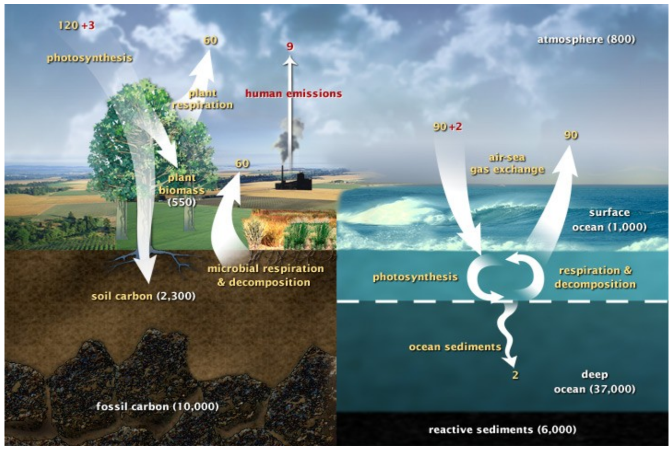
Idealized modeling of the carbon cycle in the simplified model of an educational software.

Carbon is a key component of the Earth climate. It goes from a reservoir to another, on different timescales. It can be emitted by volcanoes and biosphere; then a part of the emissions is used by vegetation for photosynthesis, another part is stored in the soils, another one is absorbed by the ocean, another one is stored by rocks, etc. These reservoirs then release the carbon they stored by biomass fires, weathering, ocean release, etc. This constitutes the carbon cycle.



To the volcanoes and biosphere emissions are added the anthropogenic carbon emissions, which have been substantially rising since the industrialization. They do not only affect the atmosphere but also the ocean, the vegetation and the soils, via the carbon cycle mechanisms.

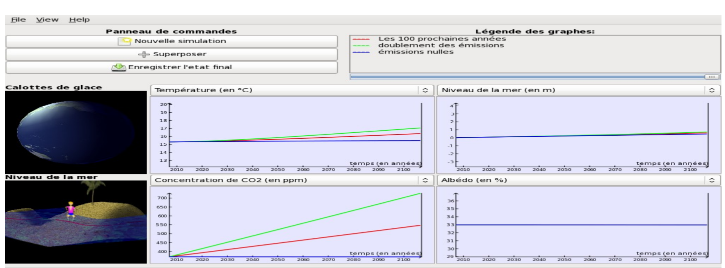
It is thus important to know how the various reservoirs react to changes in CO_2 emissions: how the emissions are distributed, after how long they are absorbed by a reservoir, and how the distribution between the reservoirs and their behavior change with global warming.

The internship is based on the highly simplified climate model from the educational software SimClimat. The software already offers a modeling of the carbon cycle, but it can be redesigned in order to be clearer with more physical sense, still keeping its simplicity.

For this internship, equations from literature will be used to re-compute the carbon cycle in a very simple way in the model of the SimClimat software.

□□□

The main goal is to apply our software to the carbon cycle comprehension. Thanks to this internship, the student will firstly acquire a better knowing of the carbon cycle and of its modifications following a disruption. The student will also learn some aspects of climate modeling.



Supplementary notes for the supervisor

Reference papers:

Joos, F., and Bruno, M., 1996: Pulse response functions are cost-efficient tools to model the link between carbon emissions, atmospheric CO_2 and global warming. *Physics and chemistry of the Earth*, 21(5), 471-476, doi: 10.1016/S0079-1946(97)81144-5.

Main concept to be explained to the student: the carbon cycle and its different time scales

The carbon cycle in SimClimat at the current state:

Related equations (see the model documentation for explanations (in french): http://www.lmd.jussieu.fr/~crlmd/simclimat/logiciel_documentation.pdf):

CO_2 concentration: $CO_2(t) = CO_2(t\text{-}dt) + F(t) \,.\, CO_2^{act}/M_{CO2}^{act} \,.\, dt$

With: $F(t) = (E_{anthr} + E_{volc} - (s_{alt} + s_{bio})\, CO_2(t))\,(1 - puits_{bio} - puits_{oce}) + F_{oce}\,(1- puits_{bio})$

Where $puits_{bio}$ represents absorption by the vegetation (photosynthesis) and s_{bio} represents biological storage (organic matter). $Puits_{oce}$ represents the absorption by the superficial ocean layer and $F_{oce}\,(1 - puits_{bio})$ the carbon exchange between the ocean and the atmosphere.

And: $F_{oce} = 1/\tau_{oce} \,.\, CO_2^{act}/M_{CO2}^{act}\,(CO_2^{eq}(T) - CO_2(t))$

Where $CO_2^{eq}(T)$ is defined as the CO_2 concentration which is in equilibrium with the ocean in terms of temperature; it represents the fact that the carbon solubility in the ocean depends on the temperature, that is that the ocean releases carbon when it warms, and pumps it when it cools. This variable is parametrized so that:

- A 10°C cooling (corresponding to the Last Glacial Maximum) induces a reduction of CO_2 toward 180 ppm.

- A CO_2 rising of 90 ppm (corresponding to the difference between the pre-industrial period and 2007) leads to a warming of 1°C.

Problems and ideas to improve the model

There are two main ideas:

1) Redesigning the carbon concentration calculation

The model considers two types of sinks:
- the oceanic and biological sinks,
- the storage in rocks and organic matter.

The first one is represented by imposing that a given percentage of emissions goes directly into these sinks. The second one is a function of the CO_2 concentration.

The main difference between these 2 categories is the timescale at which they play a role. They can also be designed as CO_2 decaying functions, with exponential shapes. This has been shown in a paper (the "Reference paper", see above), in which decaying functions "r" are suggested, and can be simplified as exponential functions.

Here we suggest to use the equations of this paper, to discretize them and to use exponential functions as decaying functions "r". The CO_2 concentration can then be computed at each time step from the previous and the initial time steps. Calculations of emissions and fluxes would not be changed.

2) Redesigning the ocean-atmosphere carbon flux

In the model, the 2007 CO_2 concentration (90 ppm more than the pre-industrial level) is used to parametrize the variable $CO_2^{eq}(T)$, in order to impose that such an increase in CO2 leads to a rising of the temperature of 1°C. The problem here is that the 2007 CO_2 concentration mainly comes from human emissions, not from ocean release. Using it to parametrize $CO_2^{eq}(T)$ as it is done in the model means that the current CO_2 level is in equilibrium with the ocean. Thus, it means that an increase of 1°C would lead to an ocean release of 90 ppm of CO_2, which is not the case.

The idea would be to use a proportion of atmospheric CO_2 which is solved in the ocean, depending on the temperature, inspiring from the Henry law.

Approximate stages of the internship:

- Introducing the software, and the theoretical concepts (see previous section).

- Introducing the related equations of the SimClimat model (see the previous section).

- Introducing the reference paper and its equations

- The study in itself, that is the first point « Redesigning the carbon concentration calculation » (see the previous section « problems and ideas to improve the model ») including:

    - Discretizing the equations in order to go from the analytic version to the numeric version.

    - Finding great decaying functions “r”, which may be exponential functions, thus finding the good arguments in the exponential so that the function has a realistic decay timescale. This implies that this realistic timescale has to be found in the literature.

    - Examining if the new version is better or less good or as good as the previous version. This implies a reflection on the judgment criterion (efficiency or degree of realism...).

    - Guiding the approach according to the model purpose, which is in our case educational. Then, we will try to reproduce the carbon cycle rather than to use its exact physical equations.

- If time is left, the student can begin the second part of the study, that is “Redesigning the ocean-atmosphere carbon flux” (see the previous section “problems and ideas to improve the model”)

Correspondences between the variables names in the documentation and in the code:

CO2(t)=CO2(t-dt)+F(t)CO2actMCO2actdt

gives in the code: zCO2=zCO2_ancien+emission_coo_ppm × dt

with: emission_coo_ppm=zsomme_flux × (concentration_coo_actuel/coo_Gt_act)

so that F(t) in the documentation is zsomme_flux in the code.

And:

Ft=Emissionsanthr+Emissionsvolc1-puitsbio-puitsoce-salt.CO2t+sbio.CO2t1-puitsbio-puitsoce+Foce1-puitsbio

gives in the code:

zsomme_flux=(s.emit_anthro_coo_value+s.volcan_value)(1-zpuit_bio-zpuit_oce)+(zC_alteration × zCO2_ancien+zC_stockage × zCO2_ancien))(1-zpuit_bio-zpuit_oce)+(zCO2eq_oce-zCO2_ancien)(1-zpuit_bio)zB_ocean+Fdegaz

where:

- zB_ocean is a function of the latitude of the ice-sheet, so that the exchanges between ocean and atmosphere depend on the surface covered by the ocean;

- zCO2eq_oce and zCO2_ancien are respectively the CO_2 concentration in equilibrium with the ocean at time t-dt and the CO_2 concentration at time t-dt;

- Fdegaz is, for a temperature above 35°C, equal to 5 % of the difference between the temperature and 35°C.