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# Quantifying and comparing effects of climate engineering methods on the Earth system

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Different climate engineering (CE) methods have been proposed as mitigating strategies to counteract the effects of climate change. Previous model studies on potential impacts of different CE schemes have focused mainly on effects of individual CE methods as simulated by different models. Here we assess atmosphere-, ocean-, and land-based CE measures with respect to their effects and unintended consequences consistently within one comprehensive model. We use the Max Planck Institute Earth System Model (MPI-ESM) with prognostic carbon cycle to compare solar radiation management (SRM) by stratospheric sulfur injection with carbon dioxide removal methods: afforestation (AFF) and artificial ocean alkalinization (AOA). For each of the three CE methods we perform simulations forced by fossil-fuel $CO_2$ emissions according to the Representative Concentration Pathway (RCP) 8.5.

We show that driven by different target variables - atmospheric $CO_2$ for AFF and AOA, radiative forcing for SRM - the CE methods differ vastly in terms of their effects on different Earth system components. We find that mitigating feedbacks emerge: for example, as a response to SRM temperatures are reduced leading to a reduction of atmospheric $CO_2$ due to enhanced land carbon uptake. In addition, unintended side effects become clear: for example, terrestrial net primary production (NPP) is substantially reduced in the AOA scenario, while SRM has almost no net effect on terrestrial NPP due to counteracting effects of decreased water stress in low latitudes and weaker boreal forest expansion. We also identify challenges arising in a comparative assessment of different CE methods: the quantitative results depend on details of the CE scenarios and on the underlying models, and an interpretation of relative efficiency depends on the choice of variables that are analyzed. Furthermore, we show that normalisations allow for a better comparability of different CE methods. For example, we find that despite different amounts of global surface cooling achieved, local amplification factors compared to the global mean temperature changes are generally similar in the CE scenarios, with the exception of Arctic amplification, which is strengthened in SRM. We also find a higher efficiency to remove carbon from the atmosphere for AOA compared to AFF, again illustrating how carbon cycle feedbacks in the coupled Earth system alter the mitigation potential of CE methods.

We further analyze the effects of SRM and AOA on the Earth system from two different perspectives: the environmental effects on multi-decadal rates of change and the impacts on seasonality. Local rates of surface warming in terminated SRM scenarios exceed those associated with the reference RCP8.5 scenario in agreement with previous studies. Warming rates are generally similar to those of the RCP8.5 after termination of AOA, still spatial patterns differ. Furthermore, rates of increasing temperatures locally exceed those of the RCP8.5 after the terminated AOA scenario at high latitudes of the Northern hemisphere with some regions reaching trends as large as in the terminated SRM simulation. Yet, such warming trends emerge against a background of large model internal variability, which differs among the simulations and complicates the identification of local trends. Even though AOA and SRM methods target different atmospheric forcings, our scenarios do not show differences in the projected seasonal patterns of surface atmospheric temperatures by the end of this century. The impacts of SRM on the ocean carbon cycle both in multi-decadal and annual time scales are small. In contrast with SRM, terminated AOA scenarios lead to fast-paced variations in the seawater carbonate chemistry in regions with poor vertical mixing, with the Arctic Ocean and tropical oceans emerging as hot spots. Right after termination of AOA the local rates of ocean acidification become locally up to one order of magnitude higher than under the RCP8.5 scenario. Besides, AOA affects the seasonal cycle of seawater carbonate chemistry, although these effects are minor when compared to the associated effect of AOA on the mean annual state.