The geoengineering potential of artificially enhanced silicate weathering of olivine

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Abstract

Geoengineering might manipulate Earth's climate in order to counteract global warming from anthropogenic greenhouse gas emissions. We investigate in detail the potential of a specific geoengineering technique: carbon sequestration by artificially enhanced silicate weathering via the dissolution of olivine. This approach would not only operate against rising temperatures but would also counteract ocean acidification, because it influences the global climate via the carbon cycle. We here show the consequences of this technique for the chemistry of the surface ocean at rates necessary for geoengineering. We calculate that olivine dissolution has the potential to sequestrate up to 1 Pg C yr^{-1} directly, if olivine is distributed as fine powder over land areas of the humid tropics. The carbon sequestration potential in soils is limited by the saturation concentration of silicic acid. In our calculations for the Amazon and Congo river catchments, a maximum annual dissolution of 1.8 and 0.4 Pg of olivine seems possible, corresponding to the sequestration of 0.5 and 0.1 Pg C yr^{-1}. Open water dissolution of fine grained olivine and an enhancement of the biological pump by the rising riverine input of silicic acid might increase our estimate of the carbon sequestration, but additional research is needed here. We finally calculate with a carbon cycle model the consequences of sequestration rates of 1 to 5 Pg C yr^{-1} for the 21[st] century by this technique. At maximum, enhanced weathering of olivine powder in the humid tropics could reduce global warming by 1 K and counteract ocean acidification by a rise in surface ocean pH by 0.1 in the year 2100.

Background

Most geoengineering concepts focus either on the restriction of the proposed temperature rise through an artificial enhancement of the planetary albedo (Solar Radiation Management (SRM)) or on removing CO_2 from the atmosphere by various Carbon Dioxide Removal (CDR) techniques. The SRM techniques leave the carbon cycle untouched, and thus do not address the problem of ocean acidification. This would for some of the IPCC emission scenarios lead to a drop of the surface water pH of up to 0.4 and to a drop in the aragonite saturation state by a factor of two in the year 2100. It would thus bring various marine calcifying species, which depend in the build-up of their hard-shells or skeletons on the over-saturation of $CaCO_3$ in surface waters, into unfavorable environmental conditions, to which their degree of adaption is yet unknown. In the worst case their carbonate parts might dissolve.

Our analysis expands results from previous studies on the impact of natural weathering in the future. Olivine (Mg_2SiO_4) is a well studied mineral with known dissolution kinetics and has been suggested to be useful for CDR geoengineering (Figure 1). This study focuses on the humid tropical regions, because of the high temperature, wet conditions and low soil pH. These conditions allow for relatively rapid dissolution of olivine.

Fig. 1: Olivine dissolution: $Mg_2SiO_4 + 4CO_2 \Downarrow + 4H_2O \Rightarrow 2Mg^{2+} + 4HCO_3^- + H_4SiO_4$

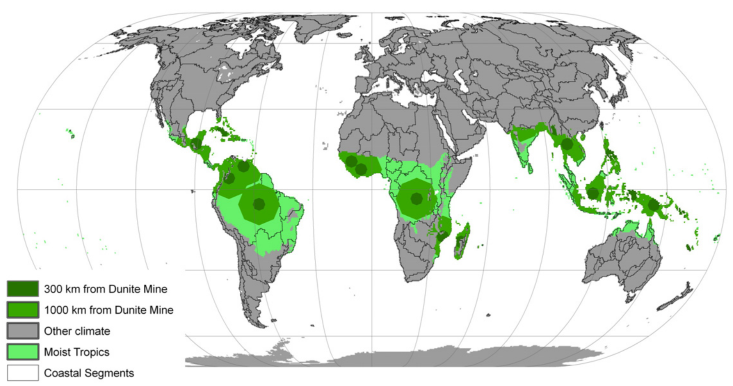

Fig. 2: Tropical regions with humid climate and their distances from known Dunite mines.

Table 1: Upper estimate of CO_2 sequestration by olivine dissolution on land, if the pH of major rivers in the humid tropics is given. Assumptions: typical riverine partial pressure of CO_2, alkalinity and runoff and a freshwater temperature of 25°C. Distinguished cases: maximum tolerable pH threshold is 8.0, 8.2 or 9.0. The enhanced silicate weathering flux would sequestrate approximately as much g of CO_2 (or about 27% as much in g C) as olivine was dissolved. TA is the total alkalinity.

Units		Amazon			Congo	
Catchment area (10^{12} m^2)		5.83			3.6	
Runoff (10^{12} m^3 yr^{-1})		6.3			1.3	
TA (mmol m^{-3})		460			250	
pCO_2 (µatm) *		4350 (385 – 13000)			3200 (385 – 35600)	
pH †		6.84 (6.38 – 7.89)			6.71 (5.67 – 7.63)	
resulting pH	8.0	8.2 **	9.0	8.0	8.2**	9.0
Δ(TA) (mmol m^{-3})	6,192	8,040	71,631	4,646	8,040	52,786
flux TA (10^{12} mol yr^{-1})	36.06	50.65	451.79	5.86	10.45	66.59
flux olivine (Pg yr^{-1}) ¶	1.37	1.77	15.81	0.21	0.37	2.33
ρ(olivine) (g m^{-2} yr^{-1})	234	305	2712	57	100	647
C-sequestration (Pg C yr^{-1})	0.38	0.49	4.35	0.06	0.10	0.64

* : Mean riverine pCO_2, minimum and maximum
¶ : The flux of olivine is following equation in Figure 1 and leads to the dissolution rate and C-sequestration, provided below.
** : Olivine dissolution leads to a H_4SiO_4 saturation concentration of 2000 mmol m^{-3} in the river.

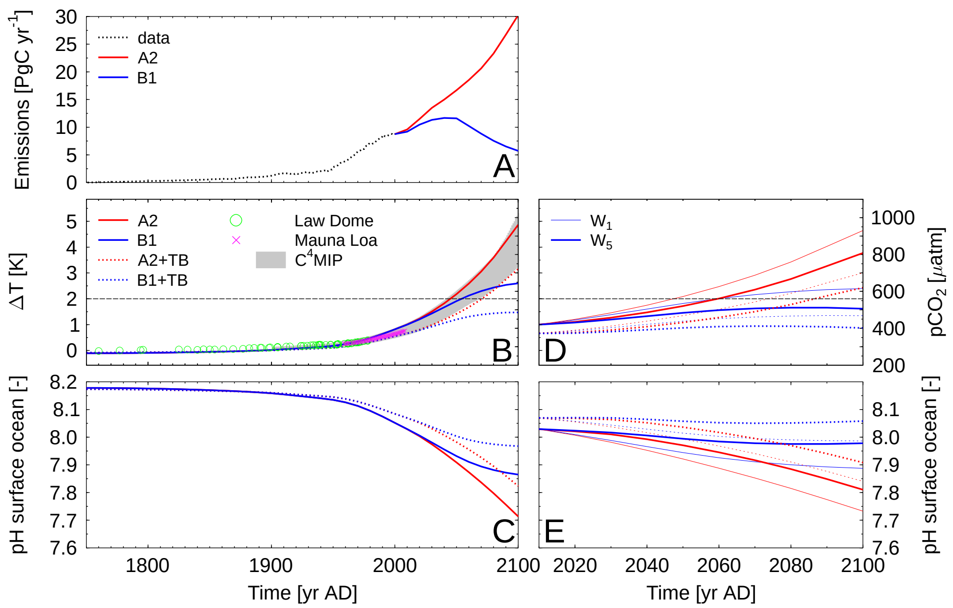

Fig. 3: A: The sum of anthropogenic emissions from fossil fuel combustion (1750–2000 AD) and land use change (1850–2000 AD; before 1850 AD: linear extrapolation of land use change to zero in 1750 AD). 2000–2100 AD: Projected emission for A2 and B1 scenarios.

B: Global transient temperature rise (left y-axis) inter(extra)-polated from a transient climate sensitivity of 2 K for a doubling of preindustrial atmospheric CO_2 and atmospheric CO_2 (right y-axis), data from Law Dome ice core and instrumental measurements on Mount Mauna Loa 1958–2008 AD. Simulation results of the emission scenarios without (A2, B1) and with (A2+TB, B1+TB) dynamical terrestrial carbon storage. Grey area covers the range of results from coupled carbon cycle-climate simulations of for the A2 emission scenario C4MIP.

C, E: Mean pH of the global surface ocean for the same scenarios as in B and D, respectively.

D: Impact of enhanced silicate weathering for 2010–2100 AD. Global temperature rise (left y-axis) and simulated atmospheric pCO_2 (right y-axis) for the A2 and B1 scenarios with and without dynamic terrestrial carbon storage for three different weathering strengths (W1 (thin): +1 Pg C yr^{-1}; W5 (bold): +5 Pg C yr^{-1}.

Findings & Conclusion

The Amazon and Congo river basins have an artificial silicate weathering potential to sequester annually up to 4.3 and 0.6 Pg of carbon, respectively, in case the resulting pH is the threshold (Table 1). That implies a potential of enhanced silicate weathering to reduce atmospheric CO_2 in magnitudes relevant for geoengineering, if applied over major humid tropical catchment areas (24×10^6 km^2) (Fig. 2). However, high dissolved silica concentration in soils probably limits weathering rates there (at ~ 2000 mmol m^{-3} equilibrium should be reached).

Altogether, enhanced weathering via the dissolution of fine grained olivine powder in the humid tropics seems to be a CDR technique able to sequester one Pg of carbon per year. Sequestration rate might be higher, in case additional regions or alternative, artificial weathering techniques are considered (House et al., 2006).

An artificial weathering rate of 1 Pg C yr^{-1}, reduces pCO_2 by less than 30 µatm (equivalent to a cooling of 0.2 K) until the year 2100 (Fig. 3), and increases ocean pH by about 0.02, regardless of the emission scenario and the assumed dynamics of the terrestrial C storage (Fig. 4).
An artificial weathering rate of sequestering 5 Pg C yr^{-1} would reduce pCO_2 by 80 to 150 µatm (cooling of 0.6-1.1 K) and would increase pH by about 0.1 until the year 2100. Sequestration of 10 Pg C yr^{-1} potentially reduces pCO_2 by 160 to 300 µatm (cooling of 1.2 to 2.2 K). The mean surface ocean pH would rise by about 0.2 in that scenario.

However, the amount of olivine necessary for these applications is huge, it lies in the range of present day global coal production.

Nevertheless, compared to other CDR techniques olivine dissolution is very effective, rated as relatively safe and moderately expensive. Ecosystem assessments for the expected impacts of the alkalinity rise are necessary before considering its implementation. Detailed studies of the impact of the proposed increase in alkalinity and pH in soils and aquatic ecosystems are needed.

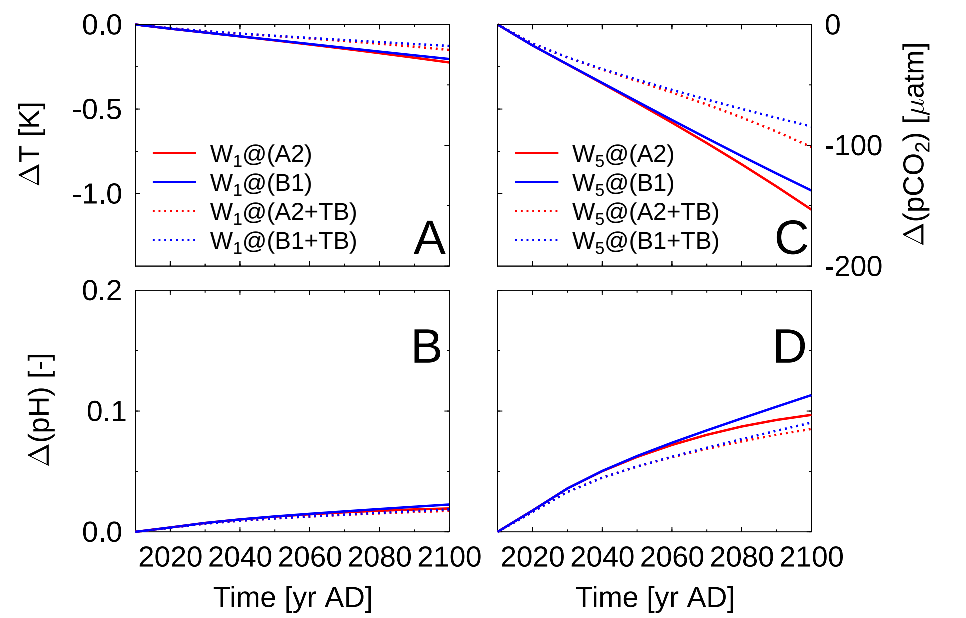

Fig. 4. Differences in global temperature, atmospheric pCO_2 and mean surface ocean pH induced by enhanced silicate weathering for the years 2010–2100 AD.

A, B: W1:+1 Pg C yr^{-1}; C, D: W5: +5 Pg C yr^{-1}.

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