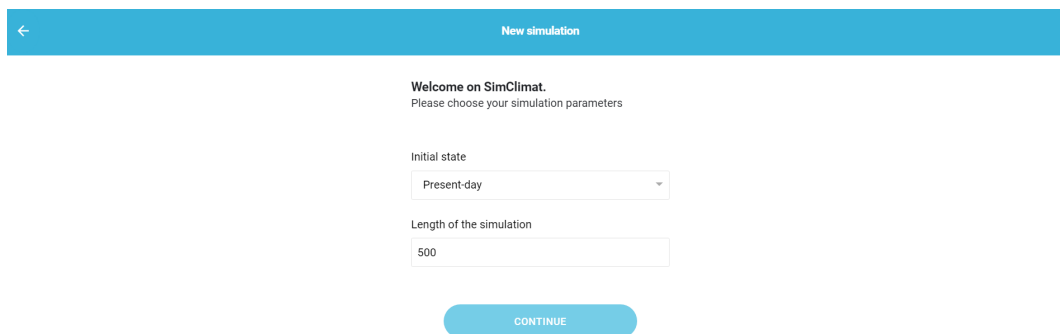


Figure 2: Screenshot of the page where the initial state and the duration can be chosen, with Windows.

4. "The final state of a saved simulation": If a final state of a simulation has already been saved, it is possible to start a simulation with this state. This allows to continue an earlier simulation.

### 1.2.2 Duration

The duration can be chosen in the same page as the initial state (figures 1,2). It can be between 100 years and 10 million years. The deadline depends on the processes that we want to study. For example, to study current global warming, durations of 100 to 500 years are recommended. To study the glacial-interglacial variations in which the ice sheets are at play, durations of tens to hundreds of thousands of years are recommended. To study continental weathering, durations of several million years are recommended.

### 1.2.3 Color and name

In the interface, the color and name can be chosen in the second page (figure 3). They can still be modified once the simulation is launched using the “curve” icon (figure 5).

Figure 3: Screenshot of the page where the simulation name and color can be chosen, with Windows.

#### 1.2.4 Parameters

We can tune 3 kinds of parameters:

1. astronomical parameters (example in section 3.2.3):
  - Earth-Sun Distance
  - Solar power
  - Eccentricity
  - Obliquity
  - Precession
2.  $CO_2$  concentration or emissions: we can choose between 2 types of simulations:
  - Set the  $CO_2$  concentration: The concentration is constant throughout the simulation, whatever  $CO_2$  fluxes, and is chosen by the user (example in section 3.2.1)..
  - Set emissions: The concentration is calculated interactively by the model, according to the sources or sinks chosen by the user. Sources or sinks that the user can tune are:
    - Anthropogenic emissions
    - Volcanism and oceanic ridge activity
    - Continental alteration
    - Biological storage
3. climate feedbacks: Four types of climate feedback are taken into account and can be optionally tuned or unplugged by the user:
  - Albedo
  - Ocean
  - Vegetation
  - Water vapor

For each parameter, we can show a small explanatory text and/or a schematic (example: figure 4).

Once the simulation is launched, we can check the value of all parameters using the “eye” icon, or modify parameters with the “key” icon (figure 6).

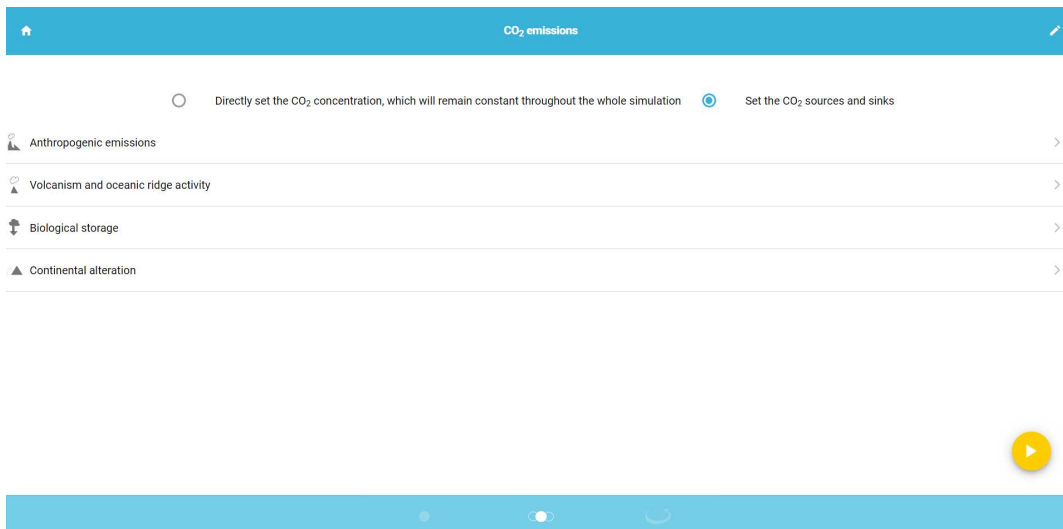


Figure 4: Screenshot of the page where parameters associated with the carbon cycle can be chosen, on Windows.

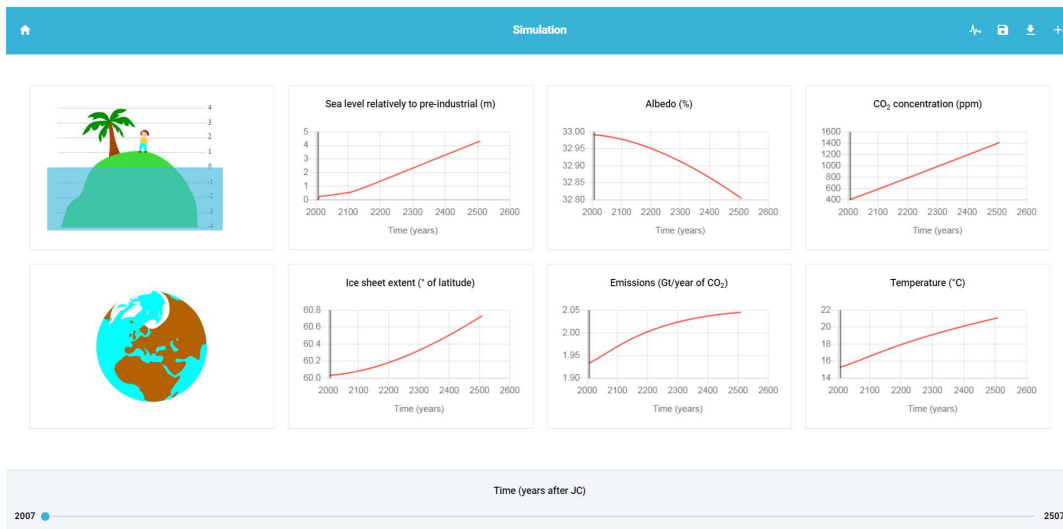


Figure 5: Screenshot of the page where results are displayed, on Windows.

## 1.3 Outputs

The model results are displayed in the interface through curves and drawings or can be exported in different formats.

### 1.3.1 Curves

Curves display:

1. The global, annual-mean temperature at the Earth's surface, in °C
2. The  $CO_2$  concentration, in ppm
3.  $CO_2$  emissions, in Gt of Carbone per year (GtC/year)
4. The sea level

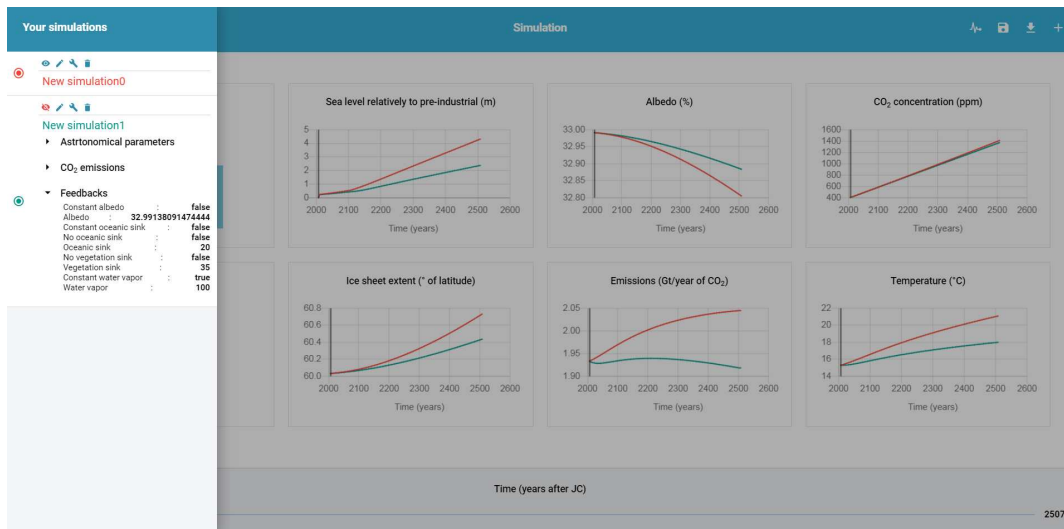


Figure 6: Screenshot of the page where results are displayed, when the “Edit simulations” icon is activated, on Windows.

5. The latitude of ice sheers, in ° of latitude
6. The global-mean planetary albedo, without unity.

The curves display time in x-axis, in year after JC, and the displayed variable in y-axis.

When superimposing several simulations, the curves are displayed in different colors. The color code connecting the color to the simulation names is indicated in the key.

### 1.3.2 Drawings

Two types of drawings are displayed:

- an Earth, on which we can see the ice-sheet extent; beware that this extent is very approximate.
- a tropical island, where you can see the sea level.

### 1.3.3 Export in .csv format

Simulation results may be downloaded as .csv numerical format, which can then be opened as an Excell sheet. To do so, click on the «download» icon near the top-right corner (figure 5).

## 1.4 Small user's guide

- Launch a first simulation: Click on "New simulation", then chose the input parameters (section 1.2). Launch the simulation by clicking on the small orange arrow..
- Add another simulation: In the display page, click on the "+" icon. Chose the new input parameters.
- Modify a simulation name and/or color: In the display page, click on the "Curves" icon. The simulation list appears on the left. Click on the "pencil" icon to edit the name or to select a new color.
- Show the input parameters for a simulation: In the display page, click on the "Curves" icon.. The simulation list appears on the left. Click on the "eye" to show all parameters.
- Modify the input parameters of an existing simulation: In the display page, click on the "Curves" icon. The simulation list appears on the left. Click on the "Key" icon to come back to the page where input parameters can be chosen. Once the parameters are modified, re-launch the simulation by clicking on the small orange arrow.

Time period	Pre-industrial	Present-day	Last Glacial Maximum (-21 ka)
Temperature	14.5°C	15.5°C	10°C
$CO_2$	280 ppm	ppm	180 ppm
Sea level	-0.2 m	0 m	-130 m
Ice sheet latitude	-	60°	45°
Planetary albedo	-	0.33	-

Table 1: Table summarizing constraints for pre-industrial, present-day and last glacial maximum time periods.

- Remove a simulation: In the display page, click on the "Curves" icon. The simulation list appears on the left. Click on the "Trash" icon to remove the simulation.
- Continue the last simulation: In the display page, click on the "+" icon. As initial state, chose «Final state of the previous simulation».
- Save a simulation to continue it later: In the display page, click on the "disk" icon.
- Continue a saved simulation: As initial state, chose «Final state of a saved simulation».
- Show this documentation: click on the «home» icon near the top-left corner of all pages.

## 2 The physical model of SimClimat

The physical model is based on a global-mean radiative equilibrium model (0 dimension) (section 2.3). This radiative equilibrium model is coupled to an extremely simple representation of the other components of the climate system: ocean, carbon cycle, ice sheets (section 2.4). The model uses physical relationships, as well as empirical relationships whose parameters are adjusted to satisfy observational or theoretical constraints (section 2.1). The model is presently coded in TypeScript.

### 2.1 Observational constraints on the model

The physical model of SimClimat is based on physical equations. It differs from typical educational animations in which results are pre-recorded. All calculations are done once the simulation is launched, depending on the parameters chosen by the user. An infinity of simulations are possible.

However, SimClimat's physical model differs from "true" climate models (detailed in section 4) to the extent that many parameters in the equations have been adjusted so that the simulations yield realistic results. This parameter adjustment is necessary because the equations are very simplified. The equations are very simplified to limit the calculation time, in order to get simulation results in a few seconds.

The parameters have been adjusted to satisfy the following observational constraints:

- temperatures,  $CO_2$  concentration, ice sheet latitude, sea level, and albedo for pre-industrial, present-day and last glacial maximum periods (Table 1);
- Extreme variations of orbital parameters induce temperature variations of the same order of magnitude as glacial-interglacial variations (10°C);
- Currently, water vapor and  $CO_2$  respectively contribute to 60% and 40% of the natural greenhouse effect;
- The warming due to a doubling of  $CO_2$  is 2.2°C when considering the effect of the water vapor but only of 1.2°C when neglecting this feedback (*[Dufresne and Bony, 2008]*).

### 2.2 Temporal integration

The SimClimat model calculates the different variables (temperature,  $CO_2$  concentration ...) as a function of time  $t$  during the duration  $D$  of the simulation, starting from the initial state. The different times  $t$  where the calculations are made are separated by a time step  $dt$ . To limit the calculation time, the time step depends on the duration of the simulation:

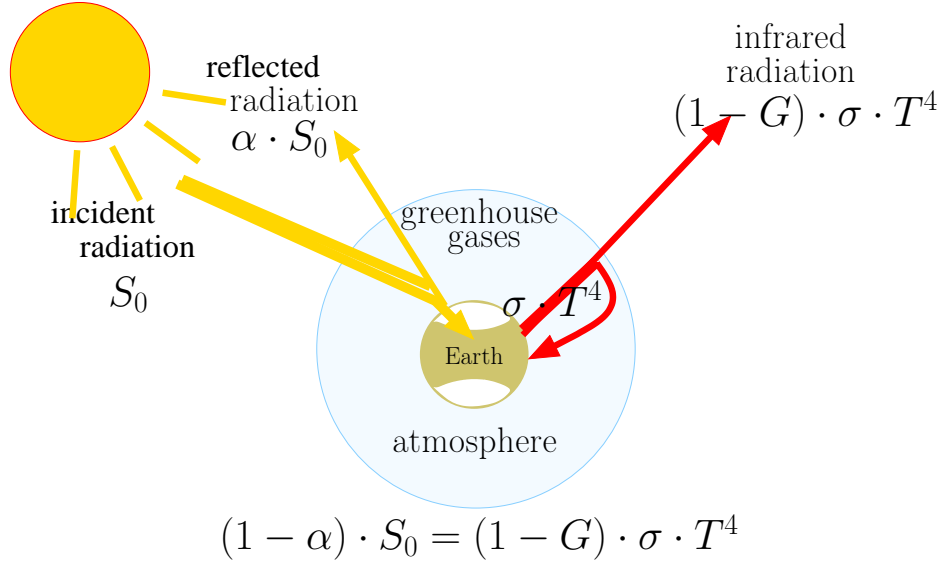


Figure 7: Global radiative equilibrium model.

- if  $D \leq 100$  years,  $dt=0.25$  years
- if  $D > 100$  years,  $dt = (D^{0.7}) \cdot 100^{0.3}/300$ . For example,  $dt \simeq 210$  years for  $D = 1$  million years, and  $dt \simeq 5283$  years pour  $D = 100$  million years.

## 2.3 Global radiative equilibrium model

At radiative equilibrium, the solar flux that is absorbed by the Earth,  $F_{in}$ , equals the infra-red radiation emitted by the Earth,  $F_{out}$  (figure 7):

$$F_{in} = F_{out}$$

Fluxes  $F_{in}$  and  $F_{out}$  are expressed in  $W/m^2$ .

### 2.3.1 Absorbed solar flux

$F_{in}$  depends on the planetary albedo:

$$F_{in} = (1 - A) \cdot F_0^{in}$$

$A$  is the Earth albedo, which depends on the ice sheet extent. It is computed as detailed in section 2.4.

$F_0^{in}$  is the global-mean, annual-mean incoming solar flux at the top of the atmosphere. Since at any time, the Sun lights up only a quarter of the Earth, we have  $F_0^{in} = \frac{S_0}{4}$ , where  $S_0 = 1370 W/m^2$  is the solar constant.

### 2.3.2 Infrared radiation emitted by the Earth

$F_{out}$  depends on temperature according to Stefan-Boltzmann's law, and is modulated by the greenhouse effect:

$$F_{out} = (1 - G) \cdot \sigma \cdot T^4$$

where:

$G$  is the greenhouse effect: it is the fraction of infrared radiation emitted by the Earth that is retained by the greenhouse effect and fails to escape to space;

$\sigma$  is Stefan-Boltzmann's constant.

This relationship is illustrated for different  $CO_2$  concentration in figure 8.



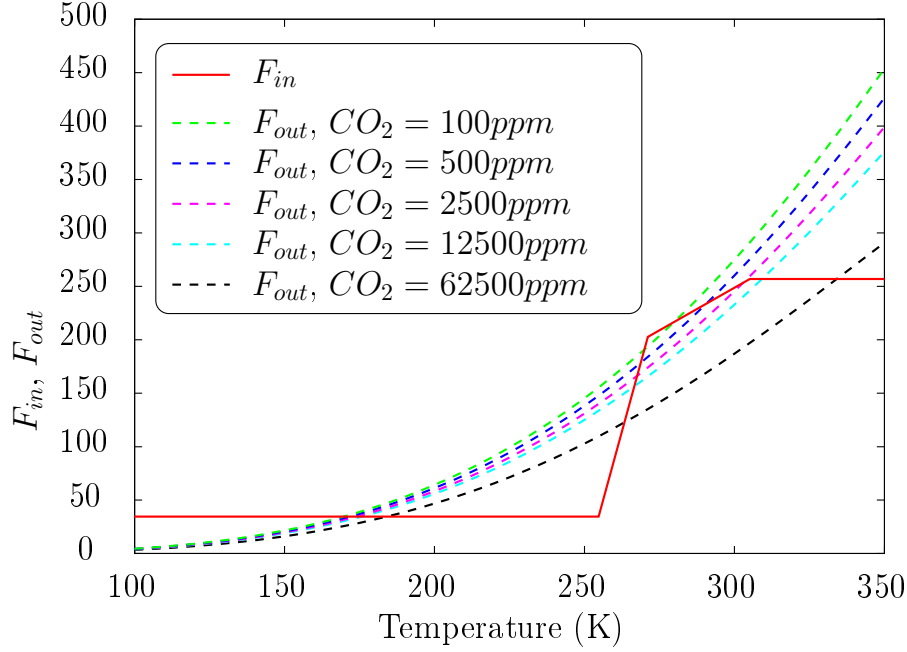


Figure 8: Absorbed solar radiation ( $F_{in}$ ) and infra-red radiation emitted by the Earth ( $F_{out}$ ), as a function of temperature. Radiative equilibrium is reached for intersection points between  $F_{in}(T)$  and  $F_{out}(T)$  curves.

### 2.3.3 Equilibrium temperature

We calculate  $T_{eq}(t)$  at each time step  $t$ , assuming radiative balance:

$$T_{eq}(t) = \left( \frac{(1 - A(t)) \cdot F_0^{in}}{(1 - G(t)) \cdot \sigma} \right)^{1/4}$$

Graphically,  $T_{eq}$  corresponds to the intersection point  $T$  between  $F_{in}(T)$  and  $F_{out}(T)$  curves (figure 8).

The temperature  $T(t)$  simulated by SimClimat follows the equilibrium temperature  $T_{eq}$ , but with some delay to represent the effect of the thermal inertia of the oceans (section 6.1).

## 2.4 Coupling the radiative equilibrium model with the other components

To calculate  $T_{eq}$ , we need the albedo  $A$  and the greenhouse effect  $G$ . It is from these variables that the radiative model is coupled to the atmospheric composition, to the carbon cycle and to the ice sheets. All these coupled components are represented in figure 9.

### 2.4.1 Greenhouse effect

The greenhouse effect  $G$  is decomposed into two components: the greenhouse effect associated with  $CO_2$  ( $G_{CO_2}^{serre}$ ) and that associated with water vapor ( $G_{H_2O}^{serre}$ ) (section 6.2.1).

- The greenhouse effect associated with the water vapor is calculated according to the water vapor concentration  $R_{H_2O}$  (section 6.2.3), which is calculated as a function of temperature (section 6.2.4).
- The greenhouse effect associated with  $CO_2$  is calculated as a function of  $CO_2$  concentration (section 6.2.2). This concentration is calculated from  $CO_2$  sources and sinks (anthropogenic emissions, volcanism, continental alteration, biological storage, storage by the ocean) (section 6.3). The  $CO_2$  solubility in the ocean is a function of temperature (6.3.2).

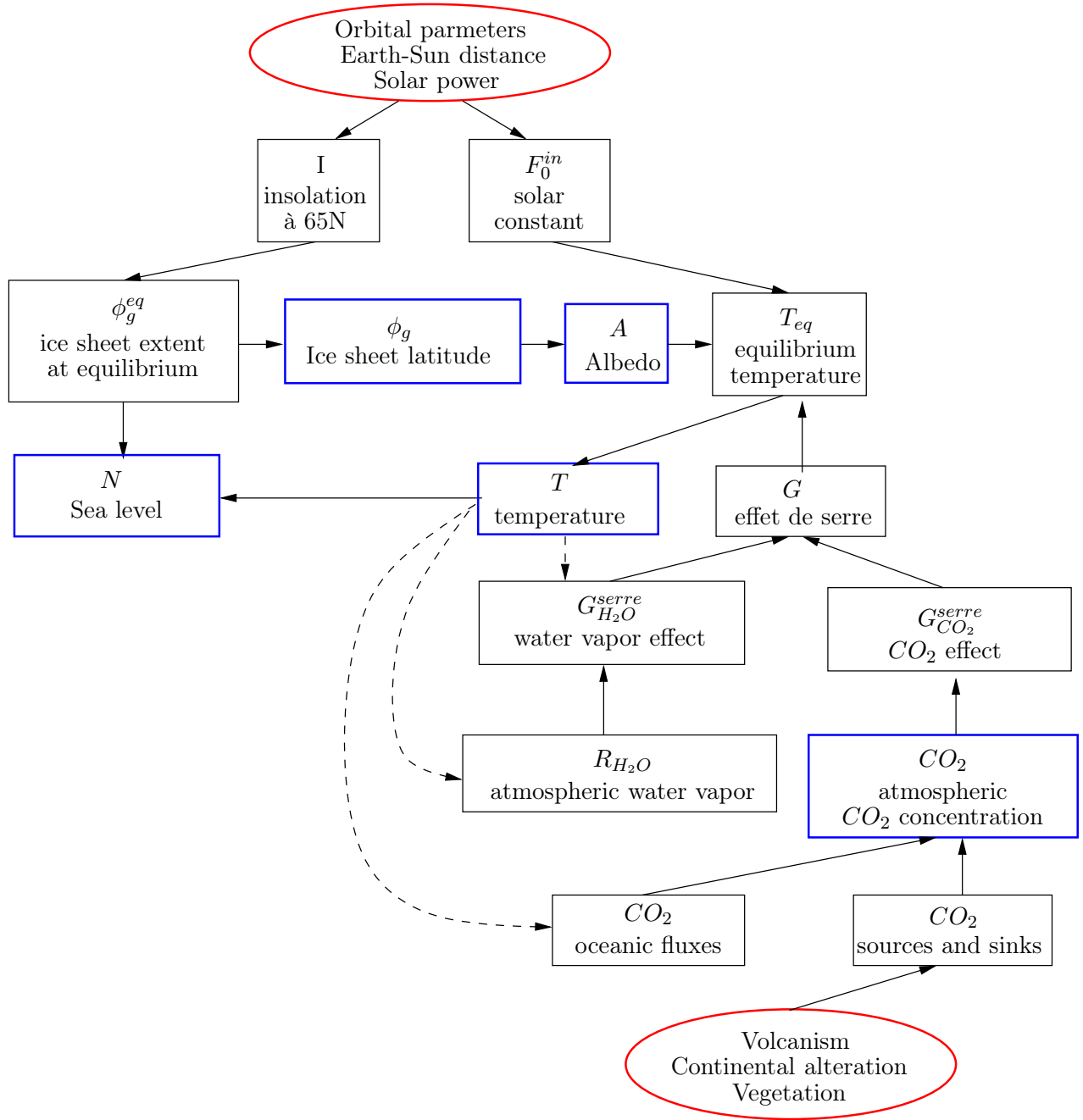


Figure 9: Diagram illustrating how the different variables are computed in the model. In red: external forcing on the climate system. In blue: state variables.

### 2.4.2 Albedo

Albedo  $A$  is calculated as a function of ice sheet extent  $\phi_g$  (section 6.4.1). This extent is calculated as a function of temperature and of the insolation at 65°N  $I$  (section 6.4.2). This insolation is determined by astronomical and orbital parameters.

### 2.4.3 Sea level

Sea levels depend both on temperature, through thermal expansion, and on ice sheet extent, which controls the available liquid water (section 6.5).

## 3 Implementing the experimental method with SimClimat

### 3.1 Why do we need numerical modeling?

The study of climate change is a special scientific field, where the classical experimental method is not always applicable. For example, we observe that for 150 years, the global temperature of the Earth has warmed by about 1°C. In parallel, the atmospheric concentration of  $CO_2$ , a greenhouse gas emitted by human activities, has increased. Is the temperature rise caused by the increase in  $CO_2$  concentration? Or is it pure coincidence? To answer this question according to the classical experimental method, one should duplicate our planet, make it go back 150 years earlier, and let it evolve until now without emitting any  $CO_2$ , and then accelerate the time to quickly get the results. Impossible! Except through numerical modeling. The goal of numerical modeling is precisely to be able to create as many Earth planets as one wants, submit them to the  $CO_2$  concentration one wants, go back in time, or accelerate the time... The experimental method is thus based on numerical experiments.

### 3.2 Implementing the experimental method with SimClimat: examples

#### 3.2.1 Role of human activities in the observed recent global warming

The experimental method begins as usual with an observation, a question and a hypothesis.

- *Observation*: We observe that the Earth has warmed by about 1°C during the past 150 years.
- *Question*: How can we explain this warming?
- *Hypothesis*: The global warming is mainly caused by the increase in the concentration of greenhouse gases emitted by human activities, in particular  $CO_2$  whose concentration has increased from 280 ppm to 405 ppm during the past 150 years.

In the case of the experimental method with numerical modeling, some additional steps are necessary before carrying out the experiments.

- *Model choice*: The model must be based on general physical equations and not on the above-mentioned observation or hypothesis. Otherwise, this is circular reasoning! In SimClimat's equations, nowhere is it written that a 125 ppm increase in  $CO_2$  concentration induces a 1°C increase in global temperature. The equations just “say” that the  $CO_2$  acts on the greenhouse effect, and that the greenhouse effect acts on the planet's radiative balance and therefore on the global temperature, with a lot of possible feedbacks that can modify the results (figure 9).
- *Control experiment*: The control experiment allows us to check the realism of the model compared to observations. Here, we perform a simulation starting from the pre-industrial era, lasting 250 years, with anthropogenic emissions of 2.5 GtC/year that lead the  $CO_2$  concentration to increase up to the present-day concentration.
- *Model validation*: We check that at the end of the simulation, the temperature has increased by 1°C, consistent with observations (figure 10, red). Note that with SimClimat, we cannot easily prescribe time-evolving anthropogenic  $CO_2$  emissions that would follow a realistic scenario. In these simulations, only the start and end of the simulation are analyzed.

Then the experimental method continues as usual with experience, result and conclusion.

- *Sensitivity experiment*: We run the same simulation as for control, but the  $CO_2$  concentration remains constant.
- *Result*: We find that if the concentration of  $CO_2$  remains constant, the overall temperature does not increase (figure 10, blue).
- *Conclusion*: We conclude that the observed global warming is caused by the increase in  $CO_2$  concentration.

### 3.2.2 Climate feedbacks at play in the recent global warming

We demonstrate in the previous section that the global warming is caused mainly by the increase in the  $CO_2$  concentration. Does  $CO_2$  act directly on the greenhouse effect? Or are there any amplifying feedbacks? We show here how to implement the experimental method with SimClimat to quantify the role of the water vapor feedback.

- *Observation*: The gas that contributes most to the natural greenhouse effect is water vapor.
- *Question*: Does water vapor play any role in global warming?
- *Hypothesis*: As the temperature increases, the humidity in the atmosphere also increases (according to the Clausius-Clapeyron relationship). In turn, the enhanced greenhouse effect associated to the water vapor leads to increased temperature.
- *Model choice*: SimClimat, whose representation of water vapor is based on physical equations.
- *Control experiment*: We run a 250-year simulation from the pre-industrial world to present-day, with anthropogenic emissions of 2.5 GtC/year that lead the  $CO_2$  concentration to increase up to the present-day concentration (figure 10, red).
- *Model validation*: We check that at the end of the simulation, the temperature has increased by 1°C, consistent with observations.
- *Sensitivity experiment*: We run the same simulation as for the control, but we "unplug" the water vapor feedback by keeping the water vapor concentration constant.
- *Result*: We find that if the  $H_2O$  concentration remains constant, the overall temperature increases less: 0.6°C only instead of 1°C (figure 10, green).
- *Conclusion*: We conclude that water vapor is involved in a positive feedback that contributes 40% to global warming.

Similarly, the role of other climate feedbacks can be highlighted by SimClimat. For example, by unplugging the surface albedo feedback, we can see that this feedback is positive but remains rather weak at short time scales. Finally, by unplugging the role of the ocean or vegetation in the carbon cycle, we can see that the increase in temperature is stronger. The concentration of  $CO_2$  also increases faster. This shows that the ocean and vegetation partially mop up  $CO_2$  human emissions, by about half.

### 3.2.3 Mechanisms at play in glacial-interglacial variations

Glacial-interglacial variations are characterized by large variations in temperature, in ice sheet extent, and in sea level, which can be observed in various paleoclimate records ([Masson-Delmotte and Chapellaz, 2002, Masson-Delmotte et al., 2015]). 21,000 years ago, the Earth underwent the last glacial maximum. The overall temperature was 5°C colder, a polar cap covered all of Northern Europe, and the sea level was 130 m lower. For 10,000 years, we have been in an interglacial period. There is an inter-glacial period every 100,000 years (Figure 11).

Here we propose to implement the experimental method in three steps to understand what causes glacial-interglacial variations.

#### Step 1: role of orbital parameters

- *Observation*: The time scales of temperature variations during inter-glacial variations are of the same order of magnitude as those of orbital parameters: obliquity (about 40,000 years), precession (about 20,000 years), eccentricity (about 400,000 years).

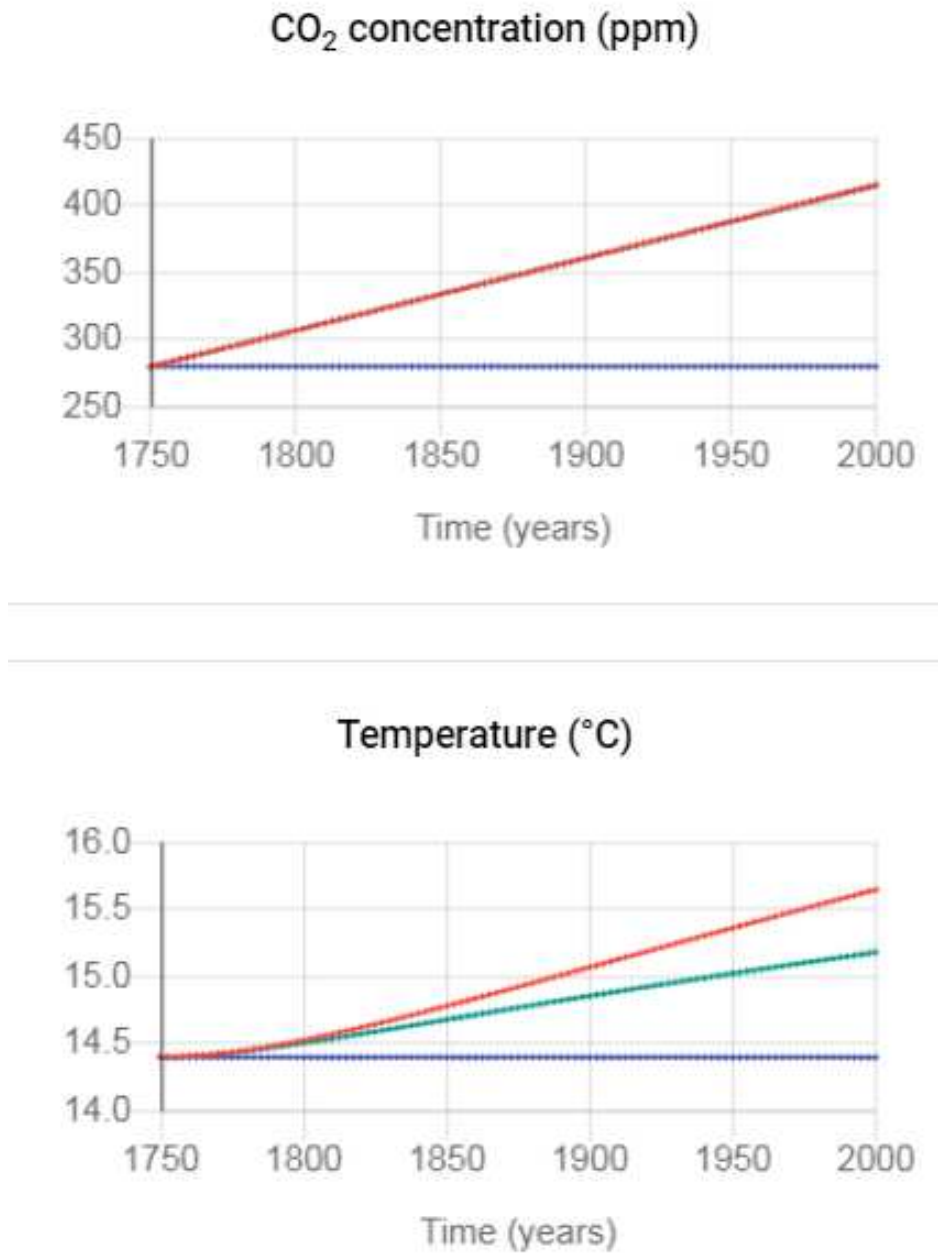


Figure 10: Screenshot of the results for a pre-industrial simulation with constant  $CO_2$  concentration (blue) and with anthropogenic emissions that lead to the current  $CO_2$  concentration (red). The green simulation is identical to the red one, except that the water vapor feedback has been "disconnected" by keeping the water vapor concentration constant. Note that for the  $CO_2$  concentration, the green curve is hidden by the red curve.

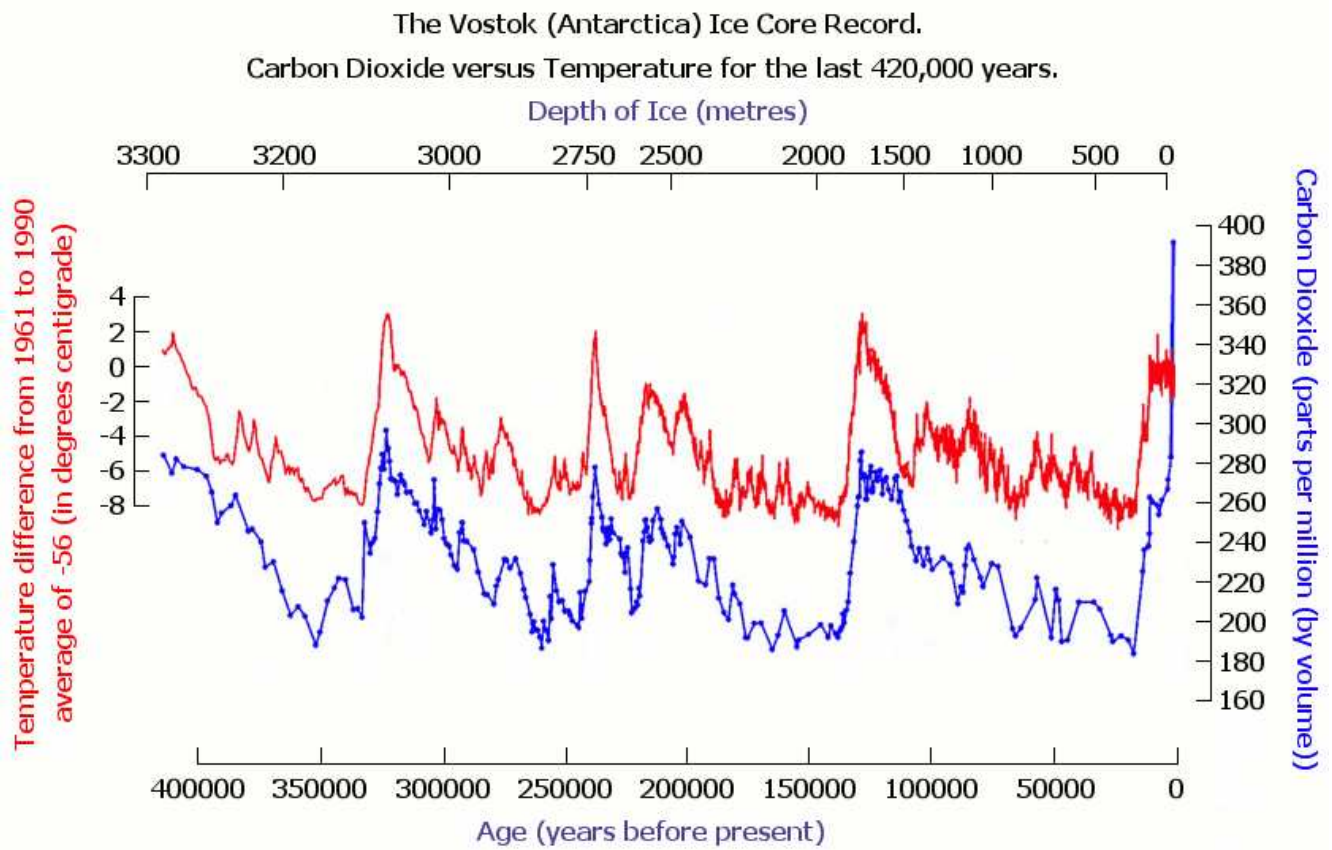


Figure 11: Variations in temperature and  $CO_2$  concentration recorded in Vostok ice core in Antarctica.

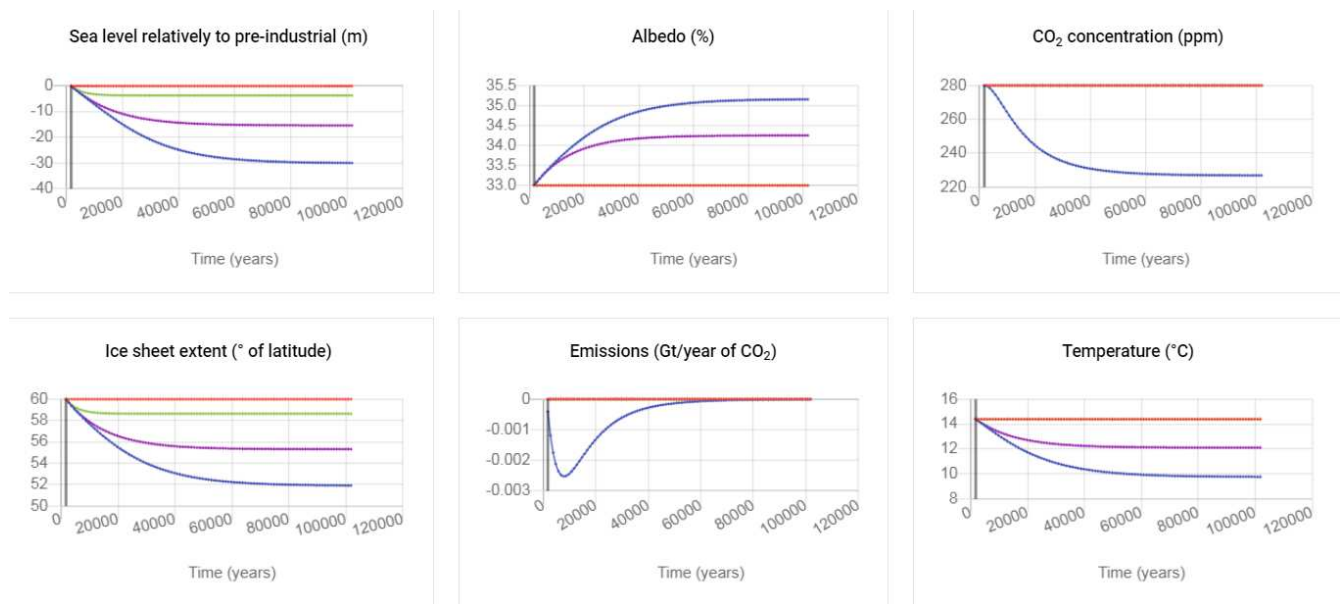


Figure 12: Screenshot of the results of a pre-industrial control simulation of 100,000 years (red), with minimal obliquity (blue), with minimal obliquity and constant albedo (green) and with minimal obliquity and the  $CO_2$  solubility in the ocean that does not depend on temperature (purple). Note that in panels where the green and purple curves are absent, they are actually hidden by the red curve.

- *Question:* Can variations in orbital parameters lead to temperature variations consistent with those observed during glacial-interglacial cycles (i. e.,  $5^\circ C$ )?
- *Hypothesis:* Yes. Let's take the obliquity as an example.
- *Model choice:* SimClimat, in which the effect of orbital parameters is described by physical equations.
- *Control experiment:* A simulation of 100,000 years is carried out starting from the pre-industrial world, all parameters being left at their default values. A sufficiently long simulation is necessary so that the ice sheet have time to reach equilibrium (figure 12, red).
- *Model validation:* The temperature remains constant at a value consistent with the observed global temperature.
- *Sensitivity experiment:* The simulation is the same as the control, but with the obliquity at its minimum value (figure 12, blue).
- *Result:* The temperature decreases by several  $^\circ C$ . There is also a large increase in the ice sheet extent, and a decrease in the sea level of the same order of magnitude as observed for the glacial period.
- *Conclusion:* We conclude that obliquity variations can lead to temperature variations consistent with those observed during glacial-interglacial cycles.

The same approach can be applied to the other orbital parameters.

## Step 2: role of summer insolation in polar regions

- *Observation:* When we modify the orbital parameters, we do not modify the global-mean, annual-mean incoming solar energy. Orbital parameters only change the distribution of incoming energy as a function of latitude and season.
- *Question:* How can orbital parameters change the global temperature?
- *Hypothesis:* By acting on the incoming energy in the polar regions in summer, the orbital parameters modulate ice sheet melting. In turn, the extent of polar ice sheets influences the planetary albedo and thus its temperature.

- *Model Choice*: SimClimat.
- *Control experiment*: The previous 100,000 year-long experiment with minimal obliquity (figure 12, blue).
- *Model validation*: The temperature decreases consistently with a glacial period.
- *Sensitivity experiment*: The simulation is the same as the control experiment, but the albedo feedback is “unplugged” by setting the albedo to a constant, pre-industrial value (figure 12, green).
- *Result*: The temperature remains constant.
- *Conclusion*: We conclude that the modification of the albedo is responsible for the modification of the temperature when the obliquity decreases. As the obliquity decreases, the sun’s rays arrive more inclined in boreal polar regions in summer. This prevents ice sheet melting, and thus promotes its extension. This increases the planetary albedo and therefore decreases the temperature.

The same mechanism applies to other orbital parameters. The obliquity is the easiest parameter to understand: if the polar axis is more inclined, in boreal summer the sun rays hit more perpendicularly the Northern polar regions. It favors the melting of the ice sheet. Precession acts on the season for which the Earth is closest to the sun. Presently, the Earth is closest to the sun in boreal winter. If, on the contrary, the Earth is closer to the sun in boreal summer, then the Northern polar ice sheet receives more energy in summer, which favors its melting. Eccentricity is the most complex parameter because its effect depends on precession. For the present precession where the Earth is furthest from the sun in boreal summer, if the orbit becomes more eccentric, the Earth will be even further away from the sun in summer. The Northern polar ice sheet will then receive less energy in summer which favors its extension.

Note that what is important here is the energy received by the Northern polar ice sheet and not the Southern polar ice sheet (i.e. Antarctica). This is because the Northern polar ice sheet is free to extend over Europe, Siberia, North America. On the contrary, the Southern polar ice sheet is limited to the Antarctic continent and can not extend over the Southern Ocean.

### Step 3: Why does the $CO_2$ concentration decreases during the glacial period?

Air bubbles trapped in ice cores show that changes in  $CO_2$  concentration co-vary with temperature during glacial-interglacial variations (Figure 11). Why?

- *Observation*: When the temperature decreases, the  $CO_2$  concentration decreases. At the last glacial maximum, the  $CO_2$  concentration was 100 ppm lower while the global temperature was 5°C lower.
- *Question*: How can we explain this decrease in  $CO_2$  concentration?
- *Hypothesis*: When the oceans are colder, the  $CO_2$  solubilizes more easily.
- *Model choice*: SimClimat.
- *Control Experience*: The previous 100,000 year-long experiment with minimal obliquity (figure 12, blue).
- *Model validation*: The  $CO_2$  concentration simulated by SimClimat decreases as temperature decreases, down to values of the same order of magnitude as those observed for the last glacial maximum.
- *Sensitivity experiment*: The simulation is the same as the control simulation, but the  $CO_2$  solubility is set to a constant value whatever the temperature (figure 12, purple).
- *Result*: The  $CO_2$  concentration remains constant. In addition, the cooling is reduced.
- *Conclusion*: The colder the oceans, the higher the  $CO_2$  solubility. A larger fraction of the atmospheric  $CO_2$  is thus dissolved into the ocean. Therefore the atmospheric  $CO_2$  concentration decreases. Since  $CO_2$  is a greenhouse gas, decreasing the atmospheric  $CO_2$  concentration amplifies the cooling: it is a positive feedback.



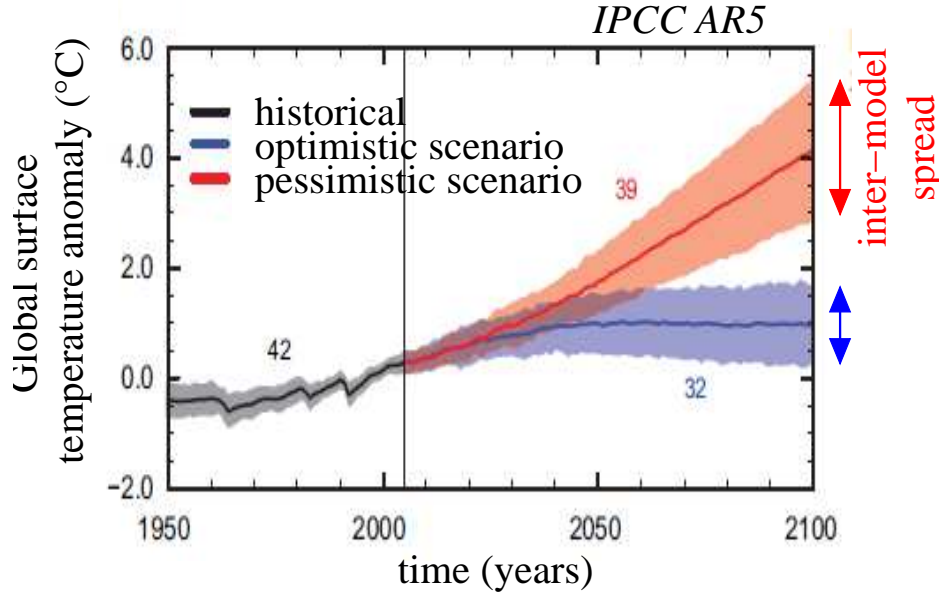


Figure 13: Temperature evolution from 1950 to 2100 simulated by models participating in CMIP5. Until the early 2000s, the simulations are forced by observed concentrations of greenhouse gases and aerosols. Beyond, simulations are forced according to two types of scenarios: optimistic (blue) or pessimistic (red). The colored envelopes represent all the models, while the solid lines represent the multi-model mean.

## 4 Comparing SimClimat to climate models used in IPCC reports

### 4.1 What kind of models are used for climate projections in IPCC reports?

Climate projections (e. g. figure 13) presented in IPCC (Intergovernmental Panel on Climate Change) reports are based on simulations with different climate models. There are around 40 climate models around the world, including models in the United States, Japan, China, France, United Kingdom, Germany, Canada. They all perform the same simulations as part of the Coupled Model Intercomparison Project (CMIP). All results are freely accessible on the web. These results are used in IPCC reports. For example, the 5th IPCC report ([[IPCC, 2013](#)]) used results from CMIP5 ([[Taylor et al., 2012](#)]).

### 4.2 How does a climate model work?

Climate models simulate the different components of the climate system: the atmosphere, the ocean, continental surfaces, ice sheets (Figure 14, red frame). The atmospheric component of climate models numerically solves the fluid mechanics equations on a 3D grid of the Earth's atmosphere (green frame). The size of grid boxes is about 100 km. Processes smaller than grid boxes, such as clouds, rain or radiation, are represented by so-called physical parameterizations. For example, physical parameterizations calculate how much water vapor is condensed from the water vapor in each grid box, what proportion of this condensed water precipitates to form rain, what proportion of this rain evaporates when falling, in average in each grid box.

### 4.3 Comparing the physical content

SimClimat has a much simpler physical content than the climate models participating in CMIP (table 2), which allows it to be much faster. It represents the atmosphere in a much coarser way (0D instead of 3D), but couples more components, notably the ice sheets and the carbon cycle. To this extent, it is rather analogous to a "model Earth system" (figure 14, purple frame). This allows SimClimat to represent climate changes at geological time scales.

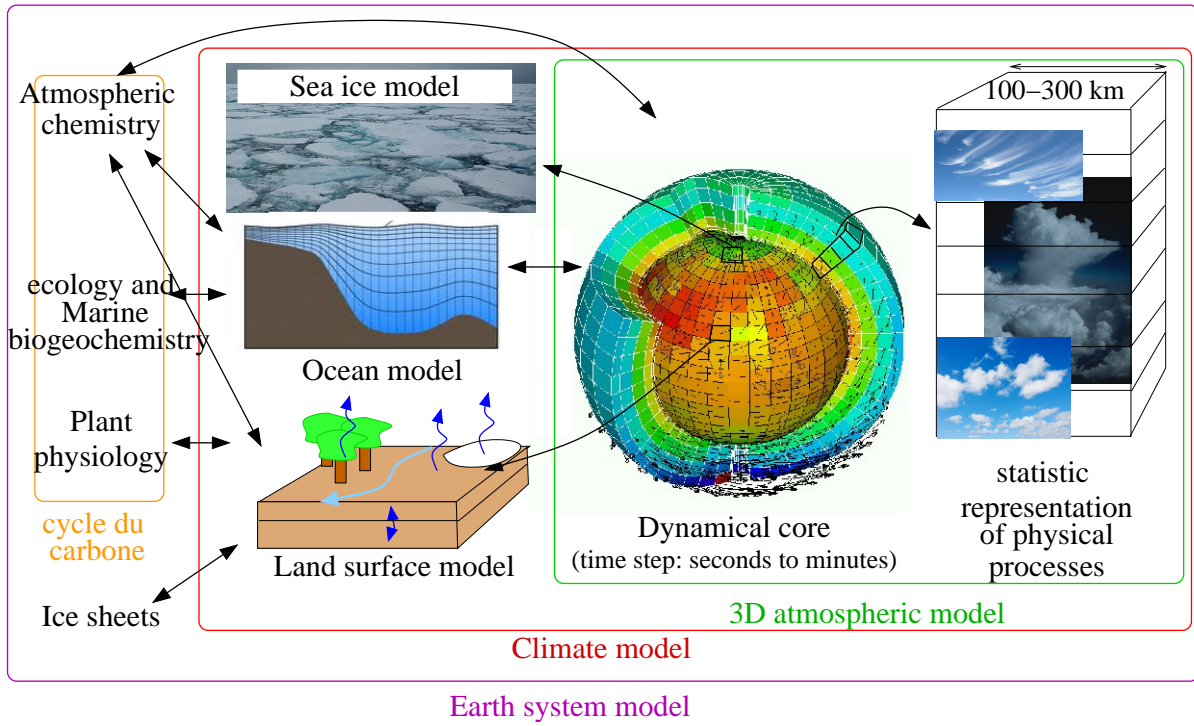


Figure 14: Schematic illustrating the different components of a climate model.

Models	Climate model participating in CMIP	SimClimat
Atmospheric grid dimension	3D	0D
Atmospheric and oceanic dynamics	yes	no
Time steps	a few seconds or minutes	several years
Radiation and Earth radiative balance	yes	very simple
Cloud effects	yes	no
Carbon cycle	no	yes
Ice sheets	no	yes
Uncertainty estimate	inter-model spread	no
Computational time for 100 years	several days	less than a second

Table 2: Table identifying the main differences between climate models participating in CMIP and SimClimat's physical model.

## 4.4 Comparing climate projections by SimClimat and climate models

SimClimat has been adjusted to realistically represent the present climate and last glacial maximum, and to provide climate projections similar to those of climate models participating in CMIP (section 2.1). Consequently, for  $CO_2$  emissions that allow SimClimat to simulate  $CO_2$  concentration evolutions similar to those of the IPCC, projections in terms of temperature and sea level rise are similar (figure 15).

## 4.5 Climate feedbacks involved in global warming

The increase in the global temperature in response to a doubling of the atmospheric  $CO_2$  concentration can be decomposed into the effect of several processes:

1. the greenhouse effect directly related to  $CO_2$ ;
2. water vapor feedback: the warmer the atmosphere, the moister the atmosphere. Since water vapor is a greenhouse gas, this leads to increase the temperature;
3. ice albedo feedback: as temperature increases, ice melts more easily, so the Earth's albedo decreases, so the Earth absorbs more solar radiation and therefore the temperature increases even more.
4. Cloud feedbacks: These are very diverse and are not represented by SimClimat.

In climate models participating to CMIP, more than one-third of the simulated warming is caused by the direct effect of  $CO_2$ . A small third is caused by the water vapor feedback. The albedo feedback accounts for only 5% to 10% of the warming (Figure 16a). These proportions are reproduced by SimClimat (figure 16c). However, SimClimat does not represent cloud feedbacks, which account for nearly a quarter of global warming, but is subject to high uncertainty (figure 16b).

## 4.6 Role of human activities in current global warming

The section 3.2.1 shows how to demonstrate with SimClimat the role of human activities in the current global warming. Climate models participating in CMIP can be used for the same purpose (figure 17).

In the control experiment, climate models are subject to increasing atmospheric concentrations in greenhouse gases ( $CO_2$ , but also  $CH_4$ ) observed over the past 150 years, as well as the observed variation in the concentration of aerosols emitted by volcanoes. The simulations reproduce well the observed warming as well as the inter-annual variability related to the volcanic eruptions (figure 17a).

In a second experiment, climate models are subject only to the observed variation in aerosol concentration, with atmospheric concentrations of greenhouse gases remaining constant. The models simulate a constant temperature. This proves that the warming observed for 150 years is indeed caused by the increase in greenhouse gases.

# 5 Updates and known bugs

## 5.1 Updates in May 2024

- Updates on various platforms
- Fixed the bug that caused the calotte design to evolve in the wrong direction.
- Added titles to precession diagrams.
- Corrected spelling errors in French
- Corrected a bug where sea levels were moving in the wrong direction in some simulations. To do this, we modify the formula giving the fraction of the ocean stored as ice. Previously, it was a 3rd degree polynomial, now it's a  $\cos$  \* power function, to ensure monotonicity.
- Added command-line output to facilitate debugging.
- Documentation updated
- Correction of a bug during simulation extension: cap extension changed abruptly when the simulation is extended.

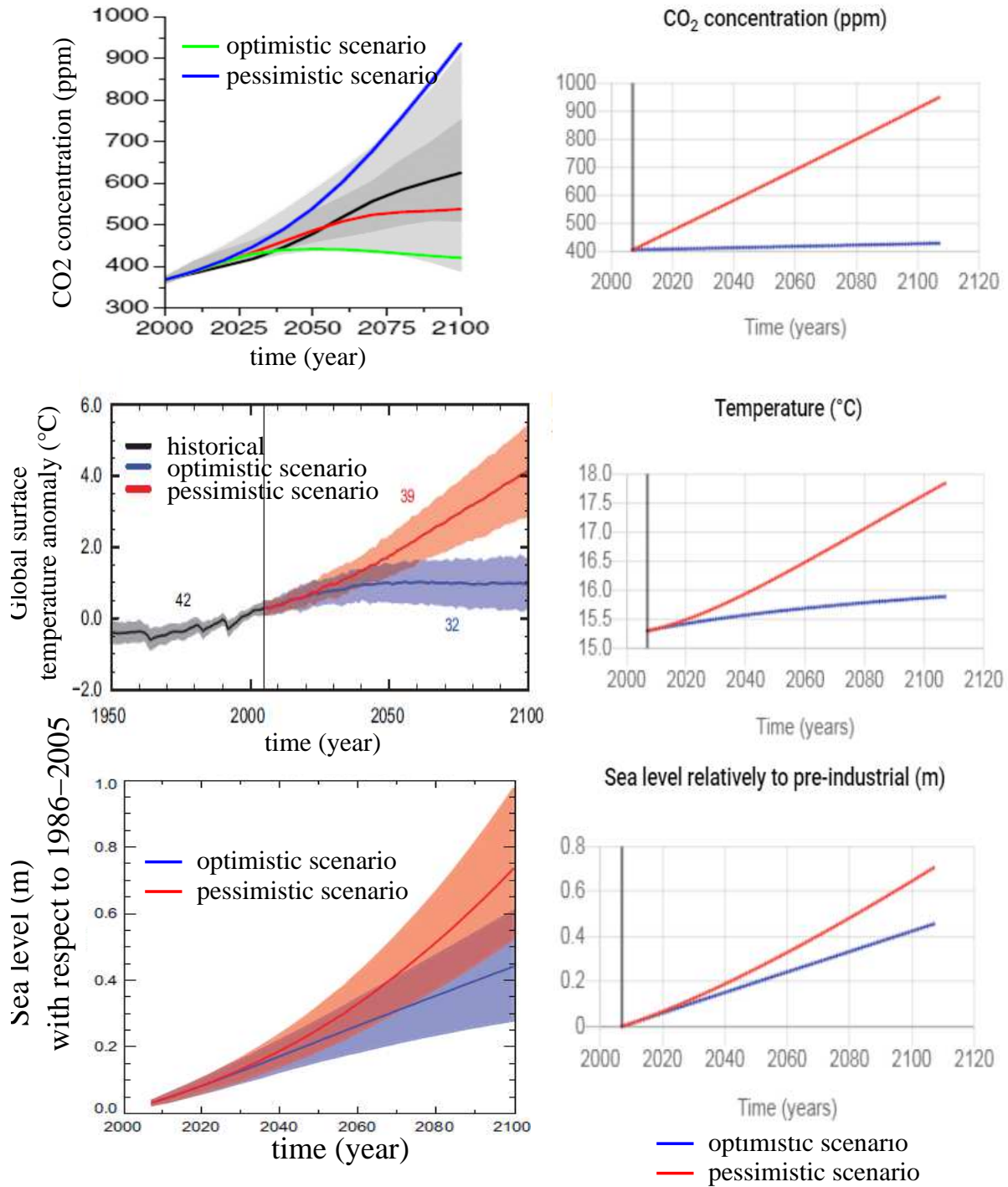


Figure 15: Comparison of projections produced by SimClimat and by models participating in CMIP. The left column presents the results shown in the 5th IPCC report ([[IPCC, 2013](#)]). The right column shows screenshots of SimClimat. The curves show the evolution of the  $CO_2$  concentration according to optimistic and pessimistic scenarios (above), the global temperature of the Earth (in the middle) and the sea level (at the bottom). For SimClimat, the optimistic and pessimistic scenarios were run with 1 GtC/year and 22 GtC/year anthropogenic emissions.

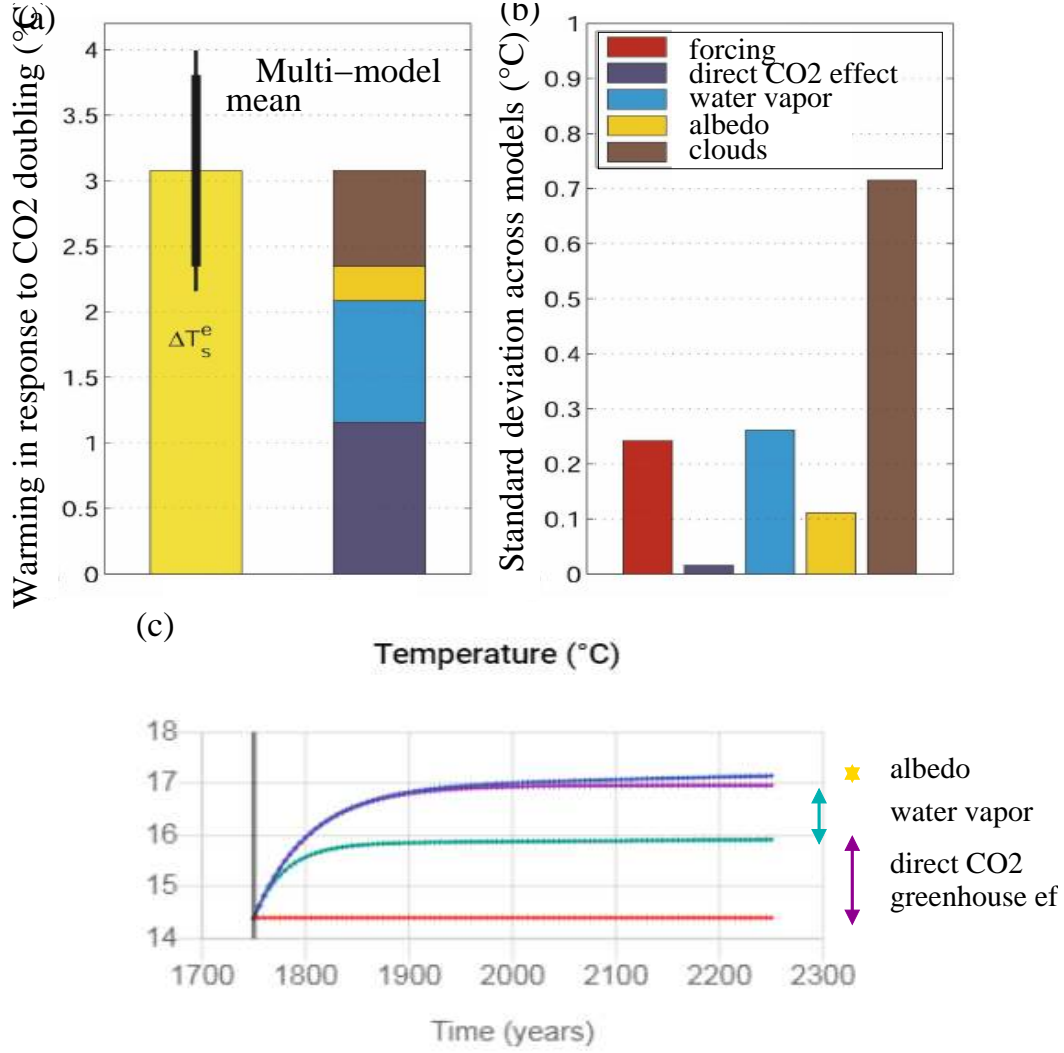


Figure 16: Comparison of climate feedbacks for a  $CO_2$  doubling simulated by SimClimat and by climate models participating to CMIP. (a) Global warming and its contributions simulated by climate models in average. (b) Standard deviation of the different contributions to the warming simulated across the different climate models. (c) Evolution of the temperature simulated by SimClimat, with and without the different feedbacks. The red curve is a pre-industrial simulation, the blue curve is a simulation with double  $CO_2$  (560 ppm), the purple curve is a simulation with double  $CO_2$  and constant albedo, and the green curve is a simulation with double  $CO_2$  and constant water vapor concentration. Panels (a) and (b) are from [Dufresne and Bony, 2008].

## Global mean surface temperature anomaly with respect to 1961–1990

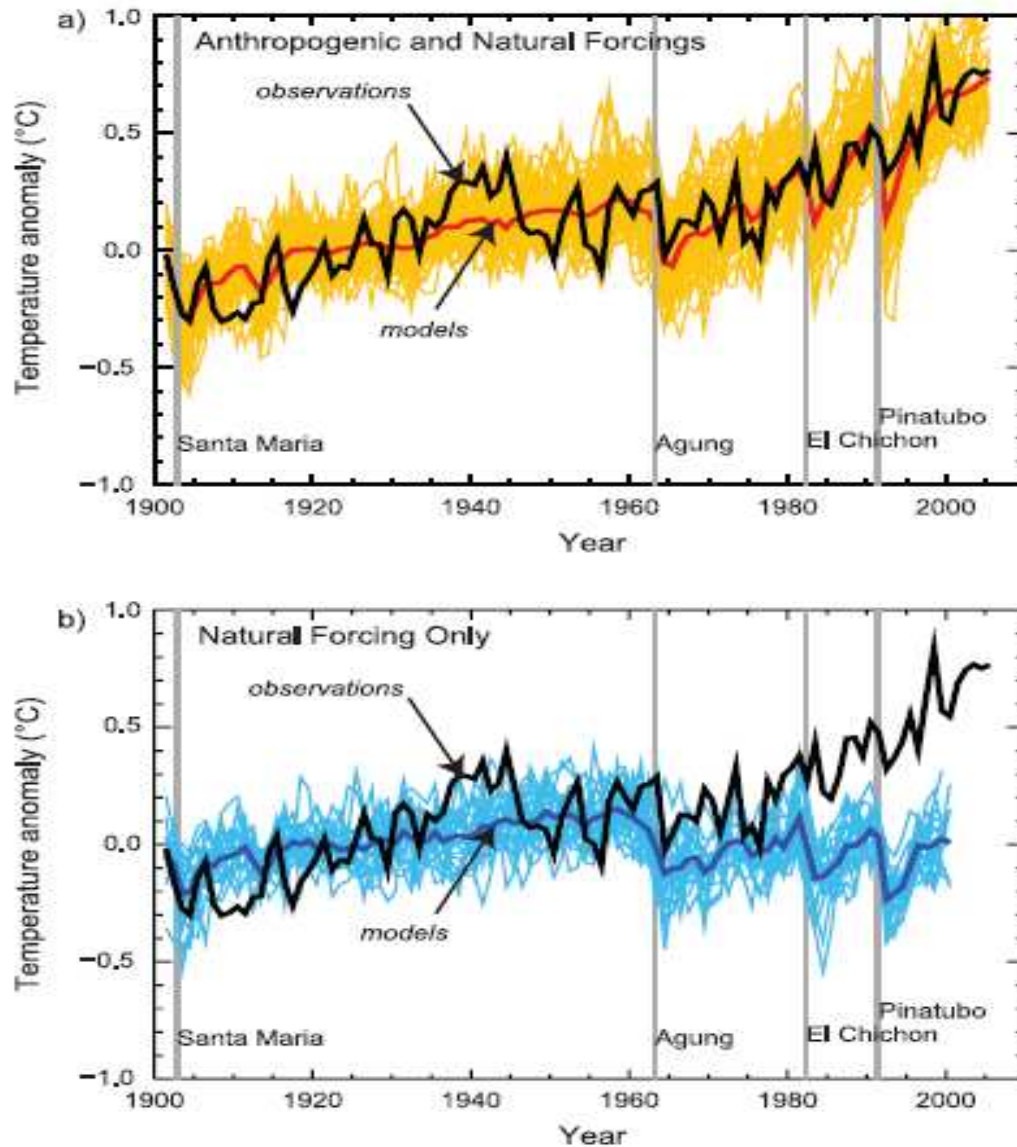


Figure 17: (a) Evolution of the global-mean temperature since 1900 for observations (black), for models participating in CMIP (yellow) and for the average between all CMIP models (red), when the greenhouse gas concentrations increase in the same way as in the observations. (b) Change in global temperature since 1900 for observations (black), for models participating in CMIP (light blue) and for the average between all CMIP models (dark blue), when the greenhouse gas concentration remain constant. Figure from the 5th IPCC Report ([[IPCC, 2013](#)]).

## 6 Appendix: equation details for the physical model

### 6.1 Evolution of global temperature

The global-mean temperature  $T(t)$  is calculated by assuming that it is relaxed towards the global-mean temperature at radiative equilibrium,  $T_{eq}$ , with a time constant  $\tau_T = 100ans$ :

$$T(t) = T(t - dt) + (T_{eq}(t) - T(t - dt))(1 - e^{-dt/\tau_T})$$

Temperature  $T_{eq}(t)$  is calculated in section 2.3.3.

### 6.2 The greenhouse effect

#### 6.2.1 The two components of the greenhouse effect

The greenhouse effect  $G$  is defined here as the fraction of infrared radiation emitted by the Earth that is retained by the greenhouse effect and fails to escape to space.  $1 - G$  represents the fraction of infra-red energy emitted by the Earth that escapes to space.

We note  $G_0$  the reference greenhouse effect, chosen at the pre-industrial time.

We assume that variations in the greenhouse effect  $G$  are related to changes in the atmospheric concentration in water vapor and in  $CO_2$ . We neglect the effect of changes in the concentration of other greenhouse gases such as  $CH_4$  or  $N_2O$ , or we consider them in terms of “ $CO_2$ -equivalent”.

We have:

$$G = G_0 + G_{H_2O}^{serre} + G_{CO_2}^{serre}$$

where  $G_{H_2O}^{serre}$  is the greenhouse effect anomaly with respect to the reference related to the water vapor concentration anomaly and  $G_{CO_2}^{serre}$  is that related to the  $CO_2$  concentration anomaly.

#### 6.2.2 The greenhouse effect related to $CO_2$ as a function of $CO_2$ concentration

$G_{CO_2}^{serre}$  is calculated as a function of  $CO_2$  concentration:  $CO_2(t)$ . In the "usual"  $CO_2$  concentration range (between 100 and 10,000 ppm), we assume a logarithmic relationship between  $G_{CO_2}^{serre}$  and  $CO_2(t)$  ([Myhre et al., 1998, Pierrehumbert et al., 2006]):

$$G_{CO_2}^{serre} = 1.8 \cdot 10^{-2} \cdot \ln\left(\frac{CO_2(t)}{CO_2^{ref}}\right)$$

Around this range, a linear approximation extends the logarithmic relationship.

The effect of the  $CO_2$  concentration on the infra-red energy emitted by the Earth escaping to the space ( $F_{out}$ ) is illustrated in figure 8.

#### 6.2.3 The greenhouse effect related to water vapor as a function of the water vapor concentration

$G_{H_2O}^{serre}$  is calculated as a function of the global-mean amount of water vapor integrated in the atmospheric column,  $H_2O(t)$ :

$$G_{H_2O}^{serre} = -Q \cdot G_0 \cdot (1 - (R_{H_2O}(t))^p) \cdot L$$

where  $R_{H_2O}(t)$  is the ratio between the amount of water vapor at time  $t$  and its reference quantity:

$$R_{H_2O}(t) = \frac{H_2O(t)}{H_2O^{ref}}$$

and  $L$  limits the greenhouse effect when  $R_{H_2O}$  becomes very strong, avoiding too strong a runaway greenhouse effect when the temperature becomes very strong:  $L = 0.3 \cdot e^{-\sqrt{R_{H_2O}(t)-1}} + 0.7$ .

To satisfy the observational constraints (section 2.1), we take  $Q = 0.6$  and  $p = 0.23$ .



### 6.2.4 The water vapor concentration as a function of temperature

In order to simulate the positive feedback of water vapor on the climate, the ratio  $R_{H_2O}(t)$  is expressed as a function of the temperature  $T(t)$  assuming that the relative humidity remains constant. Then  $R_{H_2O}(t)$  equals the ratio of partial saturation pressures  $p_{sat}$ .

$$R_{H_2O}(t) = \frac{p_{sat}(T)}{p_{sat}(T_{ref})}$$

The saturation vapor pressure is calculated by the Rankine formula:

$$p_{sat}(T) = \exp(13.7 - 5120./T)$$

The temperature is in K and  $T_{ref} = 14.4^\circ C$ .

## 6.3 The carbon cycle

$CO_2(t)$  is calculated as a function of the concentration at the previous time step by a mass budget equation:

$$CO_2(t) = CO_2(t - dt) + F(t) \cdot \frac{CO_2^{act}}{M_{CO_2}^{act}} \cdot dt$$

where  $CO_2(t)$  is the  $CO_2$  concentration in ppm and  $F(t)$  is the  $CO_2$  flux towards the atmosphere in GtC/year. Note that  $CO_2$  fluxes are expressed in GtC/year of Carbone. To convert these fluxes in Gt of  $CO_2$  per year, you need to multiply the fluxes by 44/12. The factor  $\frac{CO_2^{act}}{M_{CO_2}^{act}}$  allows us to convert a  $CO_2$  mass in Gt ( $10^9$ t) into a concentration in ppm:  $M_{CO_2}^{act}$  is the  $CO_2$  mass in the present-day atmosphere (750 Gt) and  $CO_2^{act}$  is the present-day  $CO_2$  concentration (405 ppm).

The  $CO_2$  flux,  $F(t)$ , is the sum of several contributions:

- anthropogenic emissions;
- emissions associated with volcanism and oceanic ridge activity,  $F_{volc}$ . By default,  $F_{volc}=0.0083$  GtC/year;
- Biological storage, i. e. the storage of organic matter in fossil form (oil, coal);
- continental alteration;
- $CO_2$  exchanges between the atmosphere and the ocean;
- absorption of some of the emissions by the ocean and vegetation.

Anthropogenic and volcanic emissions are assumed to be constant throughout the simulation.

### 6.3.1 Biological storage and continental alteration

We assume that the  $CO_2$  fluxes leaving the atmosphere by biological storage and continental alteration are proportional to the  $CO_2(t)$  concentration, by analogy with chemical reactions in which  $CO_2$  is the reagent:

$$F_{conso}(t) = -s \cdot CO_2(t)$$

where  $s$  is the  $CO_2$  consumption rate in GtC/ppm/year.

The user chooses the consumption rate of  $CO_2$  by biological storage  $s_{bio}$  and by continental alteration  $s_{alt}$ . When the Earth is completely frozen (snowball), these consumption rates are canceled regardless of the choice of the user: in fact, freezing does not allow the consumption of  $CO_2$  by these processes, which allows the exit of the snowball.

By default,  $s_{alt}$  is such that continental alteration balances volcanism for long time scales:  $s_{alt}^{ref} = \frac{F_{volc}}{CO_2^{ref}}$ .  $s_{bio}$  is null by default, because the current biological storage can be neglected. At Carboniferous,  $s_{bio}=-0.0014$  GtC/ppm/year, according to the  $CO_2$  fluxes reconstructed at that time ([[Berner, 2003](#)]).



### 6.3.2 $CO_2$ solubility in the ocean

In nature, the  $CO_2$  solubility in the ocean depends on the temperature. As a result, an increase in temperature leads to  $CO_2$  degassing into the atmosphere whereas a decrease in temperature leads to  $CO_2$  pumping into the ocean. This phenomenon acts on time scales of a few thousand years, and probably played a role in  $CO_2$  variations observed during glacial-interglacial oscillations (section 3.2.3).

In the model, this is represented by a flux  $F_{oce}$ , in GtC/year, written as:

$$F_{oce} = \frac{1}{\tau_{oce}} \cdot \frac{CO_2^{act}}{M_{CO_2}^{act}} \cdot (CO_2^{eq}(T) - CO_2(t))$$

where  $CO_2^{eq}(T)$  is the atmospheric  $CO_2$  concentration in equilibrium with the ocean at temperature  $T$  and  $\tau_{oce}$  is the relaxation time scale of the  $CO_2$  concentration towards this equilibrium.

$CO_2^{eq}(T)$  is parameterized according to the temperature so that (1) a cooling of 10°C (e.g. interglacial-glacial cooling) leads to a reduction of  $CO_2$  concentration down to 180 ppm (2) the model simulates a 1°C increase for a 90 ppm increase from the pre-industrial period to present-day. This function is empirical rather than physical.

### 6.3.3 Absorption of part of $CO_2$ emissions by the ocean and the vegetation

The aim is to represent in a simple way that the superficial ocean and the vegetation absorb some of the  $CO_2$  emissions: it is estimated, for example, that at present 35% of the current anthropogenic emissions are absorbed by the vegetation and 20% by the ocean. This plays a role especially at small time scales. In the model, we multiplies the  $CO_2$  fluxes by  $1 - puit_{bio} - puit_{oce}$ , where  $puit_{bio}$ =35% and  $puit_{oce}$ =20%.

## 6.4 Albedo and ice sheets

### 6.4.1 Albedo as a function of ice sheet extension

In nature, the planetary albedo mainly depends on the ice extent, cloud cover and land surface properties.

In SimClimat, only the effect of ice sheet extent is taken into account. The albedo is calculated as a function of ice sheet extent  $\phi_g(t)$  by a piece-wise linear function. The albedo is bounded between the albedo of the ice (taken at 0.9) and the albedo of the Earth without ice, taken at 0.25. This formulation of the albedo as a function of the latitude of ice sheets, which itself depends on the temperature (section 6.4.2, explains the shape of the  $F_{in}$  curve (the solar energy absorbed by the Earth) as a function of temperature in figure 8.

### 6.4.2 Ice sheet extent as a function of temperature and of summer insolation at 65°N

The latitude of the ice sheets is in degrees of latitude. It is calculated as a function of global temperature and of the summer insolation at 65°N,  $I$  (in order to take into account the variations of orbital parameters).

We calculate the ice sheet extent at equilibrium  $\phi_g^{eq}$ :

$$\phi_g^{eq} = a \cdot T + b + c \cdot (I - I_{actuel})$$

$I$  is calculated as a function of the solar constant, eccentricity, obliquity and precession (section 6.4.3).

The parameters  $a$ ,  $b$  and  $c$  are tuned to satisfy the constraints summarized in section 2.1:  $a=0.73$ ,  $b=49.53$  and  $c=0.2$ .

The ice sheets respond to climate forcing with a time scale  $\tau_g = 3000$  years. To represent this effect, the ice sheet latitude  $\phi_g(t)$  is calculated as a function of  $\phi_g(t - dt)$  assuming that  $\phi_g(t)$  tends towards  $\phi_g^{eq}$  with the time constant  $\tau_g$ :

$$\phi_g(t) = \phi_g(t - dt) + (\phi_g^{eq} - \phi_g(t - dt)) \left(1 - e^{-dt/\tau_g}\right)$$

### 6.4.3 Summer insolation at 65°N

The summer insolation at 65°N,  $I$ , is calculated as a function of the solar constant  $S_0$ , eccentricity  $x$ , obliquity  $o$  and precession  $p$  following this formula:

$$I = \frac{S_0}{4} \cdot \cos\left(\frac{(65 - o) \cdot \pi}{180}\right) * \left(\frac{1 - \frac{x_{actuel}}{2} * \sin\left(\frac{-p_{actuel} \cdot \pi}{180}\right)}{1 - \frac{x}{2} * \sin\left(\frac{-p \cdot \pi}{180}\right)}\right)^2$$

where  $x_{actuel}$  and  $p_{actuel}$  the present-day eccentricity and precession. Angles  $o$  and  $p$  are given in °.

## 6.5 Sea level

In the model, two processes impact the sea level:

- Thermal expansion, which depends on the ocean temperature  $T_{oce}$ .
- The ice sheet melting, which depends on the ice sheet extent  $\phi_g$ .

We note by  $N(t)$  the sea level anomaly with respect to the present-day level:  $N(t) = H_{mer}(t) - H_{mer,actuel}$ , where  $H_{mer}$  is the average sea depth

The average sea depth is calculated as:

$$H_{mer} = \alpha(T_{oce}) \cdot \frac{M_{mer}}{S_{mer}}$$

where  $\alpha(T_{oce})$  is the volumetric mass of water at temperature  $T_{oce}$ ,  $T_{oce}$  is the global-mean ocean temperature, which is supposed to be an average of the global surface temperatures over the previous 100 years,  $M_{mer}$  the total sea water mass and  $S_{mer}$  the surface of ocean basins.

- We calculate  $\alpha(T_{oce})$  assuming a linear relationship as a function of  $T_{oce}$ , given the thermal expansion coefficient  $c = 2.6 \cdot 10^{-4} / ^\circ C$ :

$$\alpha(T_{oce}) = \alpha(T_{oce,actuel}) (1 + c \cdot (T_{oce} - T_{oce,actuel}))$$

- We calculate  $\frac{M_{mer}}{S_{mer}}$  by a mass balance: let  $M_{tot}$  be the total mass of the water in the system {ice sheets + ocean}, and  $f(\phi_g)$  the fraction of this water trapped in ice sheets. We have:

$$M_{mer} = M_{tot} \cdot (1 - f(\phi_g))$$

Assuming that the surface of the ocean basins is constant, we get:

$$\frac{M_{mer}}{S_{mer}} = H_{tot} \cdot (1 - f(\phi_g))$$

where  $H_{tot}$  is the average sea depth if all ice sheets had melted. We take  $H_{tot} = 3.8\text{km}$  ([Herring and Clarke, 1971]). Therefore:

$$H_{mer} = (1 + c \cdot (T_{oce} - T_{oce,actuel})) \cdot H_{tot} \cdot (1 - f(\phi_g))$$

The fraction  $f(\phi_g)$  is proportional to the area covered between the latitude  $\phi_g$  and the poles:  $1 - \cos(90 - \phi_g)$ . We also assume that ice thickness increases as the latitude of the ice caps approaches the equator, according to a function in  $(1 - \phi_g/90)^{n_{mer}}$  with  $n_{mer}$  a parameter adjusted to meet the constraints summarized in section 2.1. So:

$$f(\phi_g) = (1 - \cos(90 - \phi_g)) \cdot (1 - \phi_g/90)^{n_{mer}}$$

## Acknowledgments

The application was developed by the Cabinet d'Études Informatiques Alain Deseine - <https://www.cabinfo.eu/>. This work was supported by the IPSL – Climate Graduate School which is funded by the ANR (ANR-11-IDEX-0004 - 17-EURE-0006).

I thank Jean-Louis Dufresne for discussions on the physical content of the software, Marion Saint-Lu, Michael Jentzer, Mathieu Rajchenbach and Robin Bosdeveix for discussions on educational use of the software, Mathilde Tricoire for comments on this documentation, Nicolas Gama for coding the first versions of the graphical interface in 2006-2007, Hakim Mamor for coding the Météo-France version of the graphical interface in 2011, Météo-France (and Germaine Rochas) for hosting the software from 2011 to 2019. Thanks also to the many users who reported bugs!

## References

- [Berner, 2003] Berner, R. A. (2003). Overview the long-term carbon cycle, fossil fuels and atmospheric composition. *nature*, 426:323–326. [6.3.1](#)
- [Dufresne and Bony, 2008] Dufresne, J.-L. and Bony, S. (2008). An assessment of the primary sources of spread of global warming estimates from coupled atmosphere-ocean models. *J. Clim.* [2.1](#), [16](#)
- [Herring and Clarke, 1971] Herring, P. J. and Clarke, M. R. (1971). Deep oceans. *New York: Praeger Publishers*, 13. [6.5](#)
- [IPCC, 2013] IPCC (2013). *Climate Change 2013: The Physical Science Basis*. T. F. Stocker, D. Qin, G. -K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex & P. M. Midgley (Eds.), Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. doi:10.1017/CBO9781107415324. [4.1](#), [15](#), [17](#)
- [Masson-Delmotte et al., 2015] Masson-Delmotte, V., Braconnot, P., Kageyama, M., and Sepulchre, P. (2015). Qu’apprend-on des grands changements climatiques passés ? *La Météorologie*, 88:25–35. [3.2.3](#)
- [Masson-Delmotte and Chapellaz, 2002] Masson-Delmotte, V. and Chapellaz, J. (2002). Au coeur de la glace, les secrets du climat. *La Météorologie*, 37:18–25. [3.2.3](#)
- [Myhre et al., 1998] Myhre, G., Highwood, E. J., Shine, K. P., and Stordal, F. (1998). New estimates of radiative forcing due to well mixed greenhouse gases. *Geophysical research letters*, 25(14):2715–2718. [6.2.2](#)
- [Pierrehumbert et al., 2006] Pierrehumbert, R. T., Brogniez, H., and Roca, R. (2006). On the relative humidity of the atmosphere. *The Global Circulation of the Atmosphere*, Princeton Univ. Press, Princeton, N. J.:143–185. [6.2.2](#)
- [Risi, 2015] Risi, C. (2015). Simclimat, un logiciel pédagogique de simulation du climat. *La Météorologie*, 88:15–19. [\(document\)](#)
- [Taylor et al., 2012] Taylor, K. E., Stouffer, R. J., and Meehl, G. A. (2012). An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society*, 93(4):485–498. [4.1](#)