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The Carbon Dioxide Removal Model Intercomparison Project (CDRMIP): rationale and experimental protocol for CMIP6

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Abstract. The recent IPCC reports state that continued anthropogenic greenhouse gas emissions are changing the climate, threatening "severe, pervasive and irreversible" impacts. Slow progress in emissions reduction to mitigate climate change is resulting in increased attention to what is called geoengineering, climate engineering, or climate intervention – deliberate interventions to counter climate change that seek to either modify the Earth's radiation budget or remove greenhouse gases such as CO_2 from the atmosphere. When focused on CO_2, the latter of these categories is called carbon dioxide removal (CDR). Future emission scenarios that stay well below 2 °C, and all emission scenarios that do not exceed 1.5 °C warming by the year 2100, require some form of CDR. At present, there is little consensus on the climate impacts and atmospheric CO_2 reduction efficacy of the different types of proposed CDR. To address this need, the Carbon Dioxide Removal Model Intercomparison Project (or CDRMIP) was initiated. This project brings together models of the Earth system in a common framework to explore the potential, impacts, and challenges of CDR. Here, we describe the first set of CDRMIP experiments, which are formally part of the 6th Coupled Model Intercomparison Project (CMIP6). These experiments are designed to address questions concerning CDR-induced climate "reversibility", the response of the Earth system to direct atmospheric CO_2 removal (direct air capture and storage), and the CDR potential and impacts of afforestation and reforestation, as well as ocean alkalinization.

1 Introduction

The Earth system is sensitive to the concentration of atmospheric greenhouse gases (GHGs) because they have a direct impact on the planetary energy balance (Hansen, 2005) and in many cases also on biogeochemical cycling (IPCC, 2013). The concentration of one particularly important GHG, carbon dioxide (CO_2), has increased from approximately 277 ppm in the year 1750 to over 400 ppm today as a result of anthropogenic activities (Dlugokencky and Tans, 2016; Le Quéré et al., 2015). This CO_2 increase, along with other GHG increases and anthropogenic activities (e.g., land use change), has perturbed the Earth's energy balance, leading to an observed global mean surface air temperature increase of around 0.8 °C above preindustrial (year 1850) levels in the year 2015 (updated from Morice et al., 2012). Biogeochemistry on land and in the ocean has also been affected by the increase in CO_2, with a well-observed decrease in ocean pH being one of the most notable results (Gruber, 2011; Hofmann and Schellnhuber, 2010). Many of the changes attributed to this rapid temperature increase and perturbation of the carbon cycle have been detrimental for natural and human systems (IPCC, 2014a).

While recent trends suggest that the atmospheric CO_2 concentration is likely to continue to increase (Peters et al., 2013; Riahi et al., 2017), the Paris Agreement of the 21st session of the Conference of Parties (COP21) on climate change (UNFCCC, 2016) has set the goal of limiting anthropogenic warming to well below 2 °C (ideally no more than 1.5 °C) relative to the global mean preindustrial temperature. To do this a massive climate change mitigation effort to reduce the sources or enhance the sinks of greenhouse gases (IPCC, 2014b) must be undertaken. Even if significant efforts are made to reduce CO_2 emissions, it will likely take decades before net emissions approach zero (Bauer et al., 2017; Riahi et al., 2017; Rogelj et al., 2015a), a level that is likely required to reach and maintain such temperature targets (Rogelj et al., 2015b). Changes in the climate will therefore continue for some time, with future warming strongly dependent on cumulative CO_2 emissions (Allen et al., 2009; IPCC, 2013; Matthews et al., 2009), and there is the possibility that "severe, pervasive and irreversible" impacts will occur if too much CO_2 is emitted (IPCC, 2013, 2014a). The lack of agreement on how to sufficiently reduce CO_2 emissions in a timely manner and the magnitude of the task required to transition to a low carbon world has led to increased attention to what is called geoengineering, climate engineering, or climate intervention. These terms are all used to define actions that deliberately manipulate the climate system in an attempt to ameliorate or reduce the impact of climate change by either modifying the Earth's radiation budget (solar radiation management, or SRM) or removing the primary greenhouse gas, CO_2, from the atmosphere (carbon dioxide removal, or CDR; National Research Council, 2015). In particular, there is an increasing focus and study on the potential of carbon dioxide removal (CDR) methods to offset emissions and eventually enable "net negative emissions", whereby more CO_2 is removed via CDR than is emitted by anthropogenic activities, to complement emissions reduction efforts. CDR has also been proposed as a means of "reversing" climate change if too much CO_2 is emitted; i.e., CDR may be able to reduce atmospheric CO_2 to return radiative forcing to some target level.

All integrated assessment model (IAM) scenarios of the future state that some form of CDR will be needed to prevent the mean global surface temperature from exceeding 2 °C (Bauer et al., 2017; Fuss et al., 2014; Kriegler et al., 2016; Rogelj et al., 2015a). Most of these limited warming scenarios feature overshoots in radiative forcing around mid-century, which is closely related to the amount of cumulative CDR until the year 2100 (Kriegler et al., 2013). Despite the prevalence of CDR in these scenarios and its increasing utilization in political and economic discussions, many of the methods by which this would be achieved at this point rely on immature technologies (National Research Council, 2015; Schäfer et al., 2015). Large-scale CDR methods are not yet a commercial product, and hence questions remain about their feasibility, realizable potential, and risks (Smith et al., 2015; Vaughan and Gough, 2016).

Overall, knowledge about the potential climatic, biogeochemical, biogeophysical, and other impacts in response to CDR is still quite limited, and large uncertainties remain, making it difficult to comprehensively evaluate the potential and risks of any particular CDR method and make comparisons between methods. This information is urgently needed to allow us to assess the following:

i. the degree to which CDR could help mitigate or perhaps reverse climate change;

ii. the potential risks and benefits of different CDR proposals; and

iii. how climate and carbon cycle responses to CDR could be included when calculating and accounting for the contribution of CDR in mitigation scenarios, i.e., so that CDR is better constrained when it is included in IAM-generated scenarios.

To date, modeling studies of CDR focusing on the carbon cycle and climatic responses have been undertaken with only a few Earth system models (Arora and Boer, 2014; Boucher et al., 2012; Cao and Caldeira, 2010; Gasser et al., 2015; Jones et al., 2016a; Keller et al., 2014; MacDougall, 2013; Mathesius et al., 2015; Tokarska and Zickfeld, 2015; Zickfeld et al., 2016). However, as these studies all use different experimental designs, their results are not directly comparable, and consequently building a consensus on responses is challenging. A model intercomparison study with Earth system models of intermediate complexity (EMICS) that addresses climate reversibility, among other things, has recently been published (Zickfeld et al., 2013), but the focus was on the very distant future rather than this century. Moreover, in many of these studies, atmospheric CO_2 concentrations were prescribed rather than being driven by CO_2 emissions, and thus the projected changes were independent of the strength of feedbacks associated with the carbon cycle.

Given that Earth system models are one of the few tools available for making quantifications on these scales and for making projections into the future, CDR assessments must include emissions-driven modeling studies to capture the carbon cycle feedbacks. However, such an assessment cannot be done with one or two models alone, since this will not address uncertainties due to model structure and internal variability. Below we describe the scientific foci and several experiments (Table 1) that comprise the initial phase of the

CMIP6-endorsed Carbon Dioxide Removal Model Intercomparison Project (CDRMIP).

1.1 CDRMIP scientific foci

There are three principal science motivations behind CDRMIP. First and foremost, CDRMIP will provide information that can be used to help assess the potential and risks of using CDR to address climate change. A thorough assessment will need to look at both the impacts of CDR upon the Earth system and human society. CDRMIP will focus primarily on Earth system impacts, with the anticipation that this information will also be useful for understanding potential impacts upon society. The scientific outcomes will lead to more informed decisions about the role CDR may play in climate change mitigation (defined here as a human intervention to reduce the sources or enhance the sinks of greenhouse gases). CDRMIP experiments will also provide an opportunity to better understand how the Earth system responds to perturbations, which is relevant to many of the Grand Science Challenges posed by the World Climate Research Program (WCRP; https://www.wcrp-climate.org/grand-challenges/grand-challenges-overview). CDRMIP experiments provide a unique opportunity because the perturbations are often opposite in sign to previous CMIP perturbation experiments (CO_2 is removed instead of added). Second, CDRMIP results may also be able to provide information that helps to understand how model resolution and complexity cause systematic model bias. In this instance, CDRMIP experiments may be especially useful for gaining a better understanding of the similarities and differences between global carbon cycle models because we invite a diverse group of models to participate in CDRMIP. Finally, CDRMIP results can help to quantify uncertainties in future climate change scenarios, especially those that include CDR. In this case CDRMIP results may be useful for calibrating CDR inclusion in IAMs during the scenario development process.

The initial foci that are addressed by CDRMIP include (but are not limited to) the following.

i. Climate "reversibility" by assessing the efficacy of using CDR to return high future atmospheric CO_2 concentrations to lower levels. This topic is highly idealized, as the technical ability of CDR methods to remove such enormous quantities of CO_2 on relatively short timescales (i.e., this century) is doubtful. However, the results will provide information on the degree to which a changing and changed climate could be returned to a previous state. This knowledge is especially important since socioeconomic scenarios that limit global warming to well below 2 °C often feature radiative forcing overshoots that must be "reversed" using CDR. Specific questions on reversibility will address the following.

    1. What components of the Earth's climate system exhibit "reversibility" when CO_2 increases and then decreases? On what timescales do these "reversals" occur? And if reversible, is this complete reversibility or just on average (are there spatial and temporal aspects)?
    2. Which, if any, changes are irreversible?
    3. What role does hysteresis play in these responses?

ii. The potential efficacy, feedbacks, and side effects of specific CDR methods. Efficacy is defined here as CO_2 removed from the atmosphere over a specific time horizon as a result of a specific unit of CDR action. This topic will help to better constrain the carbon sequestration potential and risks and/or benefits of selected methods. Together, a rigorous analysis of the nature, sign, and timescales of these CDR-related topics will provide important information for the inclusion of CDR in climate mitigation scenarios and in resulting mitigation and adaptation policy strategies. Specific questions on individual CDR methods will address the following.

    1. How much CO_2 would have to be removed to return to a specified concentration level, for example present day or preindustrial?
    2. What are the short-term carbon cycle feedbacks (e.g., rebound) associated with the method?
    3. What are the short- and longer-term physical, chemical, and biological impacts and feedbacks and the potential side effects of the method?
    4. For methods that enhance natural carbon uptake, for example afforestation or ocean alkalinization, where is the carbon stored (land and ocean) and for how long (i.e., issues of permanence; at least as much as this can be calculated with these models)?

1.2 Structure of this paper

Our motivation for preparing this paper is to lay out in detail the CDRMIP experimental protocol, which we request all modeling groups to follow as closely as possible. Firstly, in Sect. 2, we review the scientific background and motivation for CDR in more detail than covered in this introduction. Section 3 describes some requirements and recommendations for participating in CDRMIP and describes links to other CMIP6 activities. Section 4 describes each CDRMIP simulation in detail. Section 5 describes the model output and data policy. Section 6 presents an outlook of potential future CDRMIP activities and a conclusion. Section 7 describes how to obtain the model code and data used during the production of this paper.

2 Background and motivation

At present, there are two main proposed CDR approaches, which we briefly introduce here. The first category encompasses methods that are primarily designed to enhance the

Table 1. Overview of CDRMIP experiments. Note that each experiment is comprised of several individually named simulations (Tables 2–7). In the “Forcing methods” column, “All” means “all anthropogenic, solar, and volcanic forcing”. Anthropogenic forcing includes aerosol emissions, non-CO_2 greenhouse gas emissions, and land use changes.

Short name	Long name	Tier	Experiment description	Forcing methods	Major purpose
CDR-reversibility	Climate and carbon cycle reversibility experiment	1	CO_2 prescribed to increase at 1 % yr^{-1} to 4× preindustrial CO_2 and then decrease at 1 % yr^{-1} until again at a preindustrial level, after which the simulation continues for as long as possible	CO_2 concentration prescribed	Evaluate climate reversibility
CDR-pi-pulse	Instantaneous CO_2 removal and/or addition from an unperturbed climate experiment	1	100 Gt C is instantly removed (negative pulse) from a steady-state preindustrial atmosphere; 100 Gt C is instantly added (positive pulse) to a steady-state preindustrial atmosphere	CO_2 concentration calculated (i.e., freely evolving)	Evaluate climate and C-cycle response of an unperturbed system to atmospheric CO_2 removal; comparison with the positive pulse response
CDR-yr2010-pulse	Instantaneous CO_2 removal and/or addition from a perturbed climate experiment	3	100 Gt C is instantly removed (negative pulse) from a near 100 Gt C is instantly removed (negative pulse) from a near present day atmosphere; 100 Gt C is instantly added (positive pulse) to a near present day atmosphere	All; CO_2 concentration calculated (i.e., emission driven)*	Evaluate climate and C-cycle response of a perturbed system to atmospheric CO_2 removal; comparison with the positive pulse response
CDR-overshoot	Emission-driven SSP5-3.4-OS scenario experiment	2	SSP5-3.4 overshoot scenario in which CO_2 emissions are initially high and then rapidly reduced, becoming negative	All; CO_2 concentration calculated (i.e., emission driven)	Evaluate the Earth system response to CDR in an overshoot climate change scenario
CDR-afforestation	Afforestation–reforestation experiment	2	Long-term extension of an experiment with forcing from a high CO_2 emission scenario (SSP5-8.5), but with land use prescribed from a scenario with high levels of afforestation and reforestation (SSP1-2.6)	All; CO_2 concentration calculated (i.e., emission driven)	Evaluate the long-term Earth system response to afforestation and reforestation during a high CO_2 emission climate change scenario
CDR-ocean-alk	Ocean alkalinization in a high CO_2 world experiment	2	A high CO_2 emission scenario (SSP5-8.5) with 0.14 Pmol yr^{-1} alkalinity added to ice-free ocean surface waters from the year 2020 onward	All; CO_2 concentration calculated (i.e., emission driven)	Evaluate the Earth system response to ocean alkalinization during a high CO_2 emission climate change scenario

* In this experiment CO_2 is first prescribed to diagnose emissions; however, the key simulations calculate the CO_2 concentration.

Earth’s natural carbon sequestration mechanisms. Enhancing natural oceanic and terrestrial carbon sinks is suggested because these sinks have already *each* taken up over one-quarter of the carbon emitted as a result of anthropogenic activities (Le Quéré et al., 2016) and have the capacity to store additional carbon, although this is subject to environmental limitations. Some prominent proposed sink enhancement methods include afforestation or reforestation, enhanced terrestrial weathering, biochar, land management to enhance soil carbon storage, ocean fertilization, ocean alkalinization, and coastal management of blue carbon sinks.

The second general CDR category includes methods that rely primarily on technological means to directly remove carbon from the atmosphere, ocean, or land and isolate it from the climate system, for example storage in a geological reservoir (Scott et al., 2015). Methods that are primarily technological are suggested because they may not be as limited by environmental constraints. Some prominent proposed technological methods include direct CO_2 air capture with storage and seawater carbon capture (and storage). One other proposed CDR method, bioenergy with carbon capture and storage (BECCS), relies on both natural processes and technology. BECCS is thus constrained by some environmental limitations (e.g., suitable land area), but because the carbon is removed and ultimately stored elsewhere, it may have a higher CDR potential than if the same deployment area were used for a sink-enhancing CDR method like afforestation that stores carbon permanently above ground and reaches a saturation level for a given area (Smith et al., 2015).

From an Earth system perspective, the potential and impacts of proposed CDR methods have only been investigated in a few individual studies; see recent climate intervention assessments for a broad overview of the state of CDR research (National Research Council, 2015; Rickels et al., 2011; The Royal Society, 2009; Vaughan and Lenton, 2011) and references therein. These studies agree that CDR application on a large scale (≥ 1 Gt CO_2 yr^{-1}) would likely have a substantial impact on the climate, biogeochemistry, and the ecosystem services that the Earth provides (i.e., the benefits humans obtain from ecosystems; Millennium Ecosystem Assessment, 2005). Idealized Earth system model simulations suggest that CDR does appear to be able to limit or even reverse warming and changes in many other key climate variables (Boucher et al., 2012; Tokarska and Zickfeld, 2015; Wu et al., 2014; Zickfeld et al., 2016). However, less idealized studies, for example when some environmental limitations are accounted for, suggest that many methods have only a limited individual mitigation potential (Boysen et al., 2016, 2017; Keller et al., 2014; Sonntag et al., 2016).

Studies have also focused on the carbon cycle response to the deliberate redistribution of carbon between dynamic carbon reservoirs or permanent (geological) carbon removal. Understanding and accounting for the feedbacks between these reservoirs in response to CDR is particularly important for understanding the efficacy of any method (Keller et al., 2014). For example, when CO_2 is removed from the atmosphere in simulations, the rate of oceanic CO_2 uptake, which has historically increased in response to increasing emissions, is reduced and might eventually reverse (i.e., net outgassing) because of a reduction in the air–sea flux disequilibrium (Cao and Caldeira, 2010; Jones et al., 2016a; Tokarska and Zickfeld, 2015; Vichi et al., 2013). Equally, the terrestrial carbon sink also weakens in response to atmospheric CO_2 removal and can also become a source of CO_2 to the atmosphere (Cao and Caldeira, 2010; Jones et al., 2016a; Tokarska and Zickfeld, 2015). This "rebound" carbon flux response that weakens or reverses carbon uptake by natural carbon sinks would oppose CDR and needs to be accounted for if the goal is to limit or reduce atmospheric CO_2 concentrations to some specified level (IPCC, 2013).

In addition to the climatic and carbon cycle effects of CDR, most methods appear to have side effects (Keller et al., 2014). The impacts of these side effects tend to be method specific and may amplify or reduce the climate change mitigation potential of the method. Some significant side effects are caused by the spatial scale (e.g., millions of km^2) on which many methods would have to be deployed to have a significant impact upon CO_2 and global temperatures (Boysen et al., 2016; Heck et al., 2016; Keller et al., 2014). Side effects can also potentially alter the natural environment by disrupting biogeochemical and hydrological cycles, ecosystems, and biodiversity (Keller et al., 2014). For example, large-scale afforestation could change regional albedo and evapotranspiration and have a biogeophysical impact on the Earth's energy budget and climate (Betts, 2000; Keller et al., 2014). Additionally, if afforestation were done with non-native plants or monocultures to increase carbon removal rates, this could impact local biodiversity. For human societies, this means that CDR-related side effects could potentially impact the ecosystem services provided by the land and ocean (e.g., food production), with the information so far suggesting that there could be both positive and negative impacts on these services. Such effects could change societal responses and strategies for climate change adaptation if large-scale CDR were to be deployed.

CDR deployment scenarios have focused on both preventing climate change and reversing it. While there is some understanding of how the Earth system may respond to CDR, as described above, another dynamic comes into play if CDR were to be applied to "reverse" climate change. This is because if CDR were deployed for this purpose, it would deliberately change the climate, i.e., drive it in another direction, rather than just prevent it from changing by limiting CO_2 emissions. Few studies have investigated how the Earth system may respond if CDR is applied in this manner. The link between cumulative CO_2 emissions and global mean surface air temperature change has been extensively studied (IPCC, 2013). Can this change simply be reversed by removing the CO_2 that has been emitted since the preindustrial era? Little is known about how reversible this relationship is or whether it applies to other Earth system properties (e.g., net primary productivity, sea level, etc.). Investigations of CDR-induced climate reversibility have suggested that many Earth system properties are "reversible", but often with nonlinear responses (Armour et al., 2011; Boucher et al., 2012; MacDougall, 2013; Tokarska and Zickfeld, 2015; Wang et al., 2014; Wu et al., 2014; Zickfeld et al., 2016). However, these analyses were generally limited to global annual mean values, and most models did not include potentially important components such as permafrost or terrestrial ice sheets. Thus, there are many unknowns and much uncertainty about whether it is possible to "reverse" climate change. Obtaining knowledge about climate "reversibility" is especially important as it could be used to direct or change societal responses and strategies for adaptation and mitigation.

2.1 Why a model intercomparison study on CDR?

Although ideas for controlling atmospheric CO_2 concentrations were proposed in the middle of the last century, it is only recently that CDR methods have received widespread attention as climate intervention strategies (National Research Council, 2015; Schäfer et al., 2015; The Royal Society, 2009; Vaughan and Lenton, 2011). While some proposed CDR methods do build upon substantial knowledge bases (e.g., soil and forest carbon, and ocean biogeochemistry), little research into large-scale CDR has been conducted and limited research resources applied (National Research Council, 2015; Oschlies and Klepper, 2017). The small number of existing laboratory studies and small-scale field trials of CDR methods were not designed to evaluate climate or carbon cycle responses to CDR. At the same time it is difficult to conceive how such an investigation could be carried out without scaling a method up to the point at which it would essentially be "deployment". The few natural analogues that exist for some methods (e.g., weathering or reforestation) only provide limited insight into the effectiveness of deliberate large-scale CDR. As such, beyond syntheses of resource requirements and availabilities (e.g., Smith, 2016), there is a lack of observational constraints that can be applied to the assessment of the effectiveness of CDR methods. Lastly, many proposed CDR methods are premature at this point and technology deployment strategies would be required to overcome this barrier (Schäfer et al., 2015), which means that they can only be studied in an idealized manner, i.e., through model simulations.

Understanding the response of the Earth system to CDR is urgently needed because CDR is increasingly being utilized to inform policy and economic discussions. Examples of this include scenarios that are being developed with GHG emission forcing that exceeds (or overshoots) what is required to limit global mean temperatures to 2 or 1.5 °C, with the assumption that reversibility is possible with the future deployment of CDR. These scenarios are generated using integrated assessment models, which compute the emissions of GHGs, short-lived climate forcers, and land cover change associated with economic, technological, and policy drivers to achieve climate targets. Most integrated assessment models represent BECCS as the only CDR option, with only a few also including afforestation (IPCC, 2014b). During scenario development and calibration the output from the IAMs is fed into climate models of reduced complexity, for example MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change; Meinshausen et al., 2011), to calculate the global mean temperature achieved through the scenario choices, for example those in the Shared Socioeconomic Pathways (SSPs; Riahi et al., 2017). These climate models are calibrated to Earth system models or based on modeling intercomparison exercises like the Coupled Model Intercomparison Phase 5 (CMIP5), in which much of the climate–carbon cycle information comes from the Coupled Climate–Carbon Cycle Model Intercomparison Project (C4MIP). However, since the carbon cycle feedbacks of large-scale negative CO_2 emissions have not been explicitly analyzed in projects like CMIP5, with the exception of Jones et al. (2016a), many assumptions have been made about the effects of CDR on the carbon cycle and climate. Knowledge of these short-term carbon cycle feedbacks is needed to better constrain the effectiveness of the CDR technologies assumed in the IAM-generated scenarios.

This relates to the policy-relevant question of whether in a regulatory framework CO_2 removals from the atmosphere should be treated like emissions except for the opposite (negative) sign or if specific methods, which may or may not have long-term consequences (e.g., afforestation and reforestation vs. direct CO_2 air capture with geological carbon storage), should be treated differently. The lack of these kinds of analyses is a knowledge gap in current climate modeling (Jones et al., 2016a) and relevant for IAMs and political decisions. There is an urgent need to close this gap since additional CDR options like the enhanced weathering of rocks on land or direct air capture continue to be included in IAMs (e.g., Chen and Tavoni, 2013). For the policy-relevant questions it is also important to analyze the carbon cycle effects given realistic policy scenarios rather than idealized perturbations.

3 Requirements and recommendations for participation in CDRMIP

The CDRMIP initiative is designed to bring together a suite of Earth system models, Earth system models of intermediate complexity (EMICs), and potentially even box models in a common framework. Note that only models that meet certain requirements (https://pcmdi.llnl.gov/CMIP6/Guide/) can participate in an official CMIP6 capacity. Models of differing complexities are invited to participate because the questions posed above cannot be answered with any single class of models. For example, ESMs are primarily suited for investigations spanning only the next century because of the computational expense, while EMICs and box models are well suited to investigate the long-term questions surrounding CDR, but are often highly parameterized and may not include important processes, for example cloud feedbacks. The use of differing models will also provide insight into how model resolution and complexity controls modeled short- and long-term climate and carbon cycle responses to CDR.

All groups that are running models with an interactive carbon cycle are encouraged to participate in CDRMIP. We desire diversity and encourage groups to use older models with well-known characteristics, biases, and established responses (e.g., previous CMIP model versions), as well as state-of-the-art CMIP6 models. For longer model simulations, we would encourage modelers when possible to include additional carbon reservoirs, such as ocean sediments or permafrost, as these are not always implemented for short simulations. Models that only include atmospheric and oceanic carbon reservoirs are welcome and will be able to participate in some experiments. All models wishing to participate in CDRMIP must provide clear documentation that details the model version, components, and key run-time and initialization information (model time stepping, spin-up state at initialization, etc.). Furthermore, all model output must be standardized to facilitate analyses and public distribution (see Sects. 4 and 5).

3.1 Relations to other MIPs

There are no existing MIPs with experiments focused on climate “reversibility”, direct CO_2 air capture (with storage), or ocean alkalinization. However, this does not mean that there are no links between CDRMIP and other MIPs. CMIP6 and CMIP5 experiments, analyses, and assessments both provide a valuable baseline and model sensitivities that can be used to better understand CDRMIP results and we highly recommend that participants in CDRMIP also conduct other MIP experiments. Further, to maximize the use of computing resources, CDRMIP may use experiments from other MIPs as a control run for a CDRMIP experiment or to provide a pathway from which a CDRMIP experiment branches (Sects. 3.2 and 4, Tables 2–7). Principal among these is the CMIP Diagnostic, Evaluation, and Characterization of Klima (DECK) and historical experiments as detailed in Eyring et al. (2016) for CMIP6, since they provide the basis for many experiments with almost all MIPs leveraging these in some way.

Here, we additionally describe links to ongoing MIPs that are endorsed by CMIP6, noting that earlier versions of many of these MIPs were part of CMIP5 and provide a similar synergy for any CMIP5 models participating in CDRMIP.

Given the emphasis on carbon cycle perturbations in CDRMIP, there is a strong synergy with C4MIP that provides a baseline, standard protocols, and diagnostics for better understanding the relationship between the carbon cycle and the climate in CMIP6 (Jones et al., 2016b). For example, the C4MIP emissions-driven SSP5-8.5 scenario (a high CO_2 emission scenario with a radiative forcing of $8.5\,W\,m^{-2}$ in year 2100) simulation, *esm-ssp585*, is a control run and branching pathway for several CDRMIP experiments. CDRMIP experiments may equally be valuable for understanding model responses during related C4MIP experiments. For example, the C4MIP experiment *ssp534-over-bgc* is a concentration-driven “overshoot” scenario simulation that is run in a partially coupled mode. The simulation required to analyze this experiment is a fully coupled CO_2-concentration-driven simulation of this scenario, *ssp534-over*, from the Scenario Model Intercomparison Project (ScenarioMIP). The novel CDRMIP experiment, *CDR-overshoot*, which is a fully coupled CO_2-emission-driven version of this scenario, will provide additional information that can be used to extend the analyses to better understand climate–carbon cycle feedbacks.

The Land Use Model Intercomparison Project (LUMIP) is designed to better understand the impacts of land use and land cover change on the climate (Lawrence et al., 2016). The three main LUMIP foci overlap with some of the CDRMIP foci, especially in regards to land management as a CDR method (e.g., afforestation–reforestation). To facilitate land use and land cover change investigations LUMIP provides standard protocols and diagnostics for the terrestrial components of CMIP6 Earth system models. The inclusion of these diagnostics will be important for all CDRMIP experiments performed with CMIP6 models. The CDRMIP experiment on afforestation and reforestation, *CDR-afforestation* (*esm-ssp585-ssp126Lu-ext*), is also an extension of the LUMIP *esm-ssp585-ssp126Lu* simulation beyond 2100 to investigate the long-term consequences of afforestation and reforestation in a high CO_2 world (Sect. 4.3).

ScenarioMIP is designed to provide multi-model climate projections for several scenarios of future anthropogenic emissions and land use changes (O’Neill et al., 2016) and provides baselines or branching for many MIP experiments. The ScenarioMIP SSP5-3.4-OS experiments, *ssp534-over* and *ssp534-over-ext*, which prescribe atmospheric CO_2 to follow an emission overshoot pathway that is followed by aggressive mitigation to reduce emissions to zero by about 2070 with substantial negative global emissions thereafter, are used as control runs for the CDRMIP CO_2-emission-driven version of this scenario. Along with the partially coupled C4MIP version of this experiment, these experiments will allow for qualitative comparative analyses to better understand climate–carbon cycle feedbacks in an “overshoot” scenario with negative emissions (CDR). If it is found that the carbon cycle effects of CDR are improperly accounted for in the scenarios, then this information can be used to recalibrate older CDR-including IAM scenarios and be used to better constrain CDR when it is included in new scenarios.

The Ocean Model Intercomparison Project (OMIP), which primarily investigates the ocean-related origins and consequences of systematic model biases, will help to provide an understanding of ocean component functioning for models participating in CMIP6 (Griffies et al., 2016). OMIP will also establish standard protocols and output diagnostics for ocean model components. The biogeochemical protocols and diagnostics of OMIP (Orr et al., 2016) are particularly relevant for CMIP6 models participating in CDRMIP. While the inclusion of these diagnostics will be important for all CDRMIP experiments, these standards will be particularly important for facilitating the analysis of our marine CDR experiment on ocean alkalinization, *CDR–cean-alk* (Sect. 4.4).

3.2 Prerequisite and recommended CMIP simulations

The following CMIP experiments are considered prerequisites for specified CDRMIP experiments (Tables 2–7) and analyses.

- The CMIP prescribed atmospheric CO_2 preindustrial control simulation, *piControl*, is required for all CDRMIP experiments (many control runs and experiment prerequisites branch from this), and it is usually done as part of the spin-up process.

- The CMIP6 preindustrial control simulation with interactively simulated atmospheric CO_2 (i.e., the CO_2 concentration is internally calculated, but emissions are zero), *esm-piControl*, is required for CDR-

MIP experiments *CDR-pi-pulse*, *CDR-overshoot*, *CDR-afforestation*, and *CDR-ocean-alk*.

- The CMIP 1 % per year increasing CO_2 simulation, *1pctCO*$_2$, is initialized from a preindustrial CO_2 concentration with CO_2 then increasing by 1 % per year until the CO_2 concentration has quadrupled (approximately 139 years). This is required for CDRMIP experiment *CDR-reversibility*.

- The CMIP6 historical simulation, *historical*, in which historical atmospheric CO_2 forcing is prescribed along with land use, aerosols, and non-CO_2 greenhouse gas forcing, is required for CDRMIP experiment *CDR-yr2010-pulse*.

- The CMIP6 emissions-driven historical simulation, *esm-hist*, in which the atmospheric CO_2 concentration is internally calculated in response to historical anthropogenic CO_2 emissions forcing (other forcing such as land use, aerosols, and non-CO_2 greenhouse gases are prescribed), is required for CDRMIP experiments *CDR-overshoot*, *CDR-afforestation*, and *CDR-ocean-alk*.

- The LUMIP *esm-ssp585-ssp126Lu* simulation, which simulates afforestation in a high CO_2 emission scenario, is the basis for CDRMIP experiment *esm-ssp585-ssp126Lu-ext*.

- The C4MIP *esm-ssp585* simulation is a high emission scenario and serves as a control run and branching pathway for the CDRMIP *CDR-ocean-alk* experiment.

We also highly recommend that groups run these additional C4MIP and ScenarioMIP simulations.

- The ScenarioMIP *ssp534-over* and *ssp534-over-ext* simulations, which prescribe the atmospheric CO_2 concentration to follow an emission overshoot pathway that is followed by aggressive mitigation to reduce emissions to zero by about 2070, with substantial negative global emissions thereafter. These results can be qualitatively compared to CDRMIP experiment *CDR-overshoot*, which is the same scenario but driven by CO_2 emissions.

- The C4MIP *ssp534-over-bgc* and *ssp534-over-bgcExt* simulations, which are biogeochemically coupled versions of the *ssp534-over* and *ssp534-over-ext* simulations, i.e., only the carbon cycle components (land and ocean) see the prescribed increase in the atmospheric CO_2 concentration; the model's radiation scheme sees a fixed preindustrial CO_2 concentration. These results can be qualitatively compared to CDRMIP experiment *CDR-overshoot*, which is a fully coupled version of this scenario.

3.3 Simulation ensembles

We encourage participants whose models have internal variability to conduct multiple realizations, i.e., ensembles, for all experiments. While these are highly desirable, they are neither mandatory nor a prerequisite for participation in CDRMIP. Therefore, the number of ensemble members is at the discretion of each modeling group. However, we strongly encourage groups to submit at least three ensemble members if possible.

3.4 Climate sensitivity calculation

Knowing the climate sensitivity of each model participating in CDRMIP is important for interpreting the results. For modeling groups that have not already calculated their model's climate sensitivity, the required CMIP *1pctCO*$_2$ simulation can be used to calculate both the transient and equilibrium climate sensitivities. The transient climate sensitivity can be calculated as the difference in the global annual mean surface temperature between the start of the experiment and a 20-year period centered on the time of CO_2 doubling. The equilibrium response can be diagnosed following Gregory (2004), Frölicher et al. (2013), or if possible (desirable) by running the model to an equilibrium state at $2 \times CO_2$ or $4 \times CO_2$.

3.5 Model drift

Model drift (Gupta et al., 2013; Séférian et al., 2016) is a concern for all CDRMIP experiments because if a model is not at an equilibrium state when the experiment or prerequisite CMIP experiment begins, then the response to any experimental perturbations could be confused by drift. Thus, before beginning any of the experiments a model must be spun up to eliminate long-term drift in carbon reservoirs or fluxes. Groups participating in CMIP6 should follow the C4MIP protocols described in Jones et al. (2016b) to ensure that drift is acceptably small. This means that land, ocean, and atmosphere carbon stores should each vary by less than 10 Gt C per century (long-term average ≤ 0.1 Gt C yr^{-1}). We leave it to individual groups to determine the length of the run required to reach such a state. If older model versions, for example CMIP5, are used for any experiments, any known drift should be documented.

4 Experimental design and protocols

To facilitate multiple model needs, the experiments described below have been designed to be relatively simple to implement. In most cases, they were also designed to have high signal-to-noise ratios to better understand how the simulated Earth system responds to significant CDR perturbations. While there are many ways in which such experiments could be designed to address the questions surrounding climate reversibility and each proposed CDR method, the CDR-MIP, like all MIPs, must be limited to a small number of practical experiments. Therefore, after careful consideration, one experiment was chosen specifically to address climate reversibility and several more were chosen to investigate CDR through the idealized direct air capture of CO_2 (DAC), afforestation and reforestation, and ocean alkalinization (Table 1). Experiments are prioritized based on a tiered system, although we encourage modeling groups to complete the full suite of experiments. Unfortunately, limiting the number of experiments means that a number of potentially promising or widely utilized CDR methods or combinations of methods must wait until a later time, i.e., a second phase, to be investigated in a multi-model context. In particular, the exclusion of biomass energy with carbon capture and storage (BECCS) is unfortunate, as this is the primary CDR method in the Representative Concentration Pathway (RCP) and Shared Socioeconomic Pathway (SSP) scenarios used in CMIP5 and 6, respectively. However, there was no practical way to design a less idealized BECCS experiment as most state-of-the-art models are either incapable of simulating a biomass harvest with permanent removal or would require a substantial amount of reformulating to do so in a manner that allows for comparable multi-model analyses.

In some of the experiments described below we ask that non-CO_2 forcing (e.g., land use change, radiative forcing from other greenhouse gases, etc.) be held constant, for example at that of a specific year, so that only changes in other forcing, like CO_2 emissions, drive the main model response. For some forcing, for example aerosol emissions, this may mean that monthly changes in forcing are repeated throughout the rest of the simulation as if it was always one particular year. However, we recognize that models apply forcing in different ways and leave it to individual modeling groups to determine the best way to hold forcing constant. We request that the methodology for holding forcing constant be documented for each model.

4.1 Climate and carbon cycle reversibility experiment (*CDR-reversibility*)

If CO_2 emissions are not reduced quickly enough and more warming occurs than is desirable or tolerable, then it is important to understand if CDR has the potential to "reverse" climate change. Here we propose an idealized Tier 1 experiment that is designed to investigate CDR-induced climate "reversibility" (Fig. 1, Table 2). This experiment investigates the "reversibility" of the climate system by leveraging the prescribed $1\,\%\,yr^{-1}$ CO_2 concentration increase experiment that was done for prior CMIPs and is a key run for CMIP6 (Eyring et al., 2016; Meehl et al., 2014). The CDRMIP experiment starts from the $1\,\%\,yr^{-1}$ CO_2 concentration increase experiment, *1pctCO2*, and then at the $4 \times CO_2$ concentration level prescribes a $-1\,\%\,yr^{-1}$ removal of CO_2 from the atmosphere to preindustrial levels (Fig. 1; this is also similar

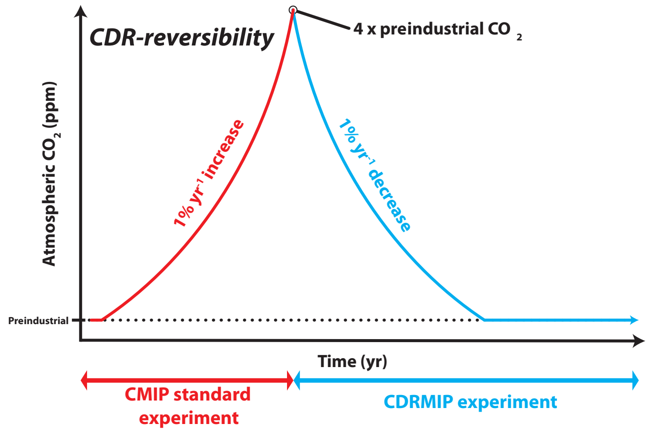

Figure 1. Schematic of the CDRMIP climate and carbon cycle reversibility experimental protocol (*CDR-reversibility*). From a preindustrial run at steady state atmospheric CO_2 is prescribed to increase and then decrease over a $\sim$ 280-year period, after which it is held constant for as long as computationally possible.

to experiments in Boucher et al., 2012, and Zickfeld et al., 2016). This approach is analogous to an unspecified CDR application or DAC, in which CO_2 is removed to permanent storage to return atmospheric CO_2 to a prescribed level, i.e., a preindustrial concentration. To do this, CDR would have to counter emissions (unless they have ceased) and changes in atmospheric CO_2 due to the response of the ocean and terrestrial biosphere. We realize that the technical ability of CDR methods to remove such enormous quantities of CO_2 on such a relatively short timescale (i.e., in a few centuries) is unrealistic. However, branching from the existing CMIP *1pctCO2* experiment provides a relatively straightforward opportunity, with a high signal-to-noise ratio, to explore the effect of large-scale removal of CO_2 from the atmosphere and issues involving reversibility (Fig. 2 shows exemplary *CDR-reversibility* results from two models).

4.1.1 Protocol for *CDR-reversibility*

Prerequisite simulations. Perform the CMIP *piControl* and the *1pctCO2* experiments. The *1pctCO2* experiment branches from the DECK *piControl* experiment, which should ideally represent a near-equilibrium state of the climate system under imposed year 1850 conditions. Starting from year 1850 conditions (*piControl* global mean atmospheric CO_2 should be 284.7 ppm) the *1pctCO2* simulation prescribes a CO_2 concentration increase at a rate of $1\,\%\,yr^{-1}$ (i.e., exponentially). The only externally imposed difference from the *piControl* experiment is the change in CO_2; i.e., all other forcing is kept at that of year 1850. A restart must be generated when atmospheric CO_2 concentrations are 4 times that of the *piControl* simulation (1138.8 ppm; this should be 140 years into the run). Groups that have already performed the *piControl* and *1pctCO2* simulations for CMIP5 or CMIP6

Table 2. Climate and carbon cycle reversibility experiment (*CDR-reversibility*) simulations. All simulations are required to complete the experiment.

CMIP6 Experiment ID	Simulation description	Owning MIP	Run length (years)	Initialized using a restart from
piControl	Preindustrial prescribed CO_2 control simulation	CMIP6 DECK	100[a]	the model spin-up
1pctCO2	Prescribed 1 % yr^{-1} CO_2 increase to 4 × the preindustrial level	CMIP6 DECK CMIP6 DECK	140[b] 140[b]	*piControl* *piControl*
1pctCO2-cdr	1 % yr^{-1} CO_2 decrease from 4 × the preindustrial level until the preindustrial CO_2 level is reached and held for as long as possible	CDRMIP	200 min. 5000 max.	*1pctCO2*

[a] This CMIP6 DECK should have been run for at least 500 years. Only the last 100 years are needed as a control for *CDR-reversibility*. [b] This CMIP6 DECK experiment is 150 years long. A restart for *CDR-reversibility* should be generated after 139 years when CO_2 is 4 times that of *piControl*.

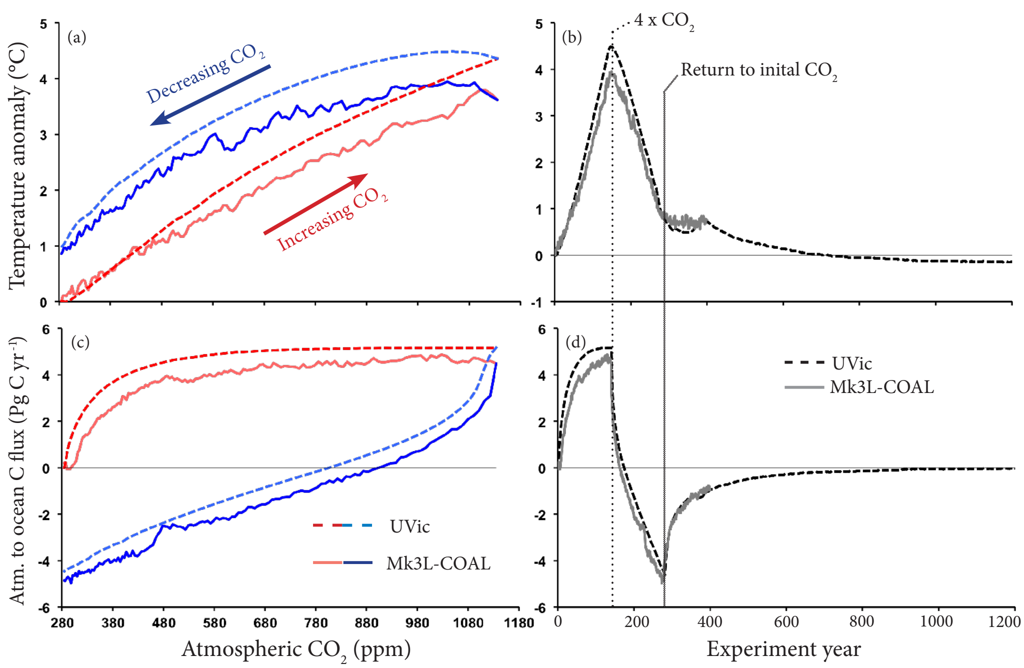

Figure 2. Exemplary climate and carbon cycle reversibility experiment (*CDR-reversibility*) results with the Mk3L-COAL Earth system model and the University of Victoria (UVic) Earth system model of intermediate complexity (models are described in Appendix D). The left panels show annual global mean **(a)** temperature anomalies (°C; relative to pre-industrial temperatures) and **(c)** the atmosphere to ocean carbon fluxes (Pg C yr^{-1}) versus the atmospheric CO_2 (ppm) during the first 280 years of the experiment (i.e., when CO_2 is increasing and decreasing). The right panels show the same **(b)** temperature anomalies and **(d)** the atmosphere to ocean carbon fluxes versus time. Note that the Mk3L-COAL simulation was only 400 years long.

may provide a link to them if they are already on the Earth System Grid Federation (ESGF) that hosts CMIP data.

The 1pctCO2-cdr simulation. Use the 4 × CO_2 restart from *1pctCO2* and prescribe a 1 % yr^{-1} removal of CO_2 from the atmosphere (start removal at the beginning of the 140th year: 1 January) until the CO_2 concentration reaches 284.7 ppm (140 years of removal). As in *1pctCO2* the only externally imposed forcing should be the change in CO_2 (all other forcing is kept at that of year 1850). The CO_2 concentration should then be held at 284.7 ppm for as long as possible (a minimum of 60 years is required), with no change in other forcing. EMICs and box models are encouraged to extend runs for at least 1000 years (and up to 5000 years) at 284.7 ppm CO_2 to investigate long-term climate system and carbon cycle reversibility (see Fig. 2b and d for examples of why it is important to understand the long-term response).

4.2 Direct CO_2 air capture with permanent storage experiments (*CDR-pi-pulse*, *CDR-year2010-pulse*, *CDR-overshoot*)

The idea of directly removing excess CO_2 from the atmosphere (i.e., concentrations above preindustrial levels) and permanently storing it in some reservoir, such as a geological formation, is appealing because such an action would theoretically address the main cause of climate change: anthropogenically emitted CO_2 that remains in the atmosphere. Laboratory studies and small-scale pilot plants have demonstrated that atmospheric CO_2 can be captured by several different methods that are often collectively referred to as direct air capture (DAC) technology (Holmes and Keith, 2012; Lackner et al., 2012; Sanz-Pérez et al., 2016). Technology has also been developed that can place captured carbon in permanent reservoirs, i.e., carbon capture and storage (CCS) methods (Matter et al., 2016; Scott et al., 2013, 2015). DAC technology is currently prohibitively expensive to deploy on large scales and may be technically difficult to scale up (National Research Council, 2015), but it does appear to be a potentially viable CDR option. However, aside from the technical questions involved in developing and deploying such technology, there remain questions about how the Earth system would respond if CO_2 were removed from the atmosphere.

Here we propose a set of experiments that are designed to investigate and quantify the response of the Earth system to idealized large-scale DAC. In all experiments, atmospheric CO_2 is allowed to freely evolve to investigate carbon cycle and climate feedbacks in response to DAC. The first two idealized experiments described below use the approach of an instantaneous (pulse) CO_2 removal from the atmosphere for this investigation. Instantaneous CO_2 removal perturbations were chosen since pulsed CO_2 addition experiments have already been proven useful for diagnosing carbon cycle and climate feedbacks in response to CO_2 perturbations. For example, previous positive CO_2 pulse experiments have been used to calculate global warming potential (GWP) and global temperature change potential (GTP) metrics (Joos et al., 2013). The experiments described below build upon the previous positive CO_2 pulse experiments, i.e., the PD100 and PI100 impulse experiments described in Joos et al. (2013), in which 100 Gt C is instantly added to preindustrial and near present day simulated climates. However, our experiments also prescribe a negative CDR pulse as opposed to just adding CO_2 to the atmosphere. Two experiments are desirable because the Earth system response to CO_2 removal will be different when starting from an equilibrium state versus starting from a perturbed state (Zickfeld et al., 2016). One particular goal of these experiments is to estimate a global cooling potential (GCP) metric based on a CDR impulse response function (IRF_{CDR}). Such a metric will be useful for calculating how much CO_2 is removed by DAC and how much DAC is needed to achieve a particular climate target.

The third experiment, which focuses on "negative emissions", is based on the Shared Socioeconomic Pathway (SSP) 5-3.4 overshoot scenario and its long-term extension (Kriegler et al., 2016; O'Neill et al., 2016). This scenario is of interest to CDRMIP because after an initially high level of emissions, which follows the SSP5-8.5 unmitigated baseline scenario until 2040, CO_2 emissions are rapidly reduced with net CO_2 emissions becoming negative after the year 2070 and continuing to be so until the year 2190 when they reach zero. In the original SSP5-3.4-OS scenario, the negative emissions are achieved using BECCS. However, as stated earlier there is currently no practical way to design a good multi-model BECCS experiment. Therefore, in our experiments negative emissions are achieved by simply removing CO_2 from the atmosphere and assuming that it is permanently stored in a geological reservoir. While this may violate the economic assumptions underlying the scenario, it still provides an opportunity to explore the response of the climate and carbon cycle to potentially achievable levels of negative emissions.

According to calculations done with a simple climate model, MAGICC version 6.8.01 BETA (Meinshausen et al., 2011; O'Neill et al., 2016), the SSP5-3.4-OS scenario considerably overshoots the $3.4\,W\,m^{-2}$ forcing level, with a peak global mean temperature of about 2.4 °C, before returning to $3.4\,W\,m^{-2}$ at the end of the century. Eventually in the long-term extension of this scenario, the forcing stabilizes just above $2\,W\,m^{-2}$, with a global mean temperature that should equilibrate at about 1.25 °C above preindustrial temperatures. Thus, in addition to allowing for an investigation into the response of the climate and carbon cycle to negative emissions, this scenario also provides the opportunity to investigate issues of reversibility, albeit on a shorter timescale and with less of an "overshoot" than in experiment *CDR-reversibility*.

4.2.1 Instantaneous CO_2 removal and addition from an unperturbed climate experimental protocol (*CDR-pi-pulse*)

This idealized Tier 1 experiment is designed to investigate how the Earth system responds to DAC when perturbed from an equilibrium state (Fig. 3, Table 3). The idea is to provide a baseline system response that can later be compared to the response of a perturbed system, i.e., experiment *CDR-yr2010-pulse* (Sect. 4.2.3). By also performing another simulation in which the same amount of CO_2 is added to the system, it will be possible to diagnose if the system responds in an inverse manner when the CO_2 pulse is positive. Many modeling groups will have already conducted the prerequisite simulation for this experiment in preparation for other modeling research, for example during model spin-up or for CMIP, which should minimize the effort needed to perform the complete experiment. The protocol is as follows.

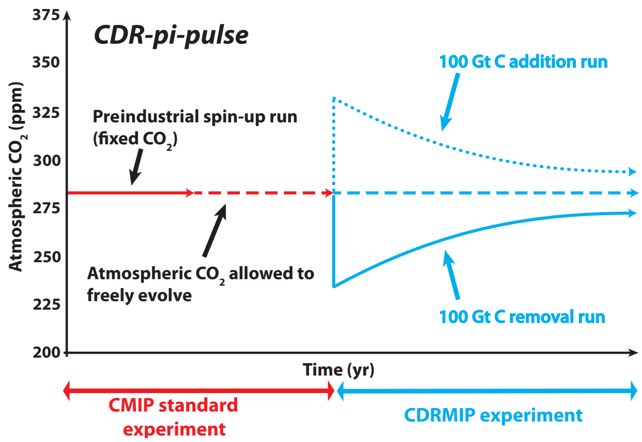

Figure 3. Schematic of the CDRMIP instantaneous CO_2 removal and addition from an unperturbed climate experimental protocol (*CDR-pi-pulse*). Models are spun up for as long as possible with a prescribed preindustrial atmospheric CO_2 concentration. Then atmospheric CO_2 is allowed to freely evolve for at least 100 years as a control run. The negative–positive pulse experiments are conducted by instantly removing or adding 100 Gt C to the atmosphere of a simulation in which the atmosphere is at steady state and CO_2 can freely evolve. These runs continue for as long as computationally possible.

Prerequisite simulation. This is a control simulation under preindustrial conditions with freely evolving CO_2. All boundary conditions (solar forcing, land use, etc.) are expected to remain constant. This is also the CMIP5 *esmControl* simulation (Taylor et al., 2012) and the CMIP6 *esm-piControl* simulation (Eyring et al., 2016). Note that this is exactly the same as PI100 run 4 in Joos et al. (2013).

The esm-pi-cdr-pulse simulation. This is as in *esm-Control* or *esm-piControl*, but with 100 Gt C instantaneously (within 1 time step) removed from the atmosphere in year 10. If models have CO_2 spatially distributed throughout the atmosphere, we suggest removing this amount in a uniform manner. After the negative pulse, ESMs should continue the run for at least 100 years, while EMICs and box models are encouraged to continue the run for at least 1000 years (and up to 5000 years if possible). Figure 4 shows example *esm-pi-cdr-pulse* model responses.

The esm-pi-CO2pulse simulation. This is the same as *esm-pi-cdr-pulse*, but add a positive 100 Gt C pulse (within 1 time step) as in Joos et al. (2013) instead of a negative one. If models have CO_2 spatially distributed throughout the atmosphere, we suggest adding CO_2 in a uniform manner. Note that this would be exactly the same as the PI100 run 5 in Joos et al. (2013) and can thus be compared to this earlier study.

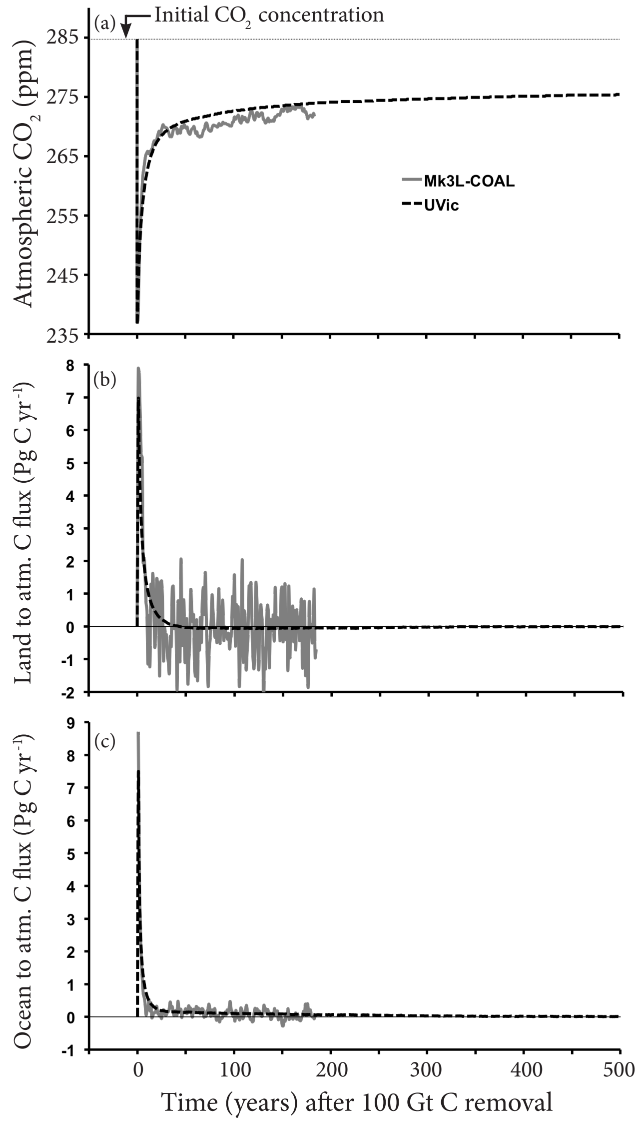

Figure 4. Exemplary instantaneous CO_2 removal from a preindustrial climate experiment (*CDR-pi-pulse*) results from the *esm-pi-cdr-pulse* simulation with the Mk3L-COAL Earth system model and the University of Victoria (UVic) Earth system model of intermediate complexity (models are described in Appendix D). **(a)** Atmospheric CO_2 vs. time, **(b)** the land to atmosphere carbon flux vs. time, and **(c)** the ocean to atmosphere carbon flux vs. time. Note that the Mk3LCOAL simulation was only 184 years long.

4.2.2 Instantaneous CO_2 removal from a perturbed climate experimental protocol (*CDR-yr2010-pulse*)

This Tier 3 experiment is designed to investigate how the Earth system responds when CO_2 is removed from an anthropogenically altered climate not in equilibrium (Fig. 5, Table 4). Many modeling groups will have already conducted part of the first run of this experiment in preparation for other

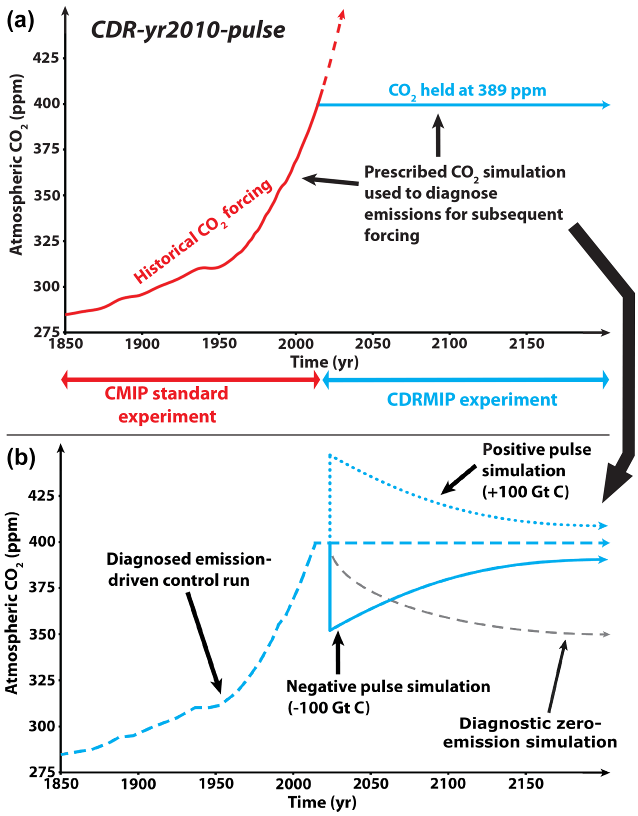

Figure 5. Schematic of the CDRMIP instantaneous CO_2 removal and addition from a perturbed climate experimental protocol (*CDR-yr2010-pulse*). **(a)** Initially historical CO2 forcing is prescribed and then held constant at 389 ppm (∼ year 2010) while CO_2 emissions are diagnosed. **(b)** A control simulation is conducted using the diagnosed emissions. The negative–positive pulse experiments are conducted by instantly removing or adding 100 Gt C to the atmosphere of the CO_2-emission-driven simulation 5 years after CO_2 reaches 389 ppm. Another control simulation is also conduced that sets emissions to zero at the time of the negative pulse. The emission-driven simulations continue for as long as computationally possible.

modeling research, for example CMIP, and may be able to use a "restart" file to initialize the first run, which should reduce the effort needed to perform the complete experiment.

Prerequisite simulation. This is a prescribed CO_2 run. Historical atmospheric CO_2 is prescribed until a concentration of 389 ppm is reached (∼ year 2010; Fig. 5a). Other historical forcing, i.e., from CMIP, should also be applied. An existing run or setup from CMIP5 or CMIP6 may also be used to reach a CO_2 concentration of 389 ppm, for example the RCP 8.5 CMIP5 simulation or the CMIP6 *historical* experiment. During this run, compatible emissions should be frequently diagnosed (at least annually).

The yr2010CO2 simulation. Atmospheric CO_2 should be held constant at 389 ppm with other forcing, like land use and aerosol emissions, also held constant (Fig. 5a). ESMs should continue the run at 389 ppm for at least 105 years, while EMICs and box models are encouraged to continue the run for as long as needed for the subsequent simulations (e.g., 1000+ years). During this run, compatible emissions should be frequently diagnosed (at least annually). Note that when combined with the prerequisite simulation described above this is exactly the same as the PD100 run 1 in Joos et al. (2013).

The esm-yr2010CO2-control simulation. This is a diagnosed emissions control run. The model is initialized from the preindustrial period (i.e., using a restart from either *piControl* or *esm-piControl*) with the emissions diagnosed in the *historical* and *yr2010CO2* simulations, i.e., year 1850 to approximately year 2115 for ESMs and longer for EMICs and box models (up to 5000 years). All other forcing should be as in the *historical* and *yr2010CO2* simulations. Atmospheric CO_2 must be allowed to freely evolve. The results should be quite close to those in the *historical* and *yr2010CO2* simulations. If there are significant differences, for example due to climate–carbon cycle feedbacks that become evident when atmospheric CO_2 is allowed to freely evolve, then they must be diagnosed and used to adjust the CO_2 emission forcing. In some cases it may be necessary to perform an ensemble of simulations to diagnose compatible emissions. Note that this is exactly the same as the PD100 run 2 in Joos et al. (2013). As in Joos et al. (2013), if computational time is an issue and if a group is sure that CO_2 remains at a nearly constant value with the emissions diagnosed in *yr2010CO2*, the *esm-yr2010CO2-control* simulation may be skipped. This may only apply to ESMs and it is strongly recommended to perform the *esm-yr2010CO2-control* simulation to avoid model drift.

The esm-yr2010CO2-cdr-pulse simulation. This is a CO_2 removal simulation. Setup is initially as in the *esm-yr2010CO2-control* simulation. However, a "negative" emissions pulse of 100 Gt C is subtracted instantaneously (within 1 time step) from the atmosphere 5 years after the time at which CO_2 was held constant in the *esm-yr2010CO2-control* simulation (this should be at the beginning of the year 2015), with the run continuing thereafter for at least 100 years (up to 5000 years if possible). If models have CO_2 spatially distributed throughout the atmosphere, we suggest removing this amount in a uniform manner. It is crucial that the negative pulse be subtracted from a constant background concentration of ∼ 389 ppm. All forcing, including CO_2 emissions, must be exactly as in the *esm-yr2010CO2-control* simulation so that the only difference between these runs is that this one has had CO_2 instantaneously removed from the atmosphere.

The esm-yr2010CO2-noemit simulation. This is a zero CO_2 emissions control run. Setup is initially as in the *esm-yr2010CO2-cdr-pulse* simulation. However, at the time of the "negative" emissions pulse in the *esm-yr2010CO2-cdr-pulse* simulation, emissions are set to zero with the run continuing thereafter for at least 100 years. If possible, extend the runs for at least 1000 years (and up to 5000 years). All other forcing must be exactly as in the *esm-yr2010CO2-*

Table 3. Instantaneous CO_2 removal from an unperturbed climate experiment (*CDR-pi-pulse*) simulation. All simulations are required to complete the experiment.

CMIP6 Experiment ID	Simulation description	Owning MIP	Run length (years)	Initialized using a restart from
esm-piControl	Preindustrial freely evolving CO_2 control simulation	CMIP6 DECK	100*	the model spin-up
esm-pi-cdr-pulse	100 Gt C is instantly removed (negative pulse) from a preindustrial atmosphere	CDRMIP	100 min. 5000 max.	*esm-piControl*
esm-pi-CO2pulse	100 Gt C is instantly added (positive pulse) to a preindustrial atmosphere	CDRMIP	100 min. 5000 max.	*esm-piControl*

* This CMIP6 DECK should have been run for at least 500 years. Only the last 100 years are needed as a control for *CDR-pi-pulse*.

Table 4. Instantaneous CO_2 removal from a perturbed climate experiment (*CDR-yr2010-pulse*) simulation. All simulations are required to complete the experiment.

CMIP6 Experiment ID	Simulation description	Owning MIP	Run length (years)	Initialized using a restart from
historical	Historical atmospheric CO_2 (and other forcing) is prescribed until a concentration of 389 ppm CO_2 is reached	CMIP6 DECK	160*	*piControl*
yr2010CO2	Branching from *historical*, atmospheric CO_2 is held constant (prescribed) at 389 ppm; other forcing is also held constant at the 2010 level	CDRMIP	105 min. 5000 max.	*historical*
esm-yr2010CO2-control	Control run forced using CO_2 emissions diagnosed from *historical* and *yr2010CO2* simulations; other forcing as in *historical* until 2010 after which it is constant	CDRMIP	265 min. 5160 max.	*esm-piControl* or *piControl*
esm-yr2010CO2-noemit	Control run that branches from *esm-yr2010CO2-control* in year 2010 with CO_2 emissions set to zero 5 years after the start of the simulation	CDRMIP	105 min. 5000 max.	*esm-yr2010CO2-control*
esm-yr2010CO2-cdr-pulse	Branches from *esm-yr2010CO2-control* in year 2010 with 100 Gt C instantly removed (negative pulse) from the atmosphere 5 years after the start of the simulation	CDRMIP	105 min. 5000 max.	*esm-yr2010CO2-control*
esm-yr2010CO2-CO2pulse	Branches from *esm-yr2010CO2-control* in year 2010 with 100 Gt C instantly added (positive pulse) to the atmosphere 5 years after the start of the simulation	CDRMIP	105 min. 5000 max.	*esm-yr2010CO2-control*

* This CMIP6 DECK continues until the year 2015 but only the first 160 years are need for *CDR-yr2010-pulse*.

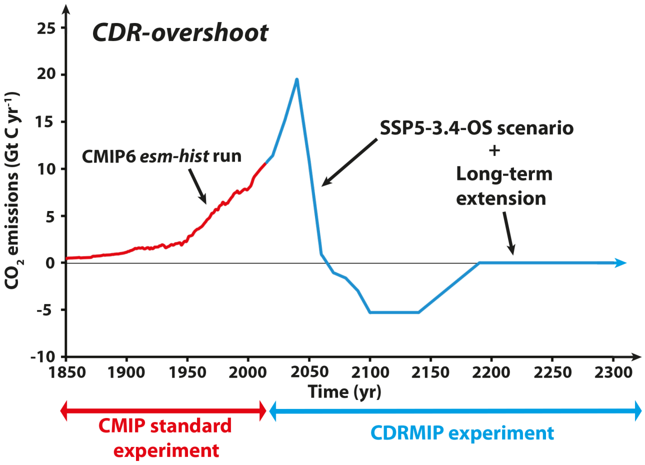

Figure 6. Schematic of the CDRMIP emission-driven SSP5-3.4-OS scenario experimental protocol (*CDR-overshoot*). A CO_2-emission-driven historical simulation is conducted until the year 2015. Then an emission-driven simulation with SSP5-3.4-OS scenario forcing is conducted. This simulation is extended until the year 2300 using SSP5-3.4-OS scenario long-term extension forcing. Thereafter, runs may continue for as long as computationally possible with constant forcing after the year 2300.

control simulation. This experiment will be used to isolate the Earth system response to the negative emissions pulse in the *esm-yr2010CO2-cdr-pulse* simulation, which convolves the response to the negative emissions pulse with the lagged response to the preceding positive CO_2 emissions (diagnosed with the zero emissions simulation). The response to the negative emissions pulse will be calculated as the difference between *esm-yr2010CO2-cdr-pulse* and *esm-yr2010CO2-noemit* simulations.

The esm-yr2010CO2-CO2pulse simulation. This is a CO_2 addition simulation. Setup is initially as in the *esm-yr2010CO2-cdr-pulse* simulation. However, a "positive" emissions pulse of 100 Gt C is added instantaneously (within 1 time step), with the run continuing thereafter for a minimum of 100 years. If models have CO_2 spatially distributed throughout the atmosphere, we suggest adding CO_2 in a uniform manner. If possible, extend the runs for at least 1000 years (and up to 5000 years). It is crucial that the positive pulse be added to a constant background concentration of ~ 389 ppm. All forcing, including CO_2 emissions, must be exactly as in the *esm-yr2010CO2-control* simulation so that the only difference between these runs is that this one has had CO_2 instantaneously added to the atmosphere. Note that this would be exactly the same as the PD100 run in Joos et al. (2013). This will be used to investigate if, after positive and negative pulses, carbon cycle and climate feedback responses, which are expected to be opposite in sign, differ in magnitude and temporal scale. The results can also be compared to Joos et al. (2013).

4.2.3 Emission-driven SSP5-3.4-OS experimental protocol (*CDR-overshoot*)

This Tier 2 experiment explores CDR in an "overshoot" climate change scenario, the SSP5-3.4-OS scenario (Fig. 6, Table 5). To start, groups must perform the CMIP6 emission-driven historical simulation, *esm-hist*. Then using this as a starting point, conduct an emissions-driven SSP5-3.4-OS scenario simulation, *esm-ssp534-over* (starting on 1 January 2015), that includes the long-term extension to the year 2300. All non-CO_2 forcing should be identical to that in the ScenarioMIP *ssp534-over* and *ssp534-over-ext* simulations. If computational resources are sufficient, we recommend that the *esm-ssp534-over* simulation be continued for at least another 1000 years with year 2300 forcing; i.e., the forcing is held constant at year 2300 levels as the simulation continues for as long as possible (up to 5000 years) to better understand processes that are slow to equilibrate, for example ocean carbon and heat exchange or permafrost dynamics.

4.3 Afforestation–reforestation experiment (*CDR-afforestation*)

Enhancing the terrestrial carbon sink by restoring or extending forest cover, i.e., reforestation and afforestation, has often been suggested as a potential CDR option (National Research Council, 2015; The Royal Society, 2009). Enhancing this sink is appealing because terrestrial ecosystems have cumulatively absorbed over one-quarter of all fossil fuel emissions (Le Quéré et al., 2016) and could potentially sequester much more. Most of the key questions concerning land use change are being addressed by LUMIP (Lawrence et al., 2016). These include investigations into the potential and side effects of afforestation and reforestation to mitigate climate change, for which they have designed four experiments (LUMIP Phase 2 experiments). However, three of these experiments are CO_2 concentration driven and thus are unable to fully investigate the climate–carbon cycle feedbacks that are important for CDRMIP. The LUMIP experiment in which CO_2 emissions force the simulation, *esm-ssp585-ssp126Lu*, will allow for climate–carbon cycle feedbacks to be investigated. Unfortunately, since this experiment ends in the year 2100 it is too short to answer some of the key CDRMIP questions (Sect. 1.2). We have therefore decided to extend this LUMIP experiment within the CDRMIP framework as a Tier 2 experiment (Table 6) to better investigate the longer-term CDR potential and risks of afforestation and reforestation.

The LUMIP experiment, *esm-ssp585-ssp126Lu*, simulates afforestation and reforestation by combining a high SSP CO_2 emission scenario, SSP5-8.5, with a future land use change scenario from an alternative SSP scenario, SSP1-2.6, which has much greater afforestation and reforestation (Kriegler et al., 2016; Lawrence et al., 2016). By comparing this combination to the SSP5-8.5 baseline scenario, it will be possible to determine the CDR potential of this particular afforestation–

Table 5. Emission-driven SSP5-3.5-OS scenario experiment (*CDR-overshoot*) simulations. All simulations are required to complete the experiment.

CMIP6 Experiment ID	Simulation description	Owning MIP	Run length (years)	Initialized using a restart from
esm-hist	Historical simulation forced with CO_2 emissions	CMIP6 DECK	265	*esm-piControl* or *piControl*
esm-ssp534-over	CO_2-emission-driven SSP5-3.4 overshoot scenario simulation	CDRMIP	85 min. 5000 max.	*esm-hist*

Table 6. Afforestation–reforestation experiment (*CDR-afforestation*) simulations. All simulations are required to complete the experiment.

CMIP6 Experiment ID	Simulation description	Owning MIP	Run length (years)	Initialized using a restart from
esm-ssp585	CO_2-emission-driven SSP5-8.5 scenario	C4MIP	85	*esm-hist*
esm-ssp585-ssp126Lu	CO_2-emission-driven SSP5-8.5 scenario with SSP1-2.6 land use forcing	LUMIP	85	*esm-hist*
esm-ssp585-ssp126Lu-ext	Long-term extension of the *esm-ssp585-ssp126Lu* simulation	CDRMIP	200 min. 5000 max.	*esm-ssp585-ssp126Lu*
esm-ssp585ext	Long-term extension of the CO_2-emission-driven SSP5-8.5 scenario	CDRMIP	200 min. 5000 max.	*esm-ssp585*

reforestation scenario in a high CO_2 world. This is similar to the approach of Sonntag et al. (2016) using RCP 8.5 emissions combined with prescribed RCP 4.5 land use.

4.3.1 *CDR-afforestation* experimental protocol

Prerequisite simulations. Conduct the C4MIP emission-driven *esm-ssp585* simulation, which is a control run, and the LUMIP Phase 2 experiment *esm-ssp585-ssp126Lu* (Lawrence et al., 2016). Generate restart files in the year 2100.

The esm-ssp585-ssp126Lu-ext simulation. Using the year 2100 restart from the *esm-ssp585-ssp126Lu* experiment, it continues the run with the same LUMIP protocol (i.e., an emission-driven SSP5-8.5 simulation with SSP1-2.6 land use instead of SSP5-8.5 land use) until the year 2300 using the SSP5-8.5 and SSP1-2.6 long-term extension data (O'Neill et al., 2016). If computational resources are sufficient, we recommend that the simulation be continued for at least another 1000 years with year 2300 forcing (i.e., forcing is held at year 2300 levels as the simulation continues for as long as possible; up to 5000 years). This is to better understand processes that are slow to equilibrate, for example ocean carbon and heat exchange or permafrost dynamics, and the issue of permanence.

The esm-ssp585ext simulation. The emission-driven esmSSP5-8.5 simulation must be extended beyond the year 2100 to serve as a control run for the *esm-ssp585-ssp126Lu-ext* simulation. This will require using the ScenarioMIP *ssp585-ext* forcing, but driving the model with CO_2 emissions instead of prescribing the CO_2 concentration. If computational resources are sufficient, the simulation should be extended even further than in the official SSP scenario, which ends in year 2300, by keeping forcing constant after this time (i.e., forcing is held at year 2300 levels as the simulation continues for as long as possible; up to 5000 years).

4.4 Ocean alkalinization experiment (*CDR-ocean-alk*)

Enhancing the natural process of weathering, which is one of the key negative climate–carbon cycle feedbacks that removes CO_2 from the atmosphere on long timescales (Colbourn et al., 2015; Walker et al., 1981), has been proposed as a potential CDR method (National Research Council, 2015; The Royal Society, 2009). Enhanced weathering ideas have been proposed for both the terrestrial environment (Hartmann et al., 2013) and the ocean (Köhler et al., 2010; Schuiling and Krijgsman, 2006). We focus on the alkalinization of the ocean given its capacity to take up vast quantities of carbon over relatively short time periods and its potential to reduce the rate and impacts of ocean acidification (Kroeker et al., 2013). The idea is to dissolve silicate or carbonate minerals in seawater to increase total alkalinity. Total alkalinity, which can chemically be defined as the excess of proton acceptors over proton donors with respect to a certain zero level of protons, is a measurable quantity that is related to the concentrations of species of the marine carbonate system (Wolf-Gladrow et al., 2007). It plays a key role in determining the air–sea gas exchange of CO_2 (Egleston et al., 2010). When total alkalinity is artificially increased in surface waters, it basically allows more CO_2 to dissolve in the seawater and be stored as ions such as bicarbonate or carbonate; i.e., the general methodology increases the carbon storage capacity of seawater.

Theoretical work and idealized modeling studies have suggested that ocean alkalinization may be an effective CDR method that is more limited by logistic constraints (e.g., mining, transport, and mineral processing) rather than natural ones, such as available ocean area, although chemical constraints and side effects do exist (González and Ilyina, 2016; Ilyina et al., 2013; Keller et al., 2014; Köhler et al., 2010, 2013). One general side effect of ocean alkalinization is that it increases the buffering capacity and pH of the seawater. While such a side effect could be beneficial or even an intended effect to counter ocean acidification (Feng et al., 2016), high levels of alkalinity may also be detrimental to some organisms (Cripps et al., 2013). Ocean alkalinization likely also has method-specific side effects. Many of these side effects are related to the composition of the alkalizing agent, for example olivine may contain nutrients or toxic heavy metals, which could affect marine organisms and ecosystems (Hauck et al., 2016; Köhler et al., 2013). Other side effects could be caused by the mining, processing, and transport of the alkalizing agent, which in some cases may offset the CO_2 sequestration potential of specific ocean alkalinization methods (e.g., through CO_2 release by fossil fuel use or during the calcination of $CaCO_3$; Kheshgi, 1995; Renforth et al., 2013).

Although previous modeling studies have suggested that ocean alkalinization may be a viable CDR method, these studies are not comparable due to different experimental designs. Here we propose an idealized Tier 2 experiment (Table 7) that is designed to investigate the response of the climate system and carbon cycle to ocean alkalinization. The amount of any particular alkalizing agent that could be mined, processed, transported, and delivered to the ocean in a form that would easily dissolve and enhance alkalinity is poorly constrained (Köhler et al., 2013; Renforth et al., 2013). Therefore, the amount of alkalinity that is to be added in our experiment is set (based on exploratory simulations conducted with the CSIRO-Mk3L-COAL model) to have a cumulative effect on atmospheric CO_2 by the year 2100 that is comparable to the amount removed in the CDRMIP instantaneous DAC simulations, i.e., an atmospheric reduction of ~ 100 Gt C; experiments *CDR-pi-pulse* and *CDR-yr2010-pulse*. The idea here is not to test the maximum potential of such a method, which would be difficult given the still relatively coarse resolution of many models and the way in which ocean carbonate chemistry is simulated, but rather to compare the response of models to a significant alkalinity perturbation. We have also included an additional "termination" simulation that can be used to investigate an abrupt stop in ocean alkalinization deployment.

4.4.1 *CDR-ocean-alk* experimental protocol

Prerequisite simulation. Conduct the C4MIP emission-driven *esm-ssp585* simulation as described by Jones et al. (2016b). This is the SSP5-8.5 high CO_2 emission scenario, and it serves as the control run and branching point for the ocean alkalinization experiment. A restart must be generated at the end of the year 2019.

The esm-ssp585-ocn-alk simulation. Begin an 81+-year run using the *esm-ssp585* year 2020 restart (starting on 1 January 2020) and add 0.14 Pmol total alkalinity (TA) yr^{-1} to the upper grid boxes of each model's ocean component, i.e., branch from the C4MIP *esm-ssp585* simulation in 2020. The alkalinity additions should be limited to mostly ice-free, year-round ship-accessible waters, which for simplicity should be set between 70° N and 60° S (note that this ignores the presence of seasonal sea ice in some small regions). For many models, this will in practice result in an artificial TA flux at the air–sea interface with realized units that might, for example, be something like µmol TA s^{-1} cm^{-2}. Adding 0.14 Pmol TA yr^{-1} is equivalent to adding 5.19 Pg yr^{-1} of an alkalizing agent like $Ca(OH)_2$ or 4.92 Pg yr^{-1} of forsterite (Mg_2SiO_4), a form of olivine (assuming theoretical net instant dissolution reactions, which for every mole of $Ca(OH)_2$ or Mg_2SiO_4 added sequesters 2 or 4 mol, respectively, of CO_2; Ilyina et al., 2013; Köhler et al., 2013). As not all models include marine iron or silicate cycles, the addition of these nutrients, which could occur if some form of olivine were used as the alkalizing agent, is not considered here. All other forcing is as in the *esm-ssp585* control simulation. If the ocean alkalinization termination simulation (below) is to be conducted, generate a restart at the beginning of the year 2070.

Optional (Tier 3) esm-ssp585-ocn-alk-stop simulation. Use the year 2070 restart from the *esm-ssp585-ocn-alk* simulation and start a simulation (beginning on 1 January 2070) with the SPP5-8.5 forcing, but without adding any additional alkalinity. Continue this run until the year 2100, or beyond, if conducting a long *esm-ssp585-ocn-alk* simulation.

The following are optional (Tier 3) ocean alkalinization extension simulations.

The esm-ssp585ext simulation. If groups desire to extend the ocean alkalinization experiment beyond the year 2100, an optional simulation may be conducted to extend the control run using forcing data from the ScenarioMIP *ssp585ext* simulation; i.e., conduct a longer emission-driven control run, *esm-ssp585ext*. This extension is also a control run for those conducting the CDRMIP *CDR-afforestation* simulation (Sect. 4.3). If computational resources are sufficient, the simulation should be extended even further than in the official SSP scenario, which ends in year 2300, by keeping the forcing constant after this time (i.e., forcing is held at year 2300 levels as the simulation continues for as long as possible; up to 5000 years).

Table 7. Ocean alkalinization (*CDR-ocean-alk*) experiment simulations. "Pr" in the Tier column indicates a prerequisite experiment.

CMIP6 Experiment ID	Tier	Simulation description	Owning MIP	Run length (years)	Initialized using a restart from
esm-ssp585	Pr Pr	CO_2-emission-driven SSP5-8.5 scenario	C4MIP	85	*esm-hist*
esm-ssp585-ocn-alk	2	SSP5-8.5 scenario with 0.14 Pmol yr^{-1} alkalinity added to ice-free ocean surface waters from the year 2020 onward	CDRMIP	65 min. 5000 max.	*esm-ssp585*
esm-ssp585-ocn-alk-stop	3	Termination simulation to investigate an abrupt stop in ocean alkalinization in the year 2070	CDRMIP	30*	*esm-ssp585-ocn-alk*
esm-ssp585ext	3	Long-term extension of the CO_2-emission-driven SSP5-8.5 scenario	CDRMIP	200 min. 5000 max.	*esm-ssp585*

* If the *esm-ssp585ext* simulation is being conducted this may be extended for more than 200 more years (up to 5000 years).

5 Model output, data availability, and data use policy

5.1 Gridded model output

Models capable of generating gridded data must use a NetCDF format. The output (see Appendix A web link for the list of requested variables) follows the CMIP6 output requirements in frequency and structure. This allows groups to use CMOR software (Climate Model Rewriter Software, available at http://cmor.llnl.gov/) to generate the files that will be available for public download (Sect. 5.5). The resolution of the data should be as close to native resolution as possible, but on a regular grid. Please note that as different models have different formulations, only applicable outputs need be provided. However, groups are encouraged to generate additional output, i.e., whatever their standard output variables are, and can also make these data available (preferably following the CMIP6 CMOR standardized naming structure).

5.2 Conversion factor Gt C to ppm

For experiments in which carbon must be converted between Gt C (or Pg) and ppm CO_2, please use a conversion factor of 2.12 Gt C per ppm CO_2 to be consistent with global carbon budget (Le Quéré et al., 2015) conversion factors.

5.3 Box model output

For models that are incapable of producing gridded NetCDF data (i.e., box models), output is expected to be in an ASCII format (Appendix B). All ASCII files are expected to contain tabulated values (at a minimum global mean values), with at least two significant digits for each run. Models must be able to calculate key carbon cycle variables (Appendix C) to participate in CDRMIP experiments *CDR-reversibility*, *CDR-pi-pulse*, and *CDR-yr2010-pulse*. Please submit these files directly to the corresponding author, who will make them available for registered users to download from the CDRMIP website.

5.4 Model output frequency

The model output frequency is listed in Table 8. In all experiments box models and EMICs without seasonality are expected to generate annual mean output for the duration of the experiment, while models with seasonality are expected to generate higher-spatial-resolution data, i.e., monthly, for most simulations.

In experiment *CDR-reversibility* for the control run, *piControl*, we request that 100 years of 3-D model output be written monthly (this should be the last 100 years if conducting a 500+ year run for CMIP6). For the *1pctCO2* and *1pctCO2-cdr* simulations 3-D model output should also be written monthly, i.e., as the atmospheric CO_2 concentration is changing. We suggest that groups that have already performed the *piControl* and *1pctCO2* simulations for CMIP5 or CMIP6 with an even higher output resolution (e.g., daily) continue to use this resolution for the *1pctCO2-cdr* simulation, as this will facilitate the analysis. For groups continuing the simulations for up to 5000 years after CO_2 has returned to 284.7 ppm, at a minimum annual global mean values (non-gridded output) should be generated after the initial minimum 60 years of higher-resolution output.

For experiment *CDR-pi-pulse*, if possible, 3-D model output should be written monthly for 10 years before the negative pulse and for 100 years following the pulse. For groups that can perform longer simulations, for example thousands of years, at a minimum annual global mean values (non-gridded output) should be generated. Data for the control run, i.e., the equilibrium simulation *esm-piControl*, must also be available for analytical purposes. CMIP participants may

Table 8. Model output frequency for 3-D models with seasonality. Box models and EMICs without seasonality are expected to generate annual global mean output for the duration of all experiments. For longer simulations (right column), if possible, 3-D monthly data should be written out for 1 year every 100 years. For models with interannual variability, for example ESMs, monthly data should be written out for a 10-year period every 100 years so that a climatology may be developed. The years referred to in the table indicate simulations years, for example years from the start of the run, and not those of any particular scenario.

CDRMIP Experiment short name	Individual simulation output frequency	
	Monthly gridded 3-D output	Annual global mean output + climatological output at 100-year intervals
CDR-reversibility	*piControl* (last 100 years) *1pctCO2* *1pctCO2-cdr* (initial 200 years)	*1pctCO2-cdr* (from year 200 onward)
CDR-pi-pulse[a]	*esm-piControl* *esm-pi-cdr-pulse* (initial 100 years) *esm-pi-CO2pulse* (initial 100 years)	*esm-pi-cdr-pulse* (from year 100 onward) *esm-pi-CO2pulse* (from year 100 onward)
CDR-yr2010-pulse	*esm-yr2010CO2-control* (initial 105 years) *esm-yr2010CO2-noemit* *esm-yr2010CO2-cdr-pulse* *esm-yr2010CO2-CO2pulse*	*esm-yr2010CO2-control* *esm-yr2010CO2-noemit* *esm-yr2010CO2-cdr-pulse* *esm-yr2010CO2-CO2pulse*
CDR-overshoot	*esm-hist* *esm-ssp534-over* (initial 285 years)	*esm-ssp534-over* (from year 200 onward)[b]
CDR-afforestation	*esm-ssp585ext* (initial 200 years) *esm-ssp585-ssp126Lu* *esm-ssp585-ssp126Lu-ext* (initial 200 years)	*esm-ssp585ext* (from year 200 onward)[b] *esm-ssp585-ssp126Lu-ext* (from year 200 onward)[b]
CDR-ocean-alk	*esm-ssp585* *esm-ssp585-ocn-alk* (initial 280 years) *esm-ssp585-ocn-alk-stop* (initial 200 years) *esm-ssp585ext* (initial 200 years)	*esm-ssp585-ocn-alk-stop* (from year 200 onward)[b] *esm-ssp585ext*(from year 200 onward)[b] *esm-ssp585-ocn-alk* (from year 200 onward)[b]

[a] In the *historical* and *yr2010CO2* simulations output is needed only to diagnose (at least annually) CO_2 emissions. [b] This is from scenario year 2300 onward.

provide a link to the *esm-Control* or *esm-piControl* data on the ESGF.

For experiment *CDR-yr2010-pulse* the *historical* and *yr2010CO2* simulation output is only needed to diagnose annual CO_2 emissions and will not be archived on the ESGF, unless the *historical* run is being conducted for CMIP6. Gridded 3-D monthly mean output for the *esm-yr2010CO2-control* (starting in the year 2010), *esm-yr2010CO2-cdr-pulse*, *esm-yr2010CO2-noemit*, and *esm-yr2010CO2-CO2pulse* simulations should be written for the initial 100 years of the simulation. Thereafter, for groups that can perform longer simulations (up to 5000 years), at a minimum annual global mean values (non-gridded output) should be generated. CMIP participants are requested to provide a link to the *historical* simulation data on the ESGF.

For experiment *CDR-overshoot*, if possible, 3-D model output should be written monthly until the year 2300. We suggest that groups that have already performed the ScenarioMIP *ssp534-over* and *ssp534-over-ext* and C4MIP *ssp534-over-bgc* and *ssp534-over-bgcExt* CMIP6 simulations with an even higher output resolution (e.g., daily) continue to use this resolution as this will facilitate analyses. For groups that can perform longer simulations, for example thousands of years, at a minimum annual global mean values (non-gridded output) should be generated for every year beyond 2300. We recommend that CMIP participants provide a link to the *esm-hist* data on the ESGF. For analytical purposes, we also request that ScenarioMIP and C4MIP participants provide links to any completed *ssp534-over*, *ssp534-over-ext*, *ssp534-over-bgc*, and *ssp534-over-bgcExt* simulation data on the ESGF.

For experiment *CDR-afforestation*, if possible, 3-D model output should be written monthly until the year 2300. LUMIP participants may provide a link to the *esm-hist* and *esm-ssp585-ssp126Lu* data on the ESGF for the first portions of this run (until the year 2100). For groups that can perform longer simulations, for example thousands of years, at a minimum annual global mean values (non-gridded output) should be generated for every year beyond 2300.

For experiment *CDR-ocean-alk*, if possible, 3-D gridded model output should be written monthly for all simulations. For groups that can perform longer simulations, for example thousands of years, at a minimum annual global mean values (non-gridded output) should be generated for every year beyond 2300.

5.5 Data availability and use policy

The model output from the CDRMIP experiments described in this paper will be publically available. All gridded model output will, to the extent possible, be distributed through the Earth System Grid Federation (ESGF). Box model output will be available via the CDRMIP website (http://www.kiel-earth-institute.de/cdr-mip-data.html). The CDRMIP policy for data use is that if you use output from a particular model, you should contact the modeling group and offer them the opportunity to contribute as authors. Modeling groups will possess detailed understanding of their models and the intricacies of performing the CDRMIP experiments, so their perspectives will undoubtedly be useful. At a minimum, if the offer of author contribution is not taken up, CDRMIP and the model groups should be credited in acknowledgments with, for example, a statement like the following: "We acknowledge the Carbon Dioxide Removal Model Intercomparison Project leaders and steering committee who are responsible for CDRMIP and we thank the climate modeling groups (listed in Table XX of this paper) for producing and making their model output available."

The natural and anthropogenic forcing data that are required for some simulations are described in several papers in the Geoscientific Model Development CMIP6 special issue. These data will be available on the ESGF. Links to all forcing data can also be found on the CMIP6 Panel website (https://www.wcrp-climate.org/wgcm-cmip/wgcm-cmip6). CMIP6 and CMIP5 data should be acknowledged in the standard way.

6 CDRMIP outlook and conclusion

It is anticipated that this will be the first stage of an ongoing project exploring CDR. CDRMIP welcomes input on the development of other (future) experiments and scenarios. Potential future experiments could include biomass energy with carbon capture and storage (BECCS) or ocean fertilization. Future experiments could also include the removal of non-CO_2 greenhouse gases, for example methane, as these in many cases have a much higher global warming potential (de Richter et al., 2017; Ming et al., 2016). We also envision that it will be necessary to investigate the simultaneous deployment of several CDR or other greenhouse gas removal methods since early studies suggest that there is likely not an individually capable method (Keller et al., 2014). It is also anticipated that scenarios will be developed that might combine solar radiation management (SRM) and CDR in the future, such as a joint GeoMIP (Geoengineering Model Intercomparison Project) CDRMIP experiment.

In addition to reductions in anthropogenic CO_2 emissions, it is very likely that CDR will be needed to achieve the climate change mitigation goals laid out in the Paris Agreement. The potential and risks of large-scale CDR are poorly quantified, raising important questions about the extent to which large-scale CDR can be depended upon to meet Paris Agreement goals. As an endorsed CMIP6 activity, CDRMIP is designed to help us better understand how the Earth system might respond to CDR. Over the past 2 years the CDRMIP team has developed a set of numerical experiments to be performed with Earth system models of varying complexity. The aim of these experiments is to provide coordinated simulations and analyses that addresses several key CDR uncertainties, including

- the degree to which CDR could help mitigate climate change or even reverse it;
- the potential effectiveness and risks and benefits of different CDR proposals with a focus on direct CO_2 air capture, afforestation and reforestation, and ocean alkalinization; and
- how CDR might be appropriately accounted for within an Earth system framework and during scenario development.

We anticipate that there will be numerous forthcoming studies that utilize CDRMIP data. The model output from the CDRMIP experiments will be publically available and we welcome and encourage interested parties to download these data and utilize them to further investigate CDR.

Code and data availability. As described in Sect. 5.5, the output from models participating in CDRMIP will be made publically available. This will include data used in exemplary Figs. 2 and 4. All gridded model output will be distributed through the Earth System Grid Federation (ESGF) with digital object identifiers (DOIs) assigned. Box model output will be available via the CDRMIP website (http://www.kiel-earth-institute.de/cdr-mip-data.html). The code from the models used to generate the exemplary figures in this paper (Figs. 2 and 4, Appendix D) is available at http://thredds.geomar.de/thredds/catalog/open_access/keller_et_al_2018_gmd/catalog.html (Keller and Lenton, 2018). To obtain code from modeling groups participating in CDRMIP, please contact the modeling group using the contact information that accompanies their data.

Appendix A: Requested model output variables

A spreadsheet of the requested model output variables and their format can be found at www.kiel-earth-institute.de/files/media/downloads/CDRMIP_model_output_requirements.pdf. Please note that as different models have different formulations, only applicable outputs need be provided. However, groups are encouraged to generate additional output, i.e., whatever their standard output variables are, and can also make these data available.

Appendix B: Box model output formatting

Box model ASCII formatting example.

File name format:
RUNNAME_MODELNAME_Modelversion.dat
C1_MYBOXMODEL_V1.0_.dat
Headers and formats example.

- Start each header comment line with a #
- *Line 1*: indicate run name, e.g., # *esm-pi-cdr-pulse*
- *Line 2*: provide contact address, e.g., # B. Box, Uni of Box Models, CO2 Str., BoxCity 110110, BoxCountry
- *Line 3*: provide a contact email address, e.g., # bbox@unibox.bx
- *Line 4*: indicate model name, version, e.g., # MyBoxModel Version 2.2
- *Line 5*: concisely indicate main components, e.g., # two ocean boxes (upper and lower), terrestrial biosphere, and one atmospheric box

  Line 6: indicate climate sensitivity of model; the abbreviation TCS may be used for transient climate sensitivity and ECS for equilibrium climate sensitivity, e.g., # TCS=3.2 [deg C], ECS=8.1 [deg C]
- *Line 7*: description of non-CO_2 forcing applied, e.g., # Forcing: solar
- *Line 8*: indicate the output frequency and averaging, e.g., # Output: global mean values

  Line 9: list tabulated output column headers with their units in brackets (see table below), e.g., # year tas[K]

Complete header example.

esm-pi-cdr-pulse

B. Box, Uni. of Box Models, CO2 Str., BoxCity 110110, BoxCountry

bbox@unibox.bx

MyBoxModel Version 2.2

two ocean boxes (upper and lower), terrestrial biosphere, and one atmospheric box

TCS=3.2 deg C, ECS=8.1 deg C

Forcing: solar

Output: global mean values

year tas[K] co2[Gt C] nep[Gt C yr-1] fgco2[Gt C yr-1]

Appendix C: Requested box model output variables

Table of requested box model output (at a minimum as global mean values). To participate in CDRMIP, at a minimum the variables *tas, xco2*, and *fgco2* must be provided.

Table C1. Requested box model output for CDRMIP.

Long name	Column header name*	Units	Comments
Relative year	year	year	
Near-surface air temperature	tas	K	
Atmospheric CO_2	xco2	ppm	
Surface downward CO_2 flux into the ocean	fgco2	$kg\,m^{-2}$	This is the net air to ocean carbon flux (positive flux is into the ocean)
Total atmospheric mass of CO_2	co2mass	kg	
Net carbon mass flux out of atmosphere due to net ecosystem productivity on land	nep	$kg\,m^{-2}$	This is the net air to land carbon flux (positive flux is into the land)
Total ocean carbon	cOcean	Gt C	If the ocean contains multiple boxes this output can also be provided, for example as cOcean_up and cOcean_low for upper and lower ocean boxes
Total land carbon	cLand	Gt C	This is the sum of all C pools
Ocean potential temperature	thetao	K	Please report a mean value if there are multiple ocean boxes
Upper ocean pH	pH	1	Negative log of hydrogen ion concentration with the concentration expressed as mol H kg^{-1}
Carbon mass flux out of atmosphere due to net primary production on land	npp	$kg\,m^{-2}$	This is calculated as gross primary production–autotrophic respiration (gpp-ra)
Carbon mass flux into atmosphere due to heterotrophic respiration on land	rh	$kg\,m^{-2}$	
Ocean net primary production by phytoplankton	intpp	$kg\,m^{-2}$	

* Column header names follow the CMIP CMOR notation when possible.

Appendix D: Model descriptions

The two models used to develop and test CDRMIP experimental protocols and provide example results (Figs. 2 and 4) are described below.

The University of Victoria Earth System Climate Model (UVic) version 2.9 consists of three dynamically coupled components: a three-dimensional general circulation model of the ocean that includes a dynamic–thermodynamic sea ice model, a terrestrial model, and a simple one-layer atmospheric energy–moisture balance model (Eby et al., 2013). All components have a common horizontal resolution of 3.6° longitude × 1.8° latitude. The oceanic component, which is in the configuration described by Keller et al. (2012), has 19 levels in the vertical with thicknesses ranging from 50 m near the surface to 500 m in the deep ocean. The terrestrial model of vegetation and carbon cycles (Meissner et al., 2003) is based on the Hadley Centre model TRIFFID (Top-down Representation of Interactive Foliage and Flora Including Dynamics). The atmospheric energy–moisture balance model interactively calculates heat and water fluxes to the ocean, land, and sea ice. Wind velocities, which are used to calculate the momentum transfer to the ocean and sea ice model, surface heat and water fluxes, and the advection of water vapor in the atmosphere, are determined by adding wind and wind stress anomalies. These are determined from surface pressure anomalies that are calculated from deviations in preindustrial surface air temperature to prescribed NCAR/NCEP monthly climatological wind data (Weaver et al., 2001). The model has been extensively used in climate change studies and is also well validated under preindustrial to present day conditions (Eby et al., 2009, 2013; Keller et al., 2012).

The CSIRO-Mk3L-COAL Earth system model consists of a climate model, Mk3L (Phipps et al., 2011), coupled to a biogeochemical model of carbon, nitrogen, and phosphorus cycles on land (CASA-CNP) in the Australian community land surface model, CABLE (Mao et al., 2011; Wang et al., 2010), and an ocean biogeochemical cycle model (Duteil et al., 2012; Matear and Hirst, 2003). The atmospheric model has a horizontal resolution of 5.6° longitude × 3.2° latitude and 18 vertical layers. The land carbon model has the same horizontal resolution as the atmosphere. The ocean model has a resolution of 2.8° longitude × 1.6° latitude and 21 vertical levels. Mk3L simulates the historical climate well compared to the models used for earlier IPCC assessments (Phipps et al., 2011). Furthermore, the simulated response of the land carbon cycle to increasing atmospheric CO_2 and warming are consistent with those from the Coupled Model Intercomparison Project Phase 5 (CMIP5; Zhang et al., 2014). The ocean biogeochemical model was also shown to realistically simulate the global ocean carbon cycle (Duteil et al., 2012; Matear and Lenton, 2014).

Competing interests. The authors declare that they have no conflict of interest.

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References

Allen, M. R., Frame, D. J., Huntingford, C., Jones, C. D., Lowe, J. A., Meinshausen, M., and Meinshausen, N.: Warming caused by cumulative carbon emissions towards the trillionth tonne, Nature, 458, 1163–1166, https://doi.org/10.1038/nature08019, 2009.

Armour, K. C., Eisenman, I., Blanchard-Wrigglesworth, E., McCusker, K. E., and Bitz, C. M.: The reversibility of sea ice loss in a state-of-the-art climate model, Geophys. Res. Lett., 38, 1–5, https://doi.org/10.1029/2011GL048739, 2011.

Arora, V. K. and Boer, G. J.: Terrestrial ecosystems response to future changes in climate and atmospheric CO_2 concentration, Biogeosciences, 11, 4157–4171, https://doi.org/10.5194/bg-11-4157-2014, 2014.

Bauer, N., Calvin, K., Emmerling, J., Fricko, O., Fujimori, S., Hilaire, J., Eom, J., Krey, V., Kriegler, E., Mouratiadou, I., Sytze de Boer, H., van den Berg, M., Carrara, S., Daioglou, V., Drouet, L., Edmonds, J. E., Gernaat, D., Havlik, P., Johnson, N., Klein, D., Kyle, P., Marangoni, G., Masui, T., Pietzcker, R. C., Strubegger, M., Wise, M., Riahi, K., and van Vuuren, D. P.: Shared Socio-Economic Pathways of the Energy Sector – Quantifying the Narratives, Global Environ. Chang., 42, 316–330, https://doi.org/10.1016/j.gloenvcha.2016.07.006, 2017.

Betts, R. A.: Offset of the potential carbon sink from boreal forestation by decreases in surface albedo, Nature, 409, 187–190, 2000.

Boucher, O., Halloran, P. R., Burke, E. J., Doutriaux-Boucher, M., Jones, C. D., Lowe, J., Ringer, M. A., Robertson, E., and Wu, P.: Reversibility in an Earth System model in response to CO_2 concentration changes, Environ. Res. Lett., 7, 24013, https://doi.org/10.1088/1748-9326/7/2/024013, 2012.

Boysen, L. R., Lucht, W., Gerten, D., and Heck, V.: Impacts devalue the potential of large-scale terrestrial CO_2 removal through biomass plantations, Environ. Res. Lett., 11, 95010, https://doi.org/10.1088/1748-9326/11/9/095010, 2016.

Boysen, L. R., Lucht, W., Gerten, D., Heck, V., Lenton, T. M., and Schellnhuber, H. J.: The limits to global-warming mitigation by terrestrial carbon removal, Earth's Future, 1–12, https://doi.org/10.1002/2016EF000469, 2017.

Cao, L. and Caldeira, K.: Atmospheric carbon dioxide removal: long-term consequences and commitment, Environ. Res. Lett., 5, 24011, https://doi.org/10.1088/1748-9326/5/2/024011, 2010.

Chen, C. and Tavoni, M.: Direct air capture of CO_2 and climate stabilization: A model based assessment, Climatic Change, 118, 59–72, https://doi.org/10.1007/s10584-013-0714-7, 2013.

Colbourn, G., Ridgwell, A., and Lenton, T. M.: The time scale of the silicate weathering negative feedback on atmospheric CO_2, 29, 583–596, https://doi.org/10.1002/2014GB005054, 2015.

Cripps, G., Widdicombe, S., Spicer, J. I., and Findlay, H. S.: Biological impacts of enhanced alkalinity in Carcinus maenas, Mar. Pollut. Bull., 71, 190–198, https://doi.org/10.1016/j.marpolbul.2013.03.015, 2013.

de Richter, R., Ming, T., Davies, P., Liu, W., and Caillol, S.: Removal of non-CO_2 greenhouse gases by large-scale atmospheric solar photocatalysis, Prog. Energ. Combust., 60, 68–96, https://doi.org/10.1016/j.pecs.2017.01.001, 2017.

Dlugokencky, E. and Tans, P.: Trends in atmospheric carbon dioxide, National Oceanic & Atmospheric Administration, Earth System Research Laboratory (NOAA/ESRL), available at: http://www.esrl.noaa.gov/gmd/ccgg/trends/global.html, last access: 28 October 2016.

Duteil, O., Koeve, W., Oschlies, A., Aumont, O., Bianchi, D., Bopp, L., Galbraith, E., Matear, R., Moore, J. K., Sarmiento, J. L., and Segschneider, J.: Preformed and regenerated phosphate in ocean general circulation models: can right total concentrations be wrong?, Biogeosciences, 9, 1797–1807, https://doi.org/10.5194/bg-9-1797-2012, 2012.

Eby, M., Zickfeld, K., Montenegro, A., Archer, D., Meissner, K. J., and Weaver, A. J.: Lifetime of Anthropogenic Climate Change: Millennial Time Scales of Potential CO_2 and Surface Temperature Perturbations, J. Climate, 22, 2501–2511, https://doi.org/10.1175/2008JCLI2554.1, 2009.

Eby, M., Weaver, A. J., Alexander, K., Zickfeld, K., Abe-Ouchi, A., Cimatoribus, A. A., Crespin, E., Drijfhout, S. S., Edwards, N. R., Eliseev, A. V., Feulner, G., Fichefet, T., Forest, C. E., Goosse, H., Holden, P. B., Joos, F., Kawamiya, M., Kicklighter, D., Kienert, H., Matsumoto, K., Mokhov, I. I., Monier, E., Olsen, S. M., Pedersen, J. O. P., Perrette, M., Philippon-Berthier, G., Ridgwell, A., Schlosser, A., Schneider von Deimling, T., Shaffer, G., Smith, R. S., Spahni, R., Sokolov, A. P., Steinacher, M., Tachiiri, K., Tokos, K., Yoshimori, M., Zeng, N., and Zhao, F.: Historical and idealized climate model experiments: an intercomparison of Earth system models of intermediate complexity, Clim. Past, 9, 1111–1140, https://doi.org/10.5194/cp-9-1111-2013, 2013.

Egleston, E. S., Sabine, C. L., and Morel, F. M. M.: Revelle revisited: Buffer factors that quantify the response of ocean chemistry to changes in DIC and alkalinity, Global Biogeochem. Cy., 24, GB1002, https://doi.org/10.1029/2008GB003407, 2010.

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., and Taylor, K. E.: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, Geosci. Model Dev., 9, 1937–1958, https://doi.org/10.5194/gmd-9-1937-2016, 2016.

Feng, E. Y., Keller, D. P., Koeve, W., and Oschlies, A.: Could artificial ocean alkalinization protect tropical coral ecosystems from ocean acidification?, Environ. Res. Lett., 11, 74008, https://doi.org/10.1088/1748-9326/11/7/074008, 2016.

Frölicher, T. L., Winton, M., and Sarmiento, J. L.: Continued global warming after CO_2 emissions stoppage, Nat. Clim. Chang, 4, 40–44, https://doi.org/10.1038/nclimate2060, 2013.

Fuss, S., Canadell, J. G., Peters, G. P., Tavoni, M., Andrew, R. M., Ciais, P., Jackson, R. B., Jones, C. D., Kraxner, F., Nakicenovic, N., Quéré, C. Le, Raupach, M. R., Sharifi, A., Smith, P., and Yamagata, Y.: Betting on negative emissions, Nat. Publ. Gr., 4, 850–853, https://doi.org/10.1038/nclimate2392, 2014.

Gasser, T., Guivarch, C., Tachiiri, K., Jones, C. D., and Ciais, P.: Negative emissions physically needed to keep global warming below 2? °C, Nat. Commun., 6, 7958, https://doi.org/10.1038/ncomms8958, 2015.

González, M. F. and Ilyina, T.: Impacts of artificial ocean alkalinization on the carbon cycle and climate in Earth system simulations, Geophys. Res. Lett., 43, 6493–6502, https://doi.org/10.1002/2016GL068576, 2016.

Gregory, J. M.: A new method for diagnosing radiative forcing and climate sensitivity, Geophys. Res. Lett., 31, 2–5, https://doi.org/10.1029/2003GL018747, 2004.

Griffies, S. M., Danabasoglu, G., Durack, P. J., Adcroft, A. J., Balaji, V., Böning, C. W., Chassignet, E. P., Curchitser, E., Deshayes, J., Drange, H., Fox-Kemper, B., Gleckler, P. J., Gregory, J. M., Haak, H., Hallberg, R. W., Heimbach, P., Hewitt, H. T., Holland, D. M., Ilyina, T., Jungclaus, J. H., Komuro, Y., Krasting, J. P., Large, W. G., Marsland, S. J., Masina, S., McDougall, T. J., Nurser, A. J. G., Orr, J. C., Pirani, A., Qiao, F., Stouffer, R. J., Taylor, K. E., Treguier, A. M., Tsujino, H., Uotila, P., Valdivieso, M., Wang, Q., Winton, M., and Yeager, S. G.: OMIP contribution to CMIP6: experimental and diagnostic protocol for the physical component of the Ocean Model Intercomparison Project, Geosci. Model Dev., 9, 3231–3296, https://doi.org/10.5194/gmd-9-3231-2016, 2016.

Gruber, N.: Warming up, turning sour, losing breath: ocean biogeochemistry under global change, Philos. T. Roy. Soc. A, 369, 1980–1996, https://doi.org/10.1098/rsta.2011.0003, 2011.

Gupta, A. Sen, Jourdain, N. C., Brown, J. N., and Monselesan, D.: Climate Drift in the CMIP5 Models, J. Climate, 26, 8597–8615, https://doi.org/10.1175/JCLI-D-12-00521.1, 2013.

Hansen, J.: Efficacy of climate forcings, J. Geophys. Res., 110, D18104, https://doi.org/10.1029/2005JD005776, 2005.

Hartmann, J., West, J., Renforth, P., Köhler, P., De La Rocha, C. L., Wolf-Gladrow, D., Dürr, H., and Scheffran, J.: Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification, Rev. Geophys., 51, 113–149, https://doi.org/10.1002/rog.20004, 2013.

Hauck, J., Köhler, P., Wolf-Gladrow, D., and Völker, C.: Iron fertilisation and century-scale effects of open ocean dissolution of olivine in a simulated CO_2 removal experiment, Environ. Res. Lett., 11, 24007, https://doi.org/10.1088/1748-9326/11/2/024007, 2016.

Heck, V., Gerten, D., Lucht, W., and Boysen, L. R.: Is extensive terrestrial carbon dioxide removal a "green" form of geoengineering? A global modelling study, Global Planet. Change, 137, 123–130, https://doi.org/10.1016/j.gloplacha.2015.12.008, 2016.

Hofmann, M. and Schellnhuber, H. J.: Ocean acidification: a millennial challenge, Energy Environ. Sci., 3, 1883–1896, 2010.

Holmes, G. and Keith, D. W.: An air-liquid contactor for large-scale capture of CO_2 from air, Philos. T. Roy. Soc. A, 370, 4380–4403, https://doi.org/10.1098/rsta.2012.0137, 2012.

Ilyina, T., Wolf-Gladrow, D., Munhoven, G., and Heinze, C.: Assessing the potential of calcium-based artificial ocean alkalinization to mitigate rising atmospheric CO_2 and ocean acidification, Geophys. Res. Lett., 40, 5909–5914, https://doi.org/10.1002/2013GL057981, 2013.

IPCC: Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp., 2013.

IPCC: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects, Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Field, C. B., Barros, V. R., Dokken, D. J., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014a.

IPCC: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T., and Minx, J. C., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014b.

Jones, C. D., Ciais, P., Davis, S. J., Friedlingstein, P., Gasser, T., Peters, G. P., Rogelj, J., van Vuuren, D. P., Canadell, J. G., Cowie, A., Jackson, R. B., Jonas, M., Kriegler, E., Littleton, E., Lowe, J. A., Milne, J., Shrestha, G., Smith, P., Torvanger, A., and Wiltshire, A.: Simulating the Earth system response to negative emissions, Environ. Res. Lett., 11, 95012, https://doi.org/10.1088/1748-9326/11/9/095012, 2016a.

Jones, C. D., Arora, V., Friedlingstein, P., Bopp, L., Brovkin, V., Dunne, J., Graven, H., Hoffman, F., Ilyina, T., John, J. G., Jung, M., Kawamiya, M., Koven, C., Pongratz, J., Raddatz, T., Randerson, J. T., and Zaehle, S.: C4MIP – The Coupled Climate-Carbon Cycle Model Intercomparison Project: experimental protocol for CMIP6, Geosci. Model Dev., 9, 2853–2880, https://doi.org/10.5194/gmd-9-2853-2016, 2016b.

Joos, F., Roth, R., Fuglestvedt, J. S., Peters, G. P., Enting, I. G., von Bloh, W., Brovkin, V., Burke, E. J., Eby, M., Edwards, N. R., Friedrich, T., Frölicher, T. L., Halloran, P. R., Holden, P. B., Jones, C., Kleinen, T., Mackenzie, F. T., Matsumoto, K., Meinshausen, M., Plattner, G.-K., Reisinger, A., Segschneider, J., Shaffer, G., Steinacher, M., Strassmann, K., Tanaka, K., Timmermann, A., and Weaver, A. J.: Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis, Atmos. Chem. Phys., 13, 2793–2825, https://doi.org/10.5194/acp-13-2793-2013, 2013.

Keller, D. P. and Lenton, A.: keller_et_al_2018_gmd, available at: http://thredds.geomar.de/thredds/catalog/open_access/keller_et_al_2018_gmd/catalog.html, 2018.

Keller, D. P., Oschlies, A., and Eby, M.: A new marine ecosystem model for the University of Victoria Earth System Climate Model, Geosci. Model Dev., 5, 1195–1220, https://doi.org/10.5194/gmd-5-1195-2012, 2012.

Keller, D. P., Feng, E. Y., and Oschlies, A.: Potential climate engineering effectiveness and side effects during a high carbon dioxide-emission scenario, Nat. Commun., 5, 1–11, https://doi.org/10.1038/ncomms4304, 2014.

Kheshgi, H. S.: Sequestering atmospheric carbon dioxide by increasing ocean alkalinity, Energy, 20, 915–922, https://doi.org/10.1016/0360-5442(95)00035-F, 1995.

Köhler, P., Hartmann, J., and Wolf-Gladrow, D. A.: Geoengineering potential of artificially enhanced silicate weathering of olivine, P. Natl. Acad. Sci. USA, 107, 20228–20233, https://doi.org/10.1073/pnas.1000545107, 2010.

Köhler, P., Abrams, J. F., Völker, C., Hauck, J., and Wolf-Gladrow, D. A.: Geoengineering impact of open ocean dissolution of olivine on atmospheric CO_2, surface ocean pH and marine biology, Environ. Res. Lett., 8, 14009, available at: http://stacks.iop.org/1748-9326/8/i=1/a=014009 (last access: 21 January 2013), 2013.

Kriegler, E., Tavoni, M., Aboumahboub, T., Luderer, G., Calvin, K., Demaere, G., Krey, V., Riahi, K., Rösler, H., Schaeffer, M., and Van Vuuren, D. P.: What Does The 2°C Target Imply For A Global Climate Agreement In 2020? The Limits Study On Durban Platform Scenarios, Climate Change Economics, 4, 1340008, https://doi.org/10.1142/S2010007813400083, 2013.

Kriegler, E., Bauer, N., Popp, A., Humpenöder, F., Leimbach, M., Strefler, J., Baumstark, L., Bodirsky, B. L., Hilaire, J., Klein, D., Mouratiadou, I., Weindl, I., Bertram, C., Dietrich, J.-P., Luderer, G., Pehl, M., Pietzcker, R., Piontek, F., Lotze-Campen, H., Biewald, A., Bonsch, M., Giannousakis, A., Kreidenweis, U., Müller, C., Rolinski, S., Schultes, A., Schwanitz, J., Stevanovic, M., Calvin, K., Emmerling, J., Fujimori, S., and Edenhofer, O.: Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century, Global Environ. Chang., 42, 297–315, https://doi.org/10.1016/j.gloenvcha.2016.05.015, 2016.

Kroeker, K. J., Kordas, R. L., Crim, R., Hendriks, I. E., Ramajo, L., Singh, G. S., Duarte, C. M., and Gattuso, J.-P.: Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming, Glob. Change Biol., 19, 1884–1896, https://doi.org/10.1111/gcb.12179, 2013.

Lackner, K. S., Brennan, S., Matter, J. M., Park, A.-H. A., Wright, A., and van der Zwaan, B.: The urgency of the development of CO2 capture from ambient air, P. Natl. Acad. Sci. USA, 109, 13156–13162, https://doi.org/10.1073/pnas.1108765109, 2012.

Lawrence, D. M., Hurtt, G. C., Arneth, A., Brovkin, V., Calvin, K. V., Jones, A. D., Jones, C. D., Lawrence, P. J., de Noblet-Ducoudré, N., Pongratz, J., Seneviratne, S. I., and Shevliakova, E.: The Land Use Model Intercomparison Project (LUMIP) contribution to CMIP6: rationale and experimental design, Geosci. Model Dev., 9, 2973–2998, https://doi.org/10.5194/gmd-9-2973-2016, 2016.

Le Quéré, C., Moriarty, R., Andrew, R. M., Canadell, J. G., Sitch, S., Korsbakken, J. I., Friedlingstein, P., Peters, G. P., Andres, R. J., Boden, T. A., Houghton, R. A., House, J. I., Keeling, R. F., Tans, P., Arneth, A., Bakker, D. C. E., Barbero, L., Bopp, L., Chang, J., Chevallier, F., Chini, L. P., Ciais, P., Fader, M., Feely, R. A., Gkritzalis, T., Harris, I., Hauck, J., Ilyina, T., Jain, A. K., Kato, E., Kitidis, V., Klein Goldewijk, K., Koven, C., Landschützer, P., Lauvset, S. K., Lefèvre, N., Lenton, A., Lima, I. D., Metzl, N., Millero, F., Munro, D. R., Murata, A., Nabel, J. E. M. S., Nakaoka, S., Nojiri, Y., O'Brien, K., Olsen, A., Ono, T., Pérez, F. F., Pfeil, B., Pierrot, D., Poulter, B., Rehder, G., Rödenbeck, C., Saito, S., Schuster, U., Schwinger, J., Séférian, R., Steinhoff, T., Stocker, B. D., Sutton, A. J., Takahashi, T., Tilbrook, B., van der Laan-Luijkx, I. T., van der Werf, G. R., van Heuven, S., Vandemark, D., Viovy, N., Wiltshire, A., Zaehle, S., and Zeng, N.: Global Carbon Budget 2015, Earth Syst. Sci. Data, 7, 349-396, https://doi.org/10.5194/essd-7-349-2015, 2015.

Le Quéré, C., Andrew, R. M., Canadell, J. G., Sitch, S., Korsbakken, J. I., Peters, G. P., Manning, A. C., Boden, T. A., Tans, P. P., Houghton, R. A., Keeling, R. F., Alin, S., Andrews, O. D., Anthoni, P., Barbero, L., Bopp, L., Chevallier, F., Chini, L. P., Ciais, P., Currie, K., Delire, C., Doney, S. C., Friedlingstein, P., Gkritzalis, T., Harris, I., Hauck, J., Haverd, V., Hoppema, M., Klein Goldewijk, K., Jain, A. K., Kato, E., Körtzinger, A., Landschützer, P., Lefèvre, N., Lenton, A., Lienert, S., Lombardozzi, D., Melton, J. R., Metzl, N., Millero, F., Monteiro, P. M. S., Munro, D. R., Nabel, J. E. M. S., Nakaoka, S.-I., O'Brien, K., Olsen, A., Omar, A. M., Ono, T., Pierrot, D., Poulter, B., R"odenbeck, C., Salisbury, J., Schuster, U., Schwinger, J., Séférian, R., Skjelvan, I., Stocker, B. D., Sutton, A. J., Takahashi, T., Tian, H., Tilbrook, B., van der Laan-Luijkx, I. T., van der Werf, G. R., Viovy, N., Walker, A. P., Wiltshire, A. J., and Zaehle, S.: Global Carbon Budget 2016, Earth Syst. Sci. Data, 8, 605–649, https://doi.org/10.5194/essd-8-605-2016, 2016.

MacDougall, A. H.: Reversing climate warming by artificial atmospheric carbon-dioxide removal: Can a Holocene-like climate be restored?, Geophys. Res. Lett., 40, 5480–5485, https://doi.org/10.1002/2013GL057467, 2013.

Mao, J., Phipps, S. J., Pitman, A. J., Wang, Y. P., Abramowitz, G., and Pak, B.: The CSIRO Mk3L climate system model v1.0 coupled to the CABLE land surface scheme v1.4b: evaluation of the control climatology, Geosci. Model Dev., 4, 1115-1131, https://doi.org/10.5194/gmd-4-1115-2011, 2011.

Matear, R. J. and Hirst, A. C.: Long-term changes in dissolved oxygen concentrations in the ocean caused by protracted global warming, Global Biogeochem. Cy., 17, 1125, https://doi.org/10.1029/2002GB001997, 2003.

Matear, R. J. and Lenton, A.: Quantifying the impact of ocean acidification on our future climate, Biogeosciences, 11, 3965–3983, https://doi.org/10.5194/bg-11-3965-2014, 2014.

Mathesius, S., Hofmann, M., Caldeira, K., and Schellnhuber, H. J.: Long-term response of oceans to CO_2 removal from the atmosphere, Nat. Clim. Chang., 5, 1107–1113, https://doi.org/10.1038/nclimate2729, 2015.

Matter, J. M., Stute, M., Snaebjornsdottir, S. O., Oelkers, E. H., Gislason, S. R., Aradottir, E. S., Sigfusson, B., Gunnarsson, I., Sigurdardottir, H., Gunnlaugsson, E., Axelsson, G., Alfredsson, H. A., Wolff-Boenisch, D., Mesfin, K., Taya, D. F. d. L. R., Hall, J., Dideriksen, K., and Broecker, W. S.: Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions, Science, 352, 1312–1314, https://doi.org/10.1126/science.aad8132, 2016.

Matthews, H. D., Gillett, N. P., Stott, P. A., and Zickfeld, K.: The proportionality of global warming to cumulative carbon emissions, Nature, 459, 829–32, https://doi.org/10.1038/nature08047, 2009.

Meehl, G. A., Moss, R., Taylor, K. E., Eyring, V., Stouffer, R. J., Bony, S., and Stevens, B.: Climate Model Intercomparisons: Preparing for the Next Phase, Eos Trans. Am. Geophys. Union, 95, 77–78, https://doi.org/10.1002/2014EO090001, 2014.

Meinshausen, M., Raper, S. C. B., and Wigley, T. M. L.: Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 1: Model description and calibration, Atmos. Chem. Phys., 11, 1417–1456, https://doi.org/10.5194/acp-11-1417-2011, 2011.

Meissner, K. J., Weaver, A. J., Matthews, H. D., and Cox, P. M.: The role of land surface dynamics in glacial inception: A study with the UVic Earth System Model, Clim. Dynam., 21, 515–537, 2003.

Millennium Ecosystem Assesment: Ecosystems and Human Well-Being, Synthesis, Island Press, Washington, DC, 2005.

Ming, T., de Richter, R., Shen, S., and Caillol, S.: Fighting global warming by greenhouse gas removal: destroying atmospheric nitrous oxide thanks to synergies between two breakthrough technologies, Environ. Sci. Pollut. R., 23, 6119–6138, https://doi.org/10.1007/s11356-016-6103-9, 2016.

Morice, C. P., Kennedy, J. J., Rayner, N. A., and Jones, P. D.: Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 data set, J. Geophys. Res.-Atmos., 117, 1–22, https://doi.org/10.1029/2011JD017187, 2012.

National Research Council: Climate Intervention, National Academies Press, Washington, DC, 2015.

O'Neill, B. C., Tebaldi, C., van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J.-F., Lowe, J., Meehl, G. A., Moss, R., Riahi, K., and Sanderson, B. M.: The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6, Geosci. Model Dev., 9, 3461–3482, https://doi.org/10.5194/gmd-9-3461-2016, 2016.

Orr, J. C., Najjar, R. G., Aumont, O., Bopp, L., Bullister, J. L., Danabasoglu, G., Doney, S. C., Dunne, J. P., Dutay, J.-C., Graven, H., Griffies, S. M., John, J. G., Joos, F., Levin, I., Lindsay, K., Matear, R. J., McKinley, G. A., Mouchet, A., Oschlies, A., Romanou, A., Schlitzer, R., Tagliabue, A., Tanhua, T., and Yool, A.: Biogeochemical protocols and diagnostics for the CMIP6 Ocean Model Intercomparison Project (OMIP), Geosci. Model Dev., 10, 2169–2199, https://doi.org/10.5194/gmd-10-2169-2017, 2017.

Oschlies, A. and Klepper, G.: Research for assessment, not deployment, of Climate Engineering: The German Research Foundation's Priority Program SPP 1689, Earth's Future, 5, 128–134, https://doi.org/10.1002/2016EF000446, 2017.

Peters, G. P., Andrew, R. M., Boden, T., Canadell, J. G., Ciais, P., Le Quéré, C., Marland, G., Raupach, M. R., and Wilson, C.: The challenge to keep global warming below 2 °C, Nat. Clim. Chang., 3, 4–6, https://doi.org/10.1038/nclimate1783, 2013.

Phipps, S. J., Rotstayn, L. D., Gordon, H. B., Roberts, J. L., Hirst, A. C., and Budd, W. F.: The CSIRO Mk3L climate system model version 1.0 – Part 1: Description and evaluation, Geosci. Model Dev., 4, 483–509, https://doi.org/10.5194/gmd-4-483-2011, 2011.

Renforth, P., Jenkins, B. G., and Kruger, T.: Engineering challenges of ocean liming, Energy, 60, 442–452, https://doi.org/10.1016/j.energy.2013.08.006, 2013.

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J. C., KC, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humpenöder, F., Da Silva, L. A., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Strefler, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J. C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A., and Tavoni, M.: The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview, Global Environ. Chang., 42, 153–168, https://doi.org/10.1016/j.gloenvcha.2016.05.009, 2017.

Rickels, W., Klepper, G., Dovern, J., Betz, G., Brachatzek, N., Cacean, S., Güssow, K., Heintzenberg, J., Hiller, S., Hoose, C., Leisner, T., Oschlies, A., Platt, U., Proelß, A., Renn, O., Schäfer, S., and Zürn, M.: Large-Scale Intentional Interventions into the Climate System? Assessing the Climate Engineering Debate, 2011.

Rogelj, J., Luderer, G., Pietzcker, R. C., Kriegler, E., Schaeffer, M., Krey, V., and Riahi, K.: Energy system transformations for limiting end-of-century warming to below 1.5 °C, Nat. Clim. Chang., 5, 519–527, https://doi.org/10.1038/nclimate2572, 2015a.

Rogelj, J., Schaeffer, M., Meinshausen, M., Knutti, R., Alcamo, J., Riahi, K., and Hare, W.: Zero emission targets as long-term global goals for climate protection, Environ. Res. Lett., 10, 105007, https://doi.org/10.1088/1748-9326/10/10/105007, 2015b.

Sanz-Pérez, E. S., Murdock, C. R., Didas, S. A., and Jones, C. W.: Direct Capture of CO_2 from Ambient Air, Chem. Rev., 116, 11840–11876, https://doi.org/10.1021/acs.chemrev.6b00173, 2016.

Schäfer, S., Lawrence, M., Stelzer, H., Born, W., Low, S., Aaheim, A., Adriaìzola, P., Betz, G., Boucher, O., Carius, A., Devine-Right, P., Gullberg, A. T., Haszeldine, S., Haywood, J., Houghton, K., Ibarrola, R., Irvine, P., Kristjansson, J.-E., Lenton, T., Link, J. S. A., Maas, A., Meyer, L., Muri, H., Oschlies, A., Proelß, A., Rayner, T., Rickels, W., Ruthner, L., Scheffran, J., Schmidt, H., Schulz, M., Scott, V., Shackley, S., Tänzler, D., Watson, M. and Vaughan, N.: The European Transdisciplinary Assessment of Climate Engineering (EuTRACE): Removing Greenhouse Gases from the Atmosphere and Reflecting Sunlight away from Earth, 2015.

Schuiling, R. D. and Krijgsman, P.: Enhanced weathering: An effective and cheap tool to sequester CO_2, Clim. Change, 74, 349–354, https://doi.org/10.1007/s10584-005-3485-y, 2006.

Scott, V., Gilfillan, S., Markusson, N., Chalmers, H., and Haszeldine, R. S.: Last chance for carbon capture and storage, Nat. Clim. Chang., 3, 105–111, https://doi.org/10.1038/Nclimate1695, 2013.

Scott, V., Haszeldine, R. S., Tett, S. F. B., and Oschlies, A.: Fossil fuels in a trillion tonne world, Nat. Clim. Chang., 5, 419–423, https://doi.org/10.1038/nclimate2578, 2015.

Séférian, R., Gehlen, M., Bopp, L., Resplandy, L., Orr, J. C., Marti, O., Dunne, J. P., Christian, J. R., Doney, S. C., Ilyina, T., Lindsay, K., Halloran, P. R., Heinze, C., Segschneider, J., Tjiputra, J., Aumont, O., and Romanou, A.: Inconsistent strategies to spin up models in CMIP5: implications for ocean biogeochemical model performance assessment, Geosci. Model Dev., 9, 1827–1851, https://doi.org/10.5194/gmd-9-1827-2016, 2016.

Smith, P.: Soil carbon sequestration and biochar as negative emission technologies, Glob. Change Biol., 22, 1315–1324, https://doi.org/10.1111/gcb.13178, 2016.

Smith, P., Davis, S. J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R. B., Cowie, A., Kriegler, E., van Vuuren, D. P., Rogelj, J., Ciais, P., Milne, J., Canadell, J. G., McCollum, D., Peters, G., Andrew, R., Krey, V., Shrestha, G., Friedlingstein, P., Gasser, T., Grübler, A., Heidug, W. K., Jonas, M., Jones, C. D., Kraxner, F., Littleton, E., Lowe, J., Moreira, J. R., Nakicenovic, N., Obersteiner, M., Patwardhan, A., Rogner, M., Rubin, E., Sharifi, A., Torvanger, A., Yamagata, Y., Edmonds, J., and Yongsung, C.: Biophysical and economic limits to negative CO_2 emissions, Nat. Clim. Chang., 6, 42–50, https://doi.org/10.1038/nclimate2870, 2015.

Sonntag, S., Pongratz, J., Reick, C. H., and Schmidt, H.: Reforestation in a high-CO_2 world-Higher mitigation potential than expected, lower adaptation potential than hoped for, Geophys. Res. Lett., 1–8, https://doi.org/10.1002/2016GL068824, 2016.

Taylor, K. E., Stouffer, R. J., and Meehl, G. A.: An Overview of CMIP5 and the Experiment Design, B. Am. Meteorol. Soc., 93, 485–498, https://doi.org/10.1175/BAMS-D-11-00094.1, 2012.

The Royal Society: Geoengineering the climate, 2009.

Tokarska, K. B. and Zickfeld, K.: The effectiveness of net negative carbon dioxide emissions in reversing anthropogenic climate change, Environ. Res. Lett., 10, 94013, https://doi.org/10.1088/1748-9326/10/9/094013, 2015.

UNFCCC: Paris Agreement of the 21st session of the Conference of Parties on climate change, 2016.

Vaughan, N. E. and Gough, C.: Expert assessment concludes negative emissions scenarios may not deliver, Environ. Res. Lett., 11, 95003, https://doi.org/10.1088/1748-9326/11/9/095003, 2016.

Vaughan, N. E. and Lenton, T. M.: A review of climate geoengineering proposals, Climatic Change, 109, 745–790, https://doi.org/10.1007/s10584-011-0027-7, 2011.

Vichi, M., Navarra, A., and Fogli, P. G.: Adjustment of the natural ocean carbon cycle to negative emission rates, Climatic Change, 118, 105–118, https://doi.org/10.1007/s10584-012-0677-0, 2013.

Walker, J. C. G., Hays, P. B., and Kasting, J. F.: A negative feedback mechanism for the long-term stabilization of Earth's surface temperature, J. Geophys. Res., 86, 9776, https://doi.org/10.1029/JC086iC10p09776, 1981.

Wang, X., Heald, C. L., Ridley, D. A., Schwarz, J. P., Spackman, J. R., Perring, A. E., Coe, H., Liu, D., and Clarke, A. D.: Exploiting simultaneous observational constraints on mass and absorption to estimate the global direct radiative forcing of black carbon and brown carbon, Atmos. Chem. Phys., 14, 10989–11010, https://doi.org/10.5194/acp-14-10989-2014, 2014.

Wang, Y. P., Law, R. M., and Pak, B.: A global model of carbon, nitrogen and phosphorus cycles for the terrestrial biosphere, Biogeosciences, 7, 2261–2282, https://doi.org/10.5194/bg-7-2261-2010, 2010.

Wolf-Gladrow, D. A., Zeebe, R. E., Klaas, C., Körtzinger, A., and Dickson, A. G.: Total alkalinity: The explicit conservative expression and its application to biogeochemical processes, Mar. Chem., 106, 287–300, https://doi.org/10.1016/j.marchem.2007.01.006, 2007.

Wu, P., Ridley, J., Pardaens, A., Levine, R., and Lowe, J.: The reversibility of CO_2 induced climate change, Clim. Dynam., 45, 745–754, https://doi.org/10.1007/s00382-014-2302-6, 2014.

Zhang, Q., Wang, Y. P., Matear, R. J., Pitman, A. J., and Dai, Y. J.: Nitrogen and phosphorous limitations significantly reduce future allowable CO_2 emissions, Geophys. Res. Lett., 41, 632–637, https://doi.org/10.1002/2013GL058352, 2014.

Zickfeld, K., Eby, M., Weaver, A. J., Alexander, K., Crespin, E., Edwards, N. R., Eliseev, A. V., Feulner, G., Fichefet, T., Forest, C. E., Friedlingstein, P., Goosse, H., Holden, P. B., Joos, F., Kawamiya, M., Kicklighter, D., Kienert, H., Matsumoto, K., Mokhov, I. I., Monier, E., Olsen, S. M., Pedersen, J. O. P., Perrette, M., Philippon-Berthier, G. G., Ridgwell, A., Schlosser, A., Schneider Von Deimling, T., Shaffer, G., Sokolov, A., Spahni, R., Steinacher, M., Tachiiri, K., Tokos, K. S., Yoshimori, M., Zeng, N., and Zhao, F.: Long-Term Climate Change Commitment and Reversibility: An EMIC Intercomparison, J. Climate, 26, 5782–5809, https://doi.org/10.1175/jcli-d-12-00584.1, 2013.

Zickfeld, K., MacDougall, A. H., and Matthews, H. D.: On the proportionality between global temperature change and cumulative CO_2 emissions during periods of net negative CO_2 emissions, Environ. Res. Lett., 11, 55006, https://doi.org/10.1088/1748-9326/11/5/055006, 2016.