Feasibilities of carbon dioxide removal portfolios

Simulating carbon dioxide removal portfolios with a fully coupled Earth system model

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In Short

- Carbon dioxide removal (CDR) technologies are required to mitigate the anthropogenic climate change.
- A fully coupled Earth system model will be utilized to simulate multiple CDR portfolios combining different land- and ocean-based options.
- The efficacy and side effects of the CDR portfolios will be evaluated for determining the respective feasibilities.

Carbon dioxide removal (CDR) is indispensable for achieving the Paris Agreement climate target. According to the IPCC Special Report on Global Warming of 1.5 ° C, 100 to 1000 $GtCO_2$ will need to be removed over the 21st century to meet the 1.5-degree target [1]. Different CDR methods have been proposed [2], including land-based options of large-scale afforestation and reforestation, soil carbon sequestration, and bioenergy with carbon capture and storage (BECCS). On the other hand, ocean-based methods have also been proposed, such as ocean alkalinity enhancement, artificial ocean upwelling, and open-ocean macroalgae mariculture and sinking. However, any single CDR alone will unlikely to meet the required rates of carbon removal sustainably [3]. It is thus necessary to deploy combinations of different CDR methods, and it is important to explore different CDR portfolios and find out a portfolio that is the most efficient and has least negative side-effects.

In this proposal, we aim to utilize the fully coupled model Flexible Ocean and Climate Infrastructure (FOCI) [4] to investigate the efficiency and climate impacts of different CDR portfolios. The full coupling between land, ocean and atmosphere as well as inclusion of a marine biogeochemistry model enables study of interaction between different earth system components (Fig. 1), which is important for study climate feedbacks across earth system components and studies at multi-decadal time scale. The experiments will be analyzed for the output of the BMBF project CDRSynTra (`https://www.fona.de/en/measures/funding-measures/CDR/cdrsyn_en.php`). The aim is to assess side-effects, sustainability impacts, and political and socio-cultural feasibility of the CDR options and develop consistent Earth system scenarios to reach the 1.5- and 2-degree climate targets.

For better understanding the differences between CDR simulated by different models, the CDR model intercomparison project (CDRMIP) has been proposed [5]. Several experiments have been done as part of the FOCI contribution to the CDRMIP. The *esm-ssp585* experiment is used as a control experiment to evaluate effects of two highly-idealized CDR experiments. The first is a marine-based CDR of ocean alkalinity enhancement (*esm-ssp585-ocn-alk*), and the other is a land-based CDR of afforestation and reforestation (*esm-ssp585-ssp126Lu*), given their large theoretical mitigation potentials. In both experiments, the CDR methods are applied under the high CO_2 emission scenario of SSP5-8.5. In the experiment of ocean alkalinity enhancement, alkalinity is added to ice-free ocean at a rate of roughly 0.14 petamole per year from year 2020. In the experiment of afforestation and reforestation, the land use follows the scenario with high levels of afforestation and reforestation (SSP1-2.6) from year 2015.

Fig. 2 shows the air-sea CO_2 fluxes, CO_2 fluxes between land and atmosphere due to land use change and forest harvest, and the atmospheric CO_2 concentration from 2015 to 2050 of the three experiments as simulated by FOCI. It is shown that that compared with the control experiment without any CDR application, ocean alkalinity enhancement is able to enhance the CO_2 flux from the atmosphere into the ocean by ∼1 PgC/yr. The air-sea CO_2 flux is slightly reduced in the afforestation and reforestation experiment (∼0.1 PgC/yr). The CO_2 emission due to land use change is reduced by ∼0.4 PgC/yr in the afforestation and reforestation experiment by 2025. While the reduction in land use change emission

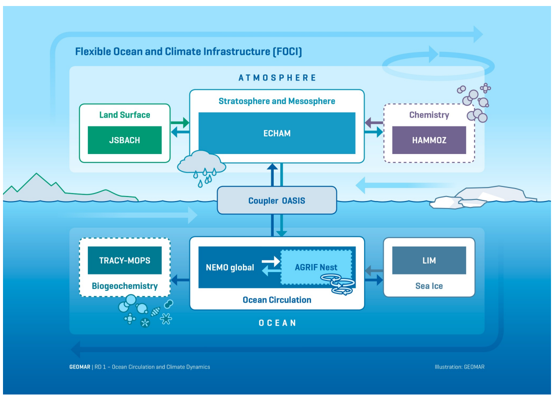

***Figure 1:** Structure of the FOCI model.*

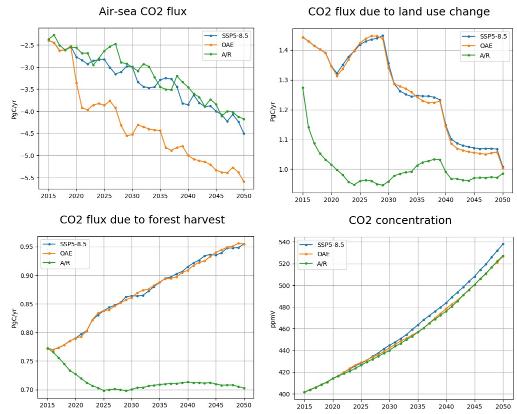

Figure 2: *CO_2 fluxes and atmospheric concentration of the control (without carbon dioxide removal) and the two experimental simulations (with carbon dioxide removal). OAE: ocean alkalinity enhancement. A/R: afforestation and reforestation. All experiments are with SSP5-8.5 emission.*

becomes smaller by 2050, the reduction of emission due to forest harvest becomes larger with time (from ~0.15 PgC/yr in 2030 to ~0.25 PgC/yr in 2050). The enhanced carbon sink in both CDR experiments results in reduction in atmospheric CO_2 concentration. For both experiments, the atmospheric CO_2 concentration is reduced for more than 10 ppm by 2050 compared with the control experiment without CDR. The results show that FOCI is able to simulate carbon removal by afforestation and ocean alkalinity enhancement, and is therefore suitable for our purposes to further explore a feasible and efficient CDR portfolio.

While the idealized experiments described in CDR-MIP facilitate understanding of processes, in the current project we focus on more realistic scenarios according to current mitigation efforts and climate targets. The experiments are planned under four scenarios. The four scenarios are combinations of three climate change scenarios and two different amounts of CDR application. For the three climate change scenarios, the high scenario corresponds to the SSP5-8.5 scenario, and overshoot is the SSP5-34-OS, and the low scenario is SSP1-2.6. For the two CDR application, one represents a low CDR scenario of 0.5 $GtCO_2$/yr, and the other is a high CDR scenario, which is 10 times the magnitude of low CDR (5 $GtCO_2$/yr). The scenarios are as below:

1. High climate change, high CDR deployment
2. Overshoot climate change, high CDR deployment
3. Low climate change, high CDR deployment
4. Low climate change, low CDR deployment

For each of the four scenarios, eight possible portfolios consisting of the following four CDR options adding up to the required high or low CDR are considered:

1. Afforestation and reforestation
2. Bioenergy with carbon capture and storage (BECCS)
3. Ocean alkalinity enhancement
4. Macroalgae farming

The portfolios will be from single deployment of individual CDR deployment to simultaneous deployment of all four options. To assess the uncertainty due to internal variability, each experiment has three ensemble members according to the CMIP protocol. For each experiment, the CDR methods will ramp up starting in year 2025 until year 2050, when they reach their maximum potential and then keep at the same level until 2100, which is in total 85 years.

With the model experiments, we will analyze the efficacy and side effects of the CDR portfolios, and the results will be evaluated for determining the respective feasibilities.

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http://www.geomar.de/en

More Information

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[3] Fuss et al., *Env. Res. Let.* (2018). doi: 10.1088/1748-9326/aabf9f

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