Modeling of the interaction of the carbon cycle and the paleoclimate

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Summary of the thesis:

Introduction

The history of the Earth climate shows many variations of the global temperature at many different timescales. Focusing here on the **very long-term** climate variations, the climate modelers are puzzled by some issues like, among others, the “Young Sun Paradox”, the Proterozoic glaciations or the warm Cretaceous period.

- The “Young Sun Paradox” states that, 3 billions years ago, the sun was less bright than today and consequently the Earth should have been completely frozen. The current climate models show that the increase of the sun brightness to today’s value would not have been able to thaw this frozen planet. That’s the paradox: our today’s planet is obviously not completely frozen.
- The paleo-indicators show that during the Proterozoic (2.5 billions to 600 millions years ago), several glaciations struck the Earth and polar caps or glaciers extended down to equatorial latitudes. The cause of such extended glaciations is unknown.
- During the Cretaceous period (145 to 65 millions years ago), the climate was globally warm and uniform from the equator to the poles and the reason of this mild climate is still unclear.

An interesting hypothesis, suggested by Marshall et al. (1988), could help to solve these three issues. This hypothesis that I would call the **silicate weathering hypothesis**, explains the long-term variation (millions of years) of the climate by considering the long-term cycle of the CO_2: these variations of the climate could be caused by a variation of the CO_2 content of the atmosphere that triggered a change of the greenhouse effect, either cooling or warming the planet. On a timescale of millions of years, the CO_2 level of the ocean-atmosphere system is controlled by the balance between the rate of release of CO_2 by volcanic activity (the source) and the precipitation of carbonates for which cations are supplied by weathering of silicate minerals on the continents (the sink of atmospheric CO_2).

In this thesis, we investigate **quantitatively** this hypothesis to check if it could explain the warm temperatures of the **Cretaceous period**.

The alteration of the silicate rocks: a sink for the atmospheric CO_2

Here we summarize in four steps the long-term geo-cycle of CO_2. At a timescale of several millions of years, the geo-cycle of CO2 is supposed to reach equilibrium between sources and sinks.

1. Formation of an acid

Atmospheric CO_2 and rain combine to form an acid

H_2O (rain)+ CO_2 (atmospheric) → H_2CO_3

2. Weathering of the silicate rocks

This acid attacks the silicate minerals on the continents. The ions and cations are transported by the rivers to the oceans. This weathering process depends on the amount of CO_2 available in the atmosphere, the temperature (the warmer, the more efficient the alteration is), the run-off and on the amount of silicate rocks on the continents.

$H_2CO_3 + CaSiO_3 \rightarrow Ca^{2+} + SiO_3^{2-} + 2H^+ + CO_3^{2-}$

It can be shown that the weathering of the carbonate minerals, on the long-term, is not a sink of CO_2 for the atmosphere-ocean system.

3. Precipitation of carbonates

The Ca^{2+} ions and the CO_3^{2-} cations are used to form the carbonated shell of small animals in the shallow seas. At the death of the animal, these shells fall on the ocean floor. As the CO_3 cations are coming from the atmosphere, **the whole process (1,2 and 3) extracts CO_2 from the atmosphere-ocean system and accumulates it in the carbonate layers that cover the shallow seas.**

$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3$ (shell)

4. Source of CO_2

Through the tectonic mechanism, the $CaCO_3$ covering the ocean plates reaches the Earth mantle in the subduction regions and is recycled as atmospheric CO_2 through **volcanism** and metamorphism, eventually a **source of the CO_2** for the atmosphere.

Numerical simulation: coupling of a climate model and of the CO_2 cycle.

The weathering of silicate rocks process provides a negative feedback that stabilizes the climate on the long run: when the atmospheric CO_2 increases, the planet average temperature increases as well and the alteration of the silicate rocks too. The CO_2 is drained out of the atmosphere, reducing the greenhouse effect and the temperature of the climate decreases. We investigate **quantitatively** this interaction of the climate and the CO_2 cycle with a simple Earth climate model (Energy Balance Model) where the Earth's infrared emission is parameterized by the atmospheric pressure of CO_2. This climate model is coupled with the long-term cycle of the CO_2 where the amount of atmospheric CO_2 is computed taking into account the surface of land exposed to weathering, their latitudinal distribution, the volcanic activity and the average temperature of the planet.

The Cretaceous

Our main test case is the **Cretaceous** period (145 to 65 My ago) for which a reconstruction of the land distribution and volcanism rate is reasonably well known. The Cretaceous climate is characterized by a global surface temperature 6 to 12 ^{o}C higher than today (~15 ^{o}C), tropical vegetation extending to high latitude, apparent lack of polar caps, warm oceanic deep water and an average equator-to-pole temperature gradient much smaller than presently observed. Measurements of the seafloor spreading and estimates of the total continental volcanic rocks suggest that the volcanism activity was about 2 times higher than today. The ocean level was higher than today, exposing less continent surface to the silicate weathering than today and the paleo-geographic reconstructions show that the continent distribution was more equatorward than today.

Results

The results of the numerical simulations applied to the Cretaceous period show that the coupling of the atmospheric model and the CO_2 cycle provides an atmospheric CO_2 pressure ~5 times higher than today and an average planet temperature 7 ^{o}C higher than today.

A further step in the modeling includes a simple description of the role of the vegetation in the CO_2 cycle: The acid attacking the silicates is mainly formed by the CO_2 in the soil, which depends on the root respiration of the vegetation. The CO_2 amount in the soil depends on the vegetation productivity and this productivity depends at least on the CO_2 content of the atmosphere but also on water and nutriment supply. We model the effect of the vegetation as a simple diffusion process between the atmospheric and the soil CO_2 reservoirs that depends on the plant productivity (Volk, 1987). The main consequence is that the CO_2 content of the soil is less sensitive to the atmospheric CO_2 variation. The coupling of the climate model, the silicate weathering and the vegetation role provides a Cretaceous CO_2 pressure 15 times higher than today and a planet average temperature ~9 ^{o}C higher than today.

Conclusions

Keeping in mind the simplicity of this modeling, we showed that the silicate weathering process is potentially able to explain an average temperature 6 to 9 ^{o}C higher than today during the Cretaceous period, consistently with the interpretation of the paleo-indicators.

We also tried to simulate the glaciations of the Proterozoic. During the Proterozoic, the continents were closer to the equator, which is favorable to an extraction of the CO_2 out of the atmosphere and thus favorable to a decrease of the average temperature of the Earth. Although the continent distribution reconstruction of the Proterozoic period is not reliable, the results show that the silicate weathering could provide an explanation to the very low latitudinal extension of the polar caps while avoiding a completely frozen planet that could not be thawed with the current solar brightness (the Young Sun Paradox).

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Bibliography

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