SimClimat documentation

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A web version of this documentation is on 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

1 Graphical interface

1.1 Supported platforms

SimClimat works on:

- personal computers with Windows, Mac or linux
- 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°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 ° C, the CO_2 concentration is 280 ppm, the sea level of -0.2m , CO_2 emissions are null.

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

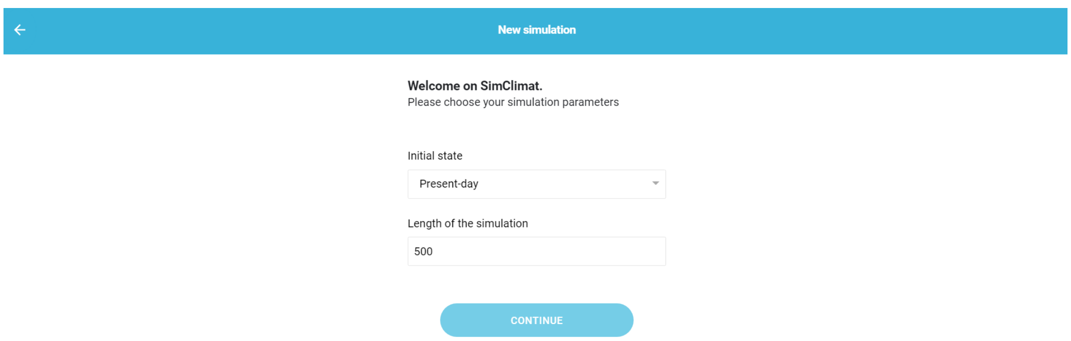

Figure 2: Screenshot of the page where the intial state and the duration can be chosen, with Windows.

3. "*The final state of the previous simulation*": This allows to continue the previous simulation.
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 wants 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.

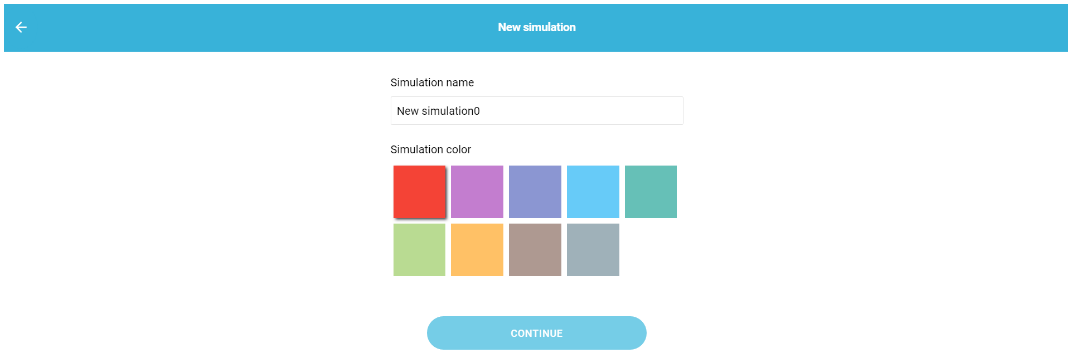

Figure 3: Screenshot of the page where the simulation name and color can be chosen, withWindows.

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).

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

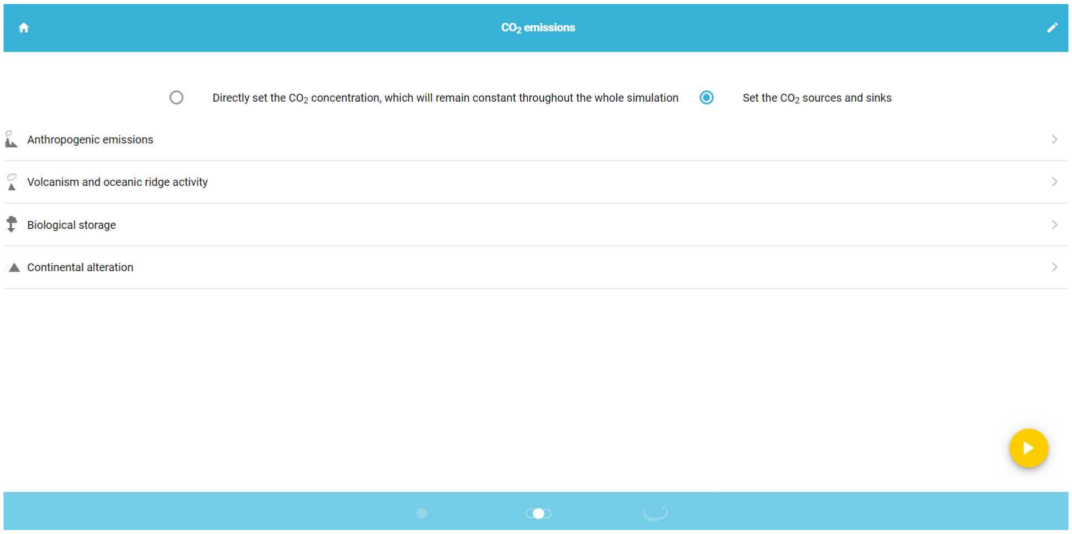

Figure 4: Screenshot of the page where parameters associated with the carbon cycle can be chosen, on Linux.

- 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 7).

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
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.

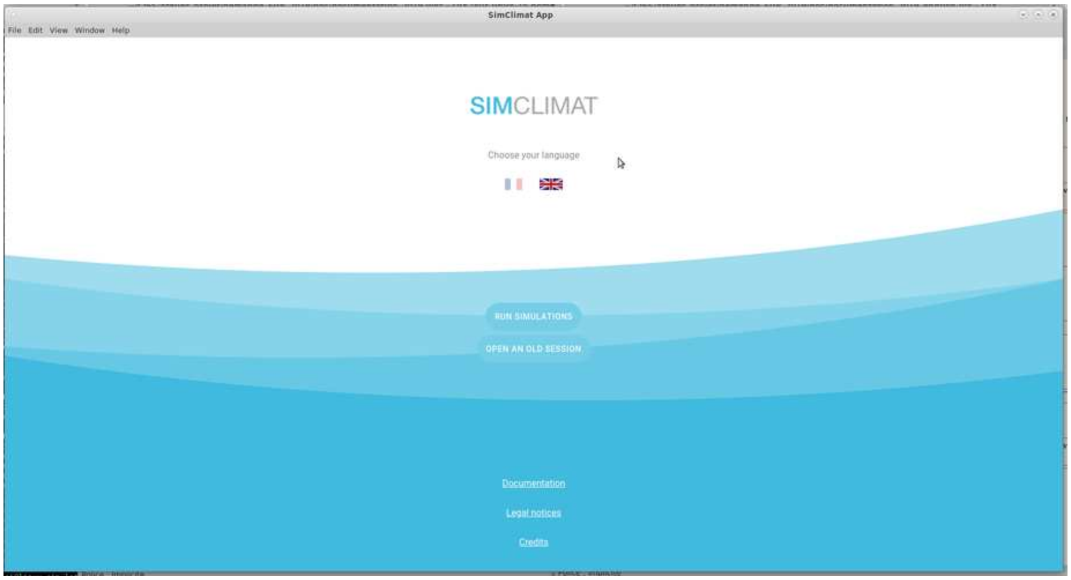

Figure 5: Screenshot of the page where results are displayed, on Linux.

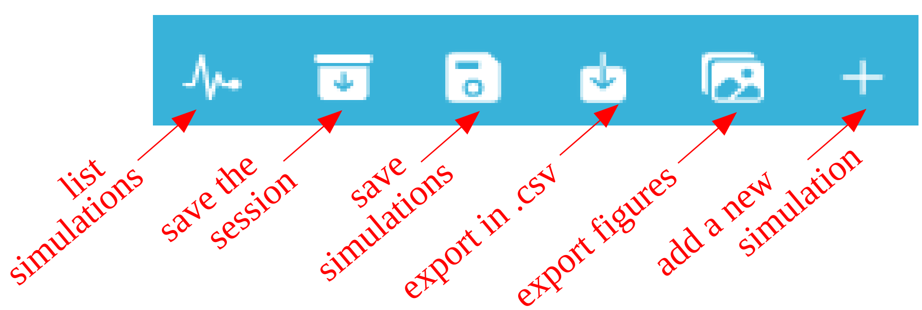

Figure 6: Zoom on the options at the top-right corner of the deiplay page, on Linux.

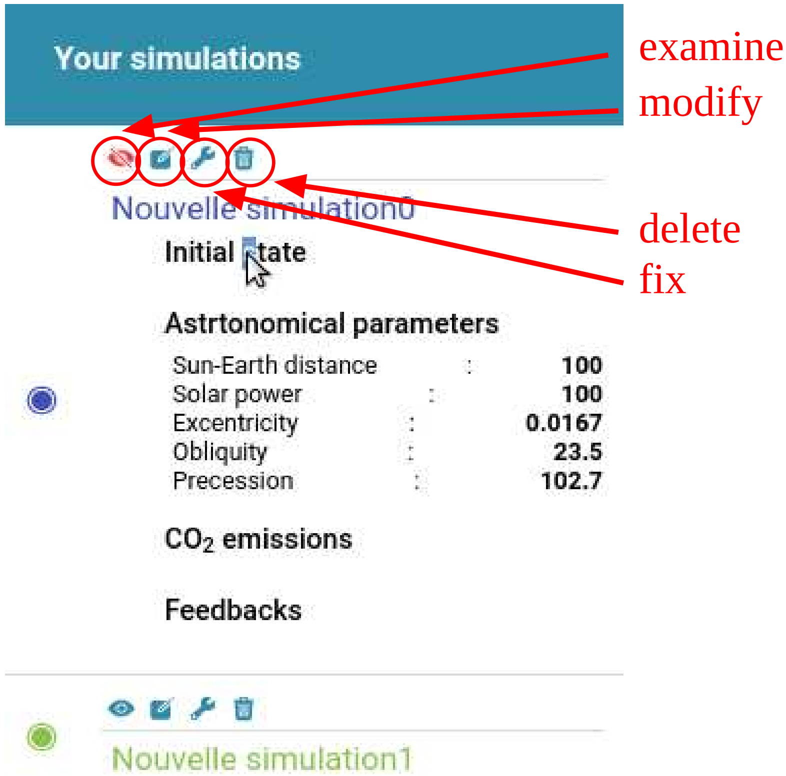

Figure 7: Zoom on the page where results are displayed, when the “Edit simulations” icon is activated, on Linux.

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 scheet. 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.
- Modifiy 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.

- 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 simulations, simulation results, or a session:
  - Save a simulation to continue it later: In the display page, click on the ”disk” icon (figure 6).
  - Save the full session: big “save” icon (figure 6). To re-run it later, choose «Re-open an old session» in the home page (figure 1).
  - Export numerical results from simulations in .csv format: small “save” icon » (figure 6)
  - Export graphical results from simulations in .png format: “draw” icon (figure 6)
  - Continue a saved simulation: As initial state, chose «Fianl state of a saved simulation».
- Continue a saved simulation: Choose as initial state: “initial 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:

- 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.

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.

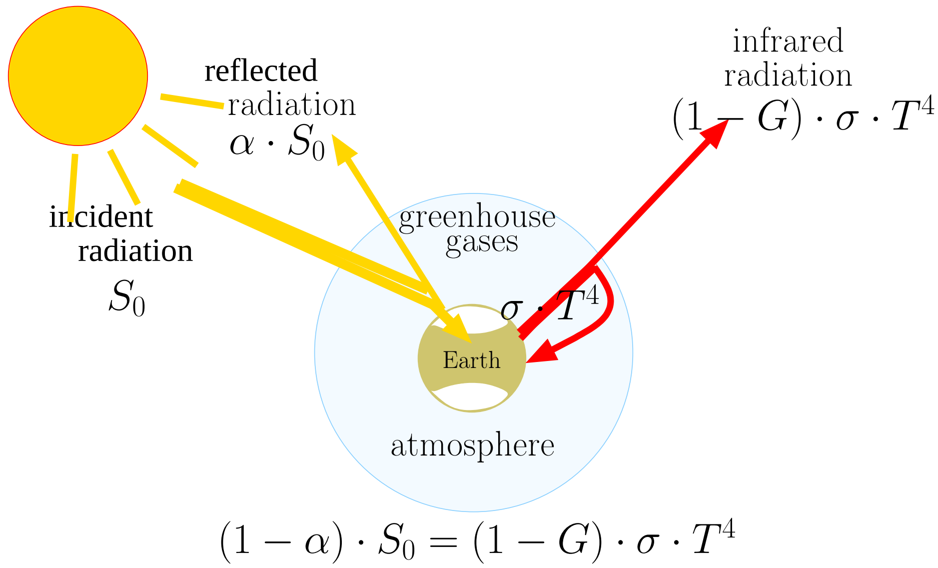

Figure 8: Global radiative equilibrium model.

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 8):

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

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:

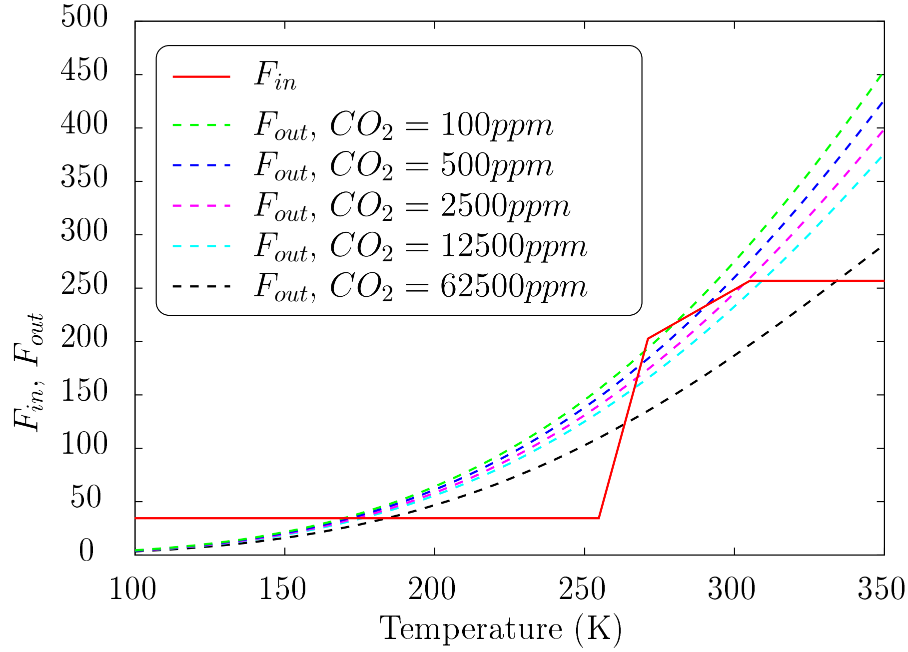

Figure 9: Absorbed solar radiation (F_{in}) and infra-red radiation emitted by the Earth (F_{out}), as a function of temperature. Radiative equilibrium is reached for intersection points between $F_{in}(T)$ and $F_{out}(T)$ curves.

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;
σ is Stefan-Boltzmann's constant.
This relationship is illustrated for different CO_2 concentration in figure 9.

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 9).
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 5.1).

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 10.

2.4.1 Greenhouse effect

The greenhouse effect G is decomposed into two components: the greenhouse effect associated with CO_2 ($G^{serre}_{CO_2}$) and that associated with water vapor ($G^{serre}_{H_2O}$) (section 5.2.1).

- The greenhouse effect associated with the water vapor is calculated according to the water vapor concentration R_{H_2O} (section 5.2.3), which is calculated as a function of temperature (section 5.2.4).
- The greenhouse effect associated with CO_2 is calculated as a function of CO_2 concentration (section 5.2.2). This concentration is calculated from CO_2 sources and sinks (anthropogenic emissions, volcanism, continental

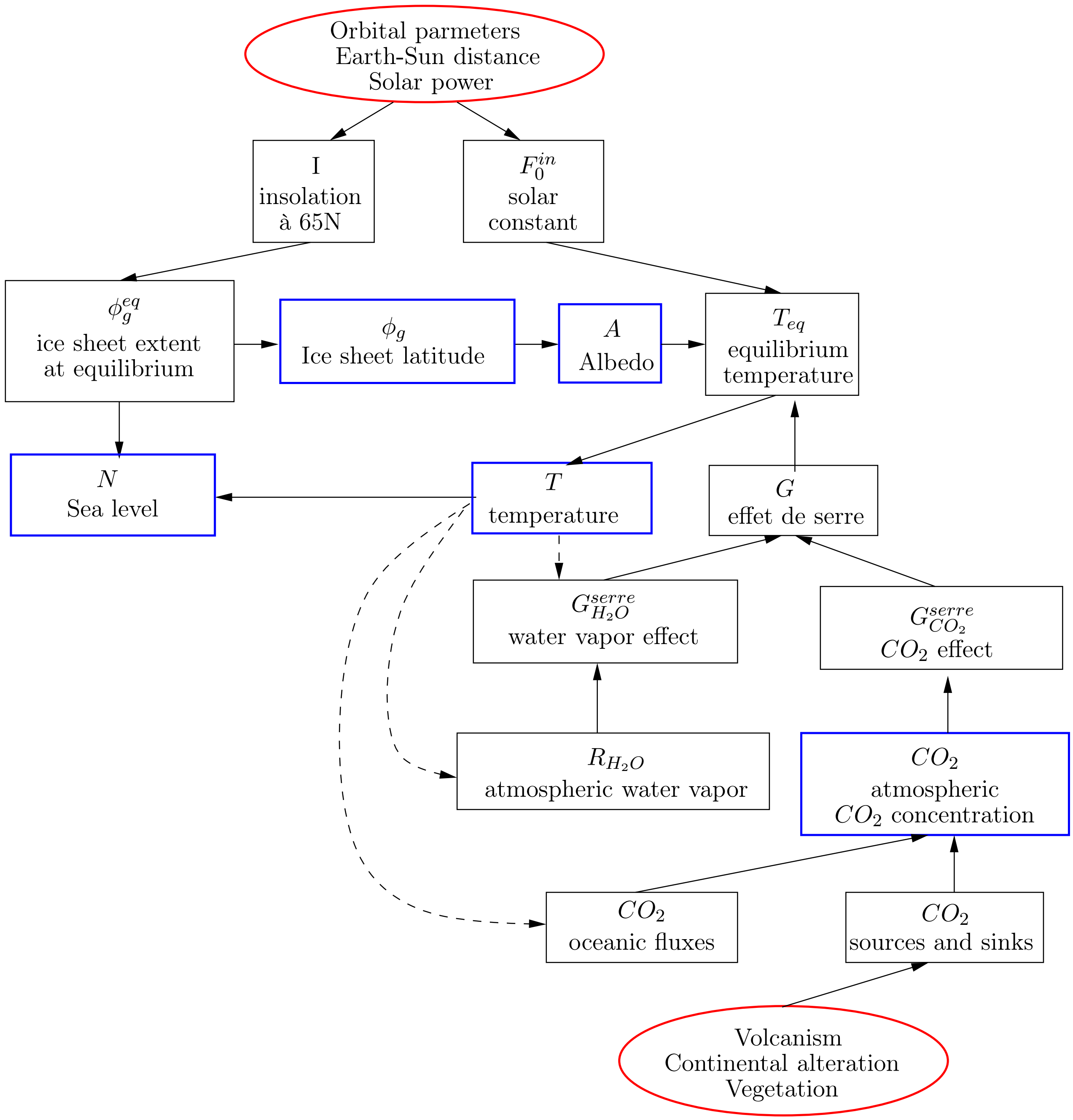

Figure 10: Diagram illustrating how the different variables are computed in the model. In red: external forcing on the climate system. In blue: state variables.

alteration, biological storage, storage by the ocean) (section 5.3). The CO_2 solubility in the ocean is a function of temperature (5.3.2).

2.4.2 Albedo

Albedo A is calculated as a function of ice sheet extent ϕ_g (section 5.4.1). This extent is calculated as a function of temperature and of the insolation at 65°N I (section 5.4.2). 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 5.5).

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 cause 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 10).
- *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 11, 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 11, 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 11, 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 11, 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 12).

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

Step 1: role of orbital parameters

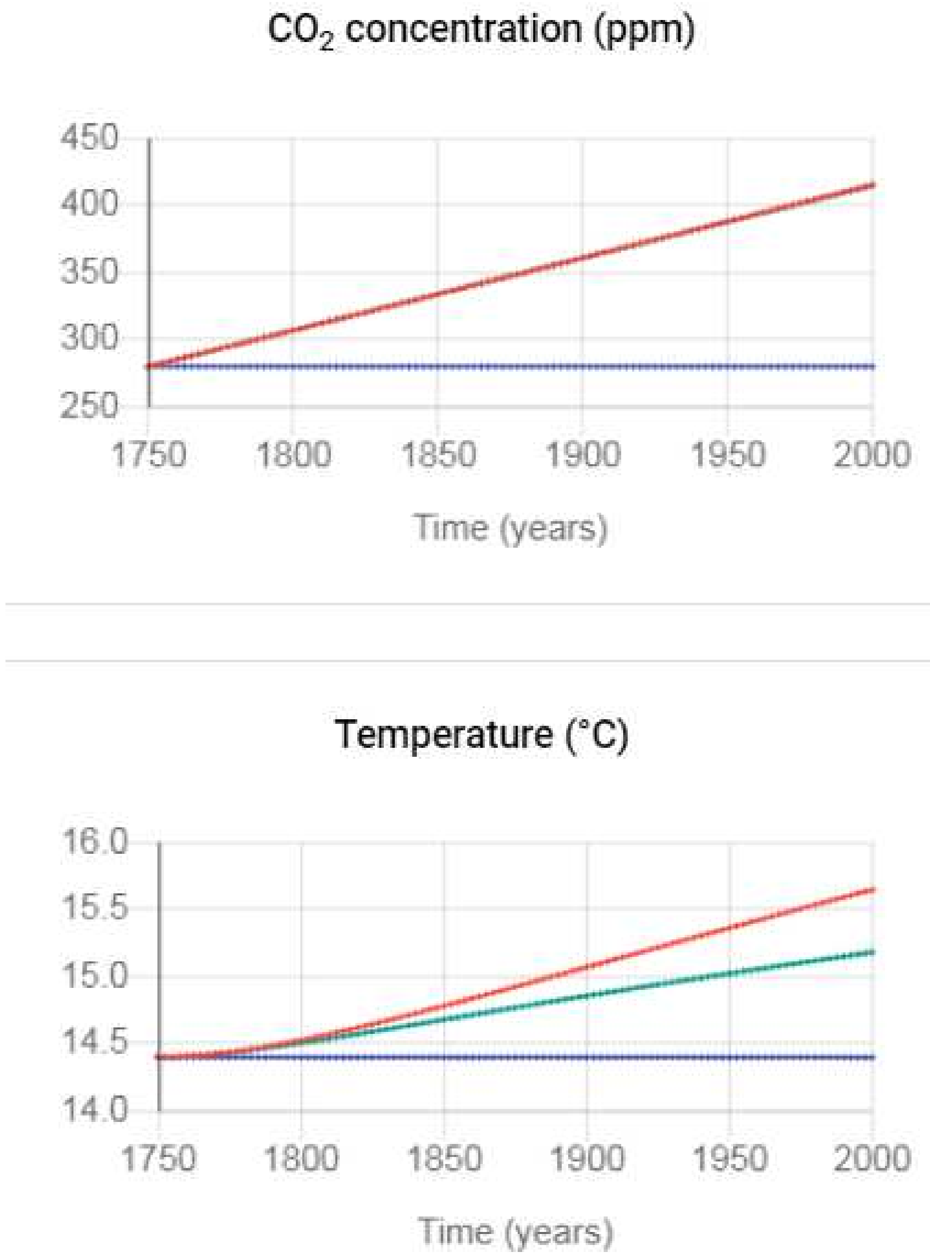

Figure 11: Screenshot of the results for a pre-industrial simulation with constant CO_2 concentration (blue) and with anthropogenic emissions that lead to the current CO_2 concentration (red). The green simulation is identical to the red one, except that the water vapor feedback has been "disconnected" by keeping the water vapor concentration constant. Note that for the CO_2 concentration, the green curve is hiden by the red curve.

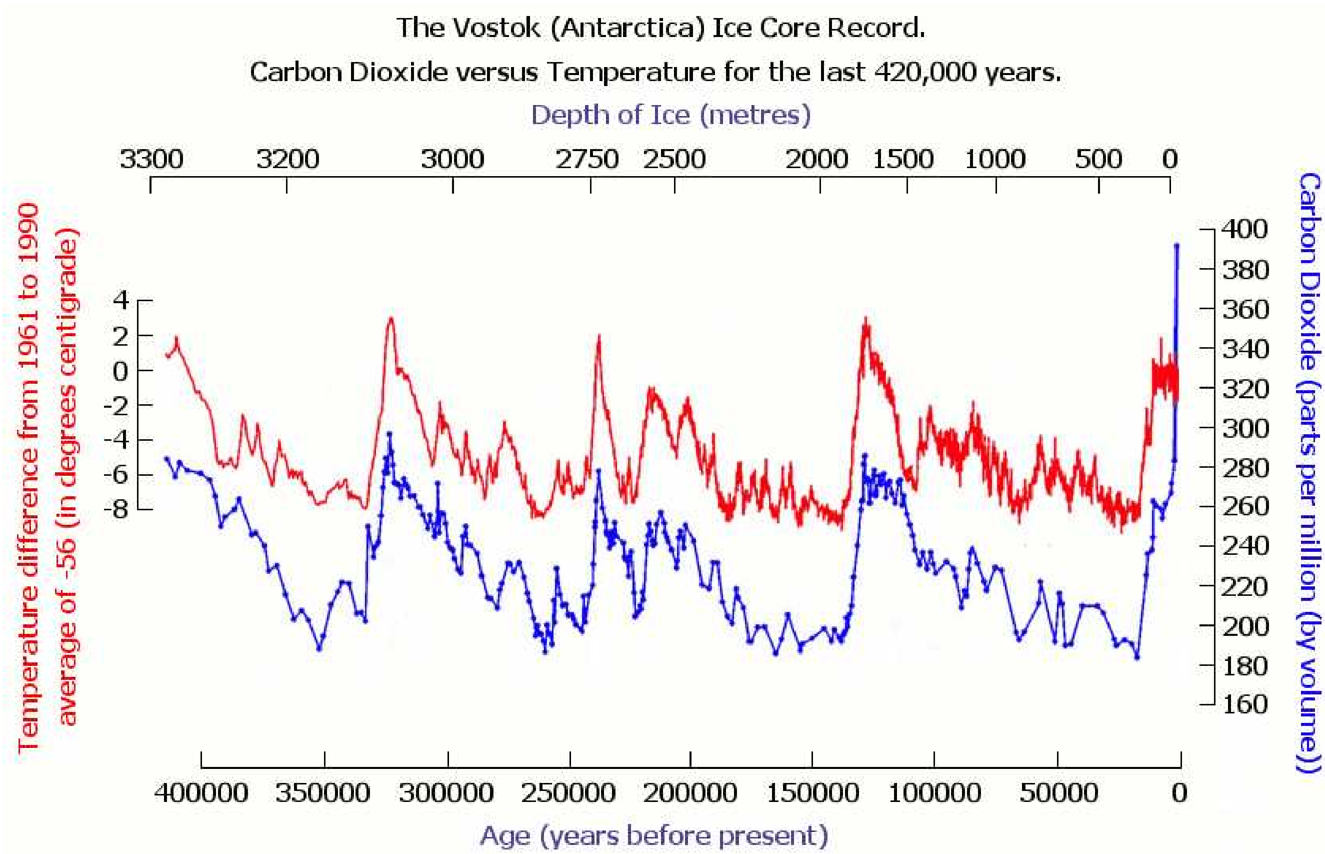

Figure 12: Variations in temperature and CO_2 concentration recorded in Vostok ice core in Antarctica.

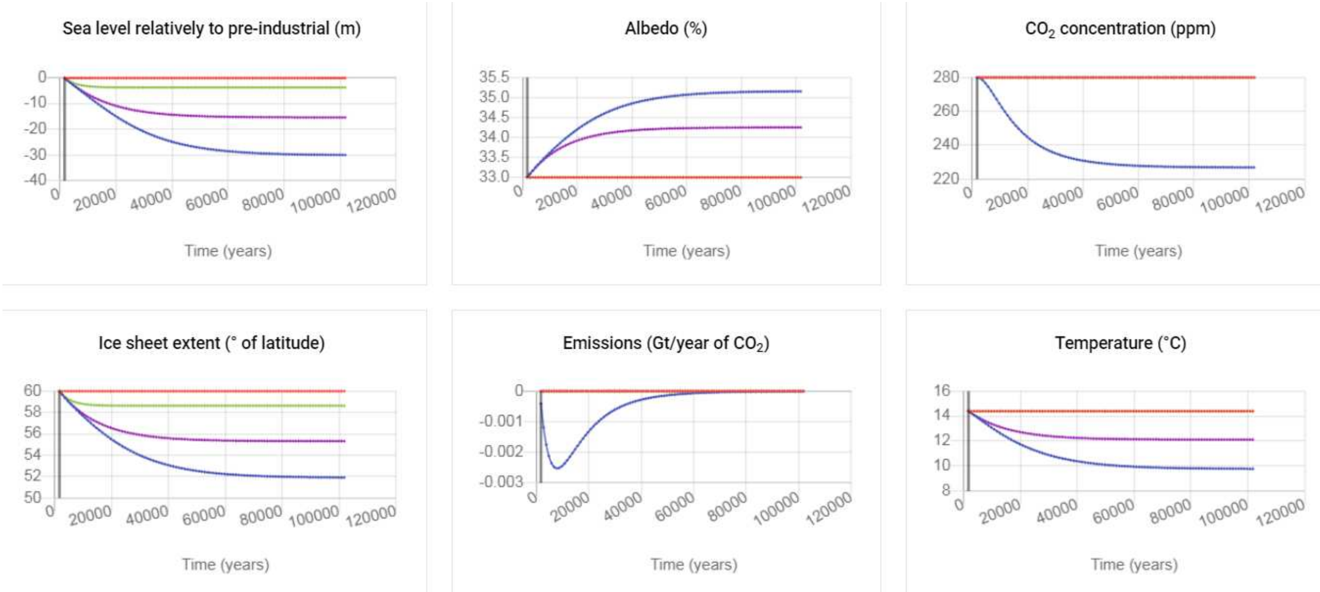

Figure 13: Screenshot of the results of a pre-industrial control simulation of 100,000 years (red), with minimal obliquity (blue), with minimal obliquity and constant albedo (green) and with minimal obliquity and the CO_2 solubility in the ocean that does not depend on temperature (purple). Note that in panels where the green and purple curves are absent, they are actually hidden by the red curve.

- *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).
- *Question*: Can variations in orbital parameters lead to temperature variations consistent with those observed during glacial-interglacial cycles (i. e., 5°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 13, 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 13, blue).
- *Result*: The temperature decreases by several °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?
- *Hypothes*is: 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 13, 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 13, 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 12). 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 13, 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 13, 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.

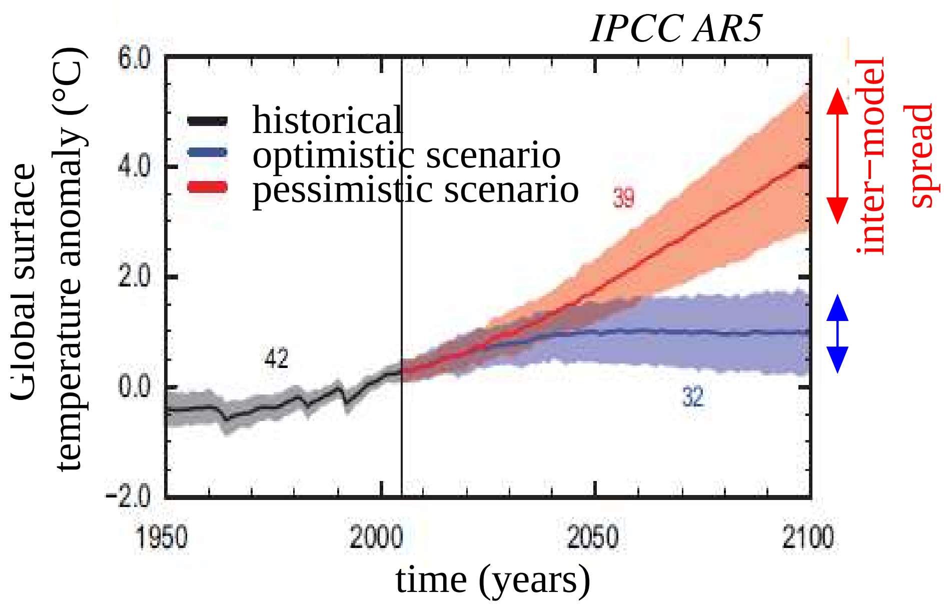

Figure 14: Temperature evolution from 1950 to 2100 simulated by models participating in CMIP5. Until the early 2000s, the simulations are forced by observed concentrations of greenhouse gases and aerosols. Beyond, simulations are forced according to two types of scenarios: optimistic (blue) or pessimistic (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 14) 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 15, 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 15, purple frame). This allows SimClimat to represent climate changes at geological time scales.

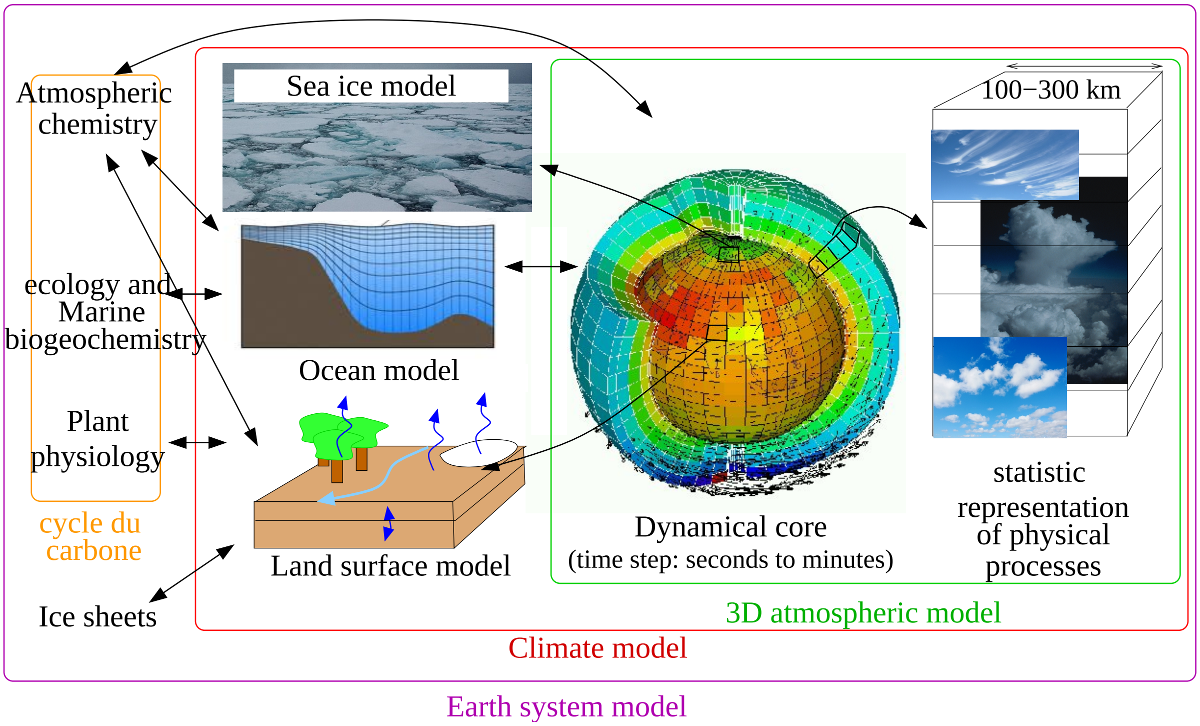

Figure 15: Schematic illustrating the different components of a climate model.

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 16).

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 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 17a). These proportions are reproduced by SimClimat (figure 17c). However, SimClimat does not represent cloud feedbacks, which account for nearly a quarter of global warming, but is subject to high uncertainty (figure 17b).

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 18).

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 18a).

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.

4.7 Arrêt des émissions de CO_2

What happens if we stop emitting greenhouse gases all at once, given that the Earth's climate is currently out of equilibrium? Will the climate continue to warm by inertia? If so, for how long? How long will it be before we return to pre-industrial temperatures and CO_2 levels? These are the questions that motivated the ZECMIP (Zero Emission Commitment Model Intercompaison Project) intercomparison exercise [MacDougall et al., 2020].

According to the results of this project, as soon as emissions stop, the CO_2 concentration decreases exponentially (figure 19a). The anthropogenic atmospheric CO_2 is absorbed by vegetation and the ocean, reaching its pre-industrial value over a period of 200 to 1 000 years (figure 19c). Temperature response varies widely from model to model (figures 19b,d), with either a slowdown in warming or a cooling back to a pre-industrial climate after 200 to 1 000 years.

At present, SimClimat simulates a reduction in CO_2 concentration that is far too slow (figures 19e,g), and the persistence of excessive global warming despite the halting of emissions (figures 19f,h). SimClimat does manage to return to its pre-industrial equilibrium state, but only after 100,000 years. This excessive climate inertia therefore limits SimClimat's applicability for this type of simulation. This problem will be addressed in future maintenance releases.

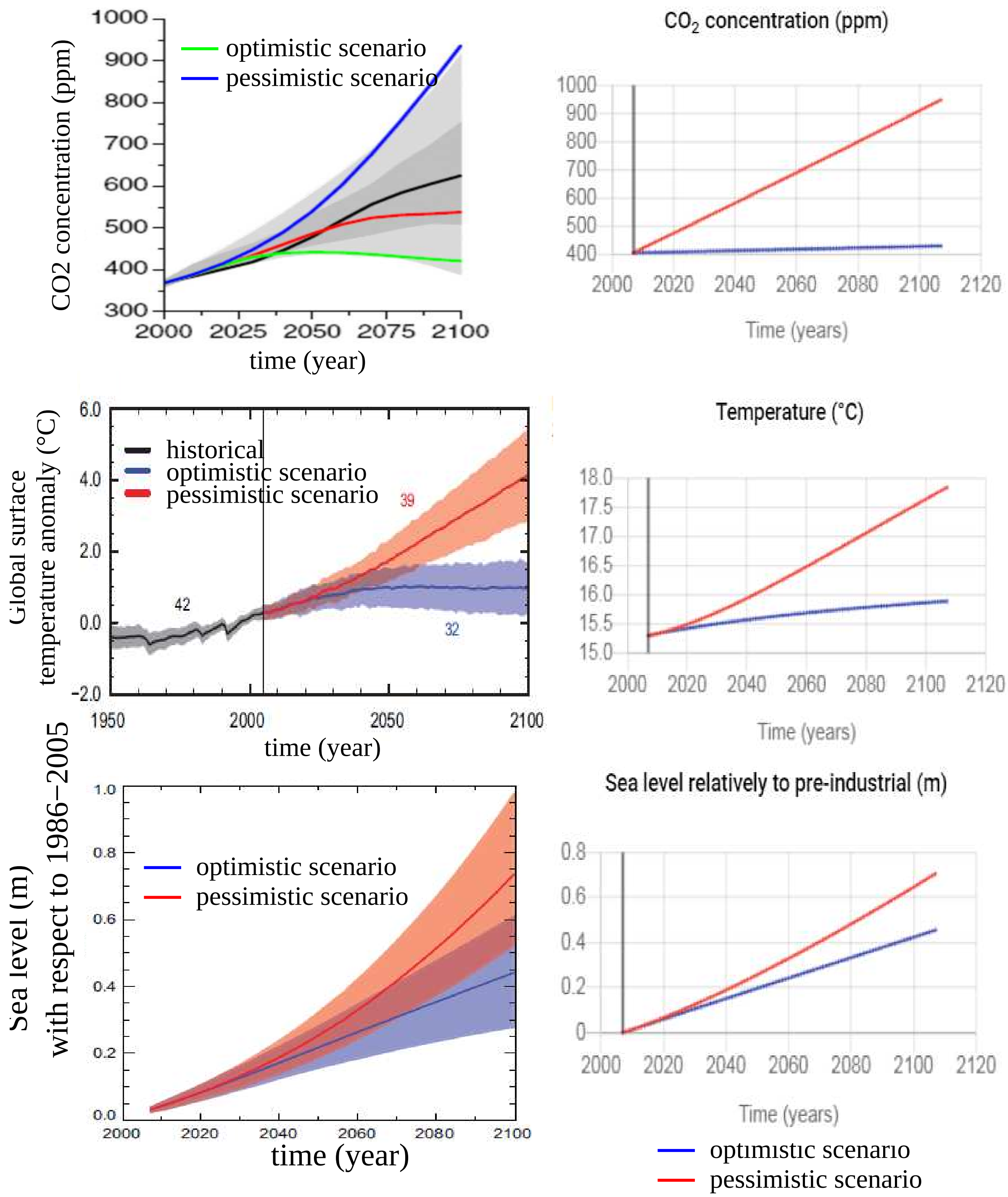

Figure 16: Comparison of projections produced by SimClimat and by models participating in CMIP. The left column presents the results shown in the 5th IPCC report ([IPCC, 2013]). The right column shows screenshots of SimClimat. The curves show the evolution of the CO_2 concentration according to optimistic 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.

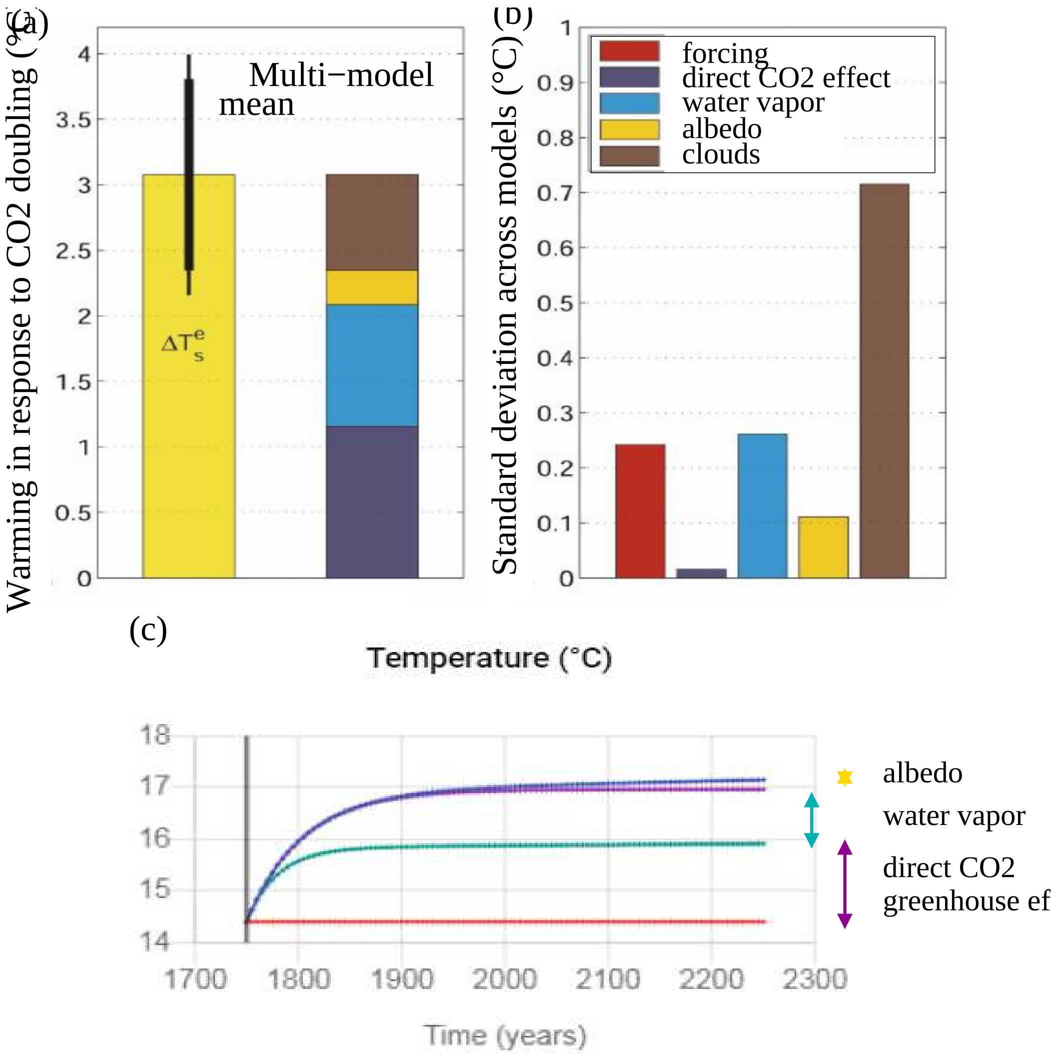

Figure 17: Comparison of climate feedbacks for a CO_2 doubling simulated by SimClimat and by climate models participating to CMIP. (a) Global warming and its contributions simulated by climate models in average. (b) Standard deviation of the different contributions to the warming simulated across the 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].

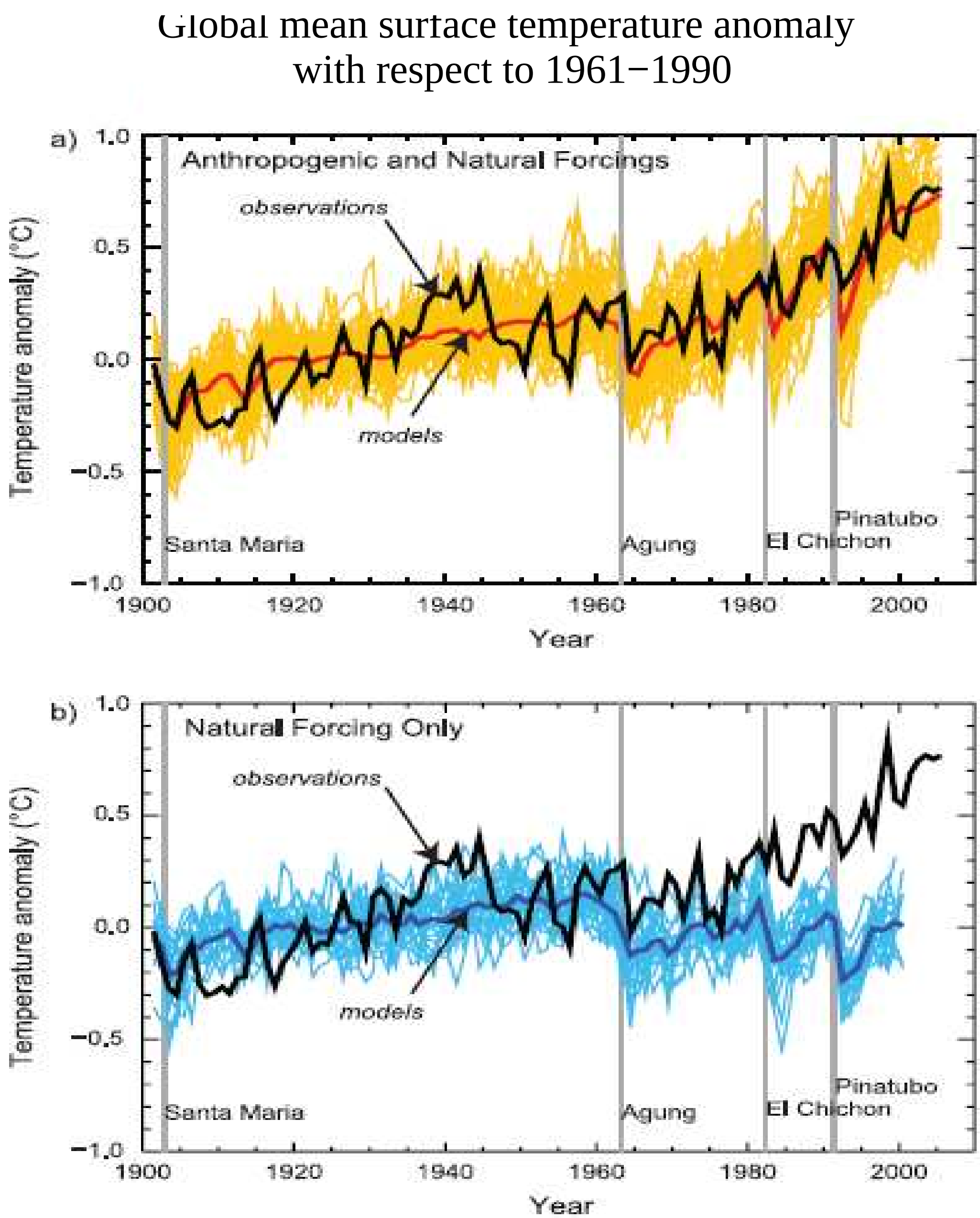

Figure 18: (a) Evolution of the global-mean temperature since 1900 for observations (black), for models participating in CMIP (yellow) and for the average between all CMIP models (red), when the greenhouse gas concentrations increase in the same way as in the observations. (b) Change in global temperature 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]).

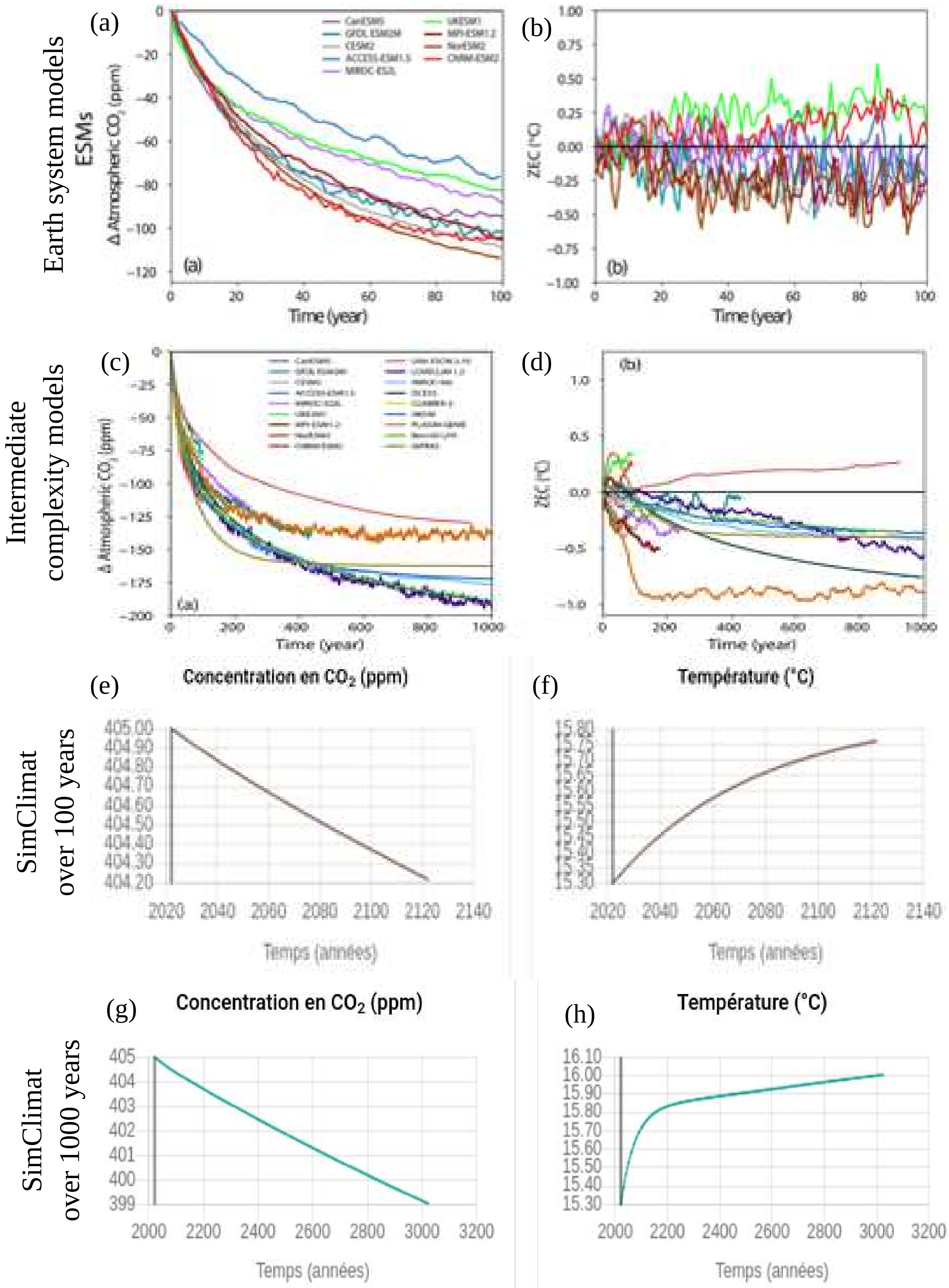

Figure 19: Results from the ZECMIP project: evolution of CO_2 concentration (a, c) and temperature (b,d) over time after total shutdown of emissions, anomalous with respect to initial values just before shutdown, simulated over 100 years by Earth system models (a-b) and over 1 000 years by models of intermediate complexity (c-d). Comparison with SimClimat over 100 years (e-f) and 1 000 years (g-h) under the same conditions.

5 Appendix: equation details for the physical model

5.1 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 $\tau_T = 30$ years:

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

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

5.2 The greenhouse effect

5.2.1 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:

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

where $G^{serre}_{H_2O}$ is the greenhouse effect anomaly with respect to the reference related to the water vapor concentration anomaly and $G^{serre}_{Co_2}$ is that related to the CO_2 concentration anomaly.

5.2.2 The greenhouse effect related to CO_2 as a function of CO_2 concentration

$G^{serre}_{Co_2}$ is calculated as a function of CO_2 concentration: $CO_2(t)$. In the "usual" CO2 concentration range (between 100 and 10,000 ppm), we assume a logarithmic relationship between $G^{serre}_{Co_2}$ and $CO_2(t)$ ([Myhre et al., 1998, Pierrehumbert et al., 2006]):

$$G^{serre}_{Co_2} = a_{CO_2} \cdot ln(\frac{CO_2(t)}{CO_2^{ref}})$$

The a_{CO_2} factor is adjusted to obtain realistic climate projections, and is currently set at 2.210^{-2}. Around this range, a linear approximation extends the logarithmic relationship.

The effect of the CO_2 concentration on he infra-red energy emitted by the Earth escaping to the space (F_{out}) is illustrated in figure 9.

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

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

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

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 $p = 0.23$.

5.2.4 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$T_{ref} = 14.4°C$.

5.3 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 (10^9t) 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.

5.3.1 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]).

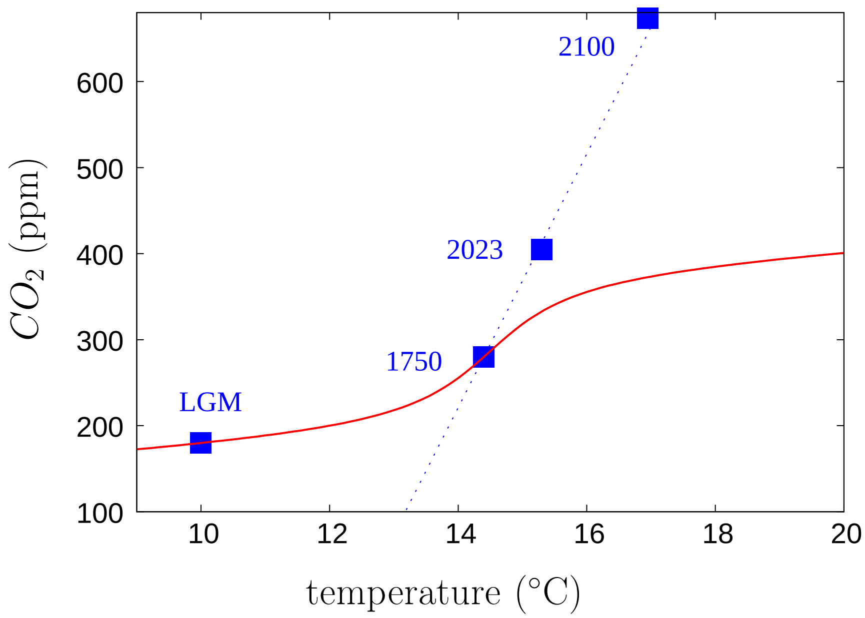

Figure 20: Curve of CO_2^{eq} versus temperature used to represent the sensitivity of CO_2 in the ocean. The LGM represents the last glacial maximum, 1750 the pre-industrial era, 2023 the current climate and 2100 the climate projection according to a pessimistic scenario.

5.3.2 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 τ_{oce} is the relaxation time scale of the CO_2 concentration towards this equilibrium.

$CO_2^{eq}(T)$ is parameterized according to the temperature according to this equation:

This curve is shown in figure 20. Parameters a, b, c, T_c are chosen according to the following constraints:

- At pre-industrial temperature, CO_2^{eq} corresponds to the pre-industrial atmospheric concentration;
- a 10°C cooling (of the interglacial-glacial type) induces a decrease in CO_2 concentration to 180 ppm;
- The model simulates an increase of 1°C for an increase of 90 ppm between the pre-industrial period and the present day.
- For the model to return to pre-industrial equilibrium when CO_2 emissions are stopped (ZECMIP-type experiment, section 4.7), CO_2^{eq} must increase less rapidly with temperature than in the current global warming (figure 20).

5.3.3 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%.

5.4 Albedo and ice sheets

5.4.1 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 5.4.2, explains the shape of the F_{in} curve (the solar energy absorbed by the Earth) as a function of temperature in figure 9.

5.4.2 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 ϕ_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 5.4.3).

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 τ_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 ϕ_g^{eq} with the time constant τ_g:

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

5.4.3 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 °.

5.5 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 ϕ_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$c = 2.6 \cdot 10^{-4}/°C$:

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

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

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

We parameterize $f(\phi_g)$ by a 3rd-degree polynomial function so as to respect the constraints summarized in section 2.1.

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