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Using Carbon Dioxide Removal for a Habitable Post-2050 Net-Zero Emission World: Contributions and Limitations

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Abstract United Nations (UN) encourages sovereign states to take prompt and concrete measures to accomplish net-zero emissions by year 2050, requesting carbon dioxide removal (CDR) technologies to be prepared and implemented in such ambitious climate action roadmap. However, whether CDR technologies should be further promoted or discontinued post net-zero emission year remains unclear. In this Earth-system modelling research, we compare UN-suggested 2050 net-zero emission scenario against other common climate mitigation scenarios outlined by shared social-economic pathways (SSPs). We also simulate continued CDR implementations after net-zero emissions, which is hypothetically achieved in year 2050 and 2070 respectively, to investigate how CDR can impact the global climate throughout the whole 21st and 22nd centuries. The modelling results find if the 2050 UN net-zero emission goal is accomplished, the global average surface air temperature (SAT) in the end of 21st century is around 1.5 °C higher compared to the pre-industrial level, promising an Earth environment more habitable than other scenarios without CDR. When CDR is applied to remove equal amount of anthropogenic CO_2 emissions since industrial revolution, it restores the global average SAT close to pre-industrial level of 13.5 °C. However, CDR-induced global carbon distribution within ocean, atmosphere, and land pools is different from the pre-industrial condition, causing reduced atmospheric CO_2 concentration by 9 to 38 ppm compared to the pre-industrial cases, and more alkalinized ocean surface with pH increase of 0.004 to 0.024. This study affirms CDR cannot be viewed as a reversed process to anthropogenic CO_2 emissions, accordingly climate policies to overcome the uncertainties after for late 21st century still require careful trade-offs for the decarbonation and the cost-benefits of CDR measures.

Key words net-zero emissions; CDR; Earth-system modelling; global warming; sea-level rise; ocean acidification

1 Introduction

1.1 Net-Zero Emission Scenario

The underlined acceleration of anthropogenic CO_2 emissions over recent decades, intensifying the trajectory of global climate change (Forster *et al.*, 2021; Gulev *et al.*, 2021; IPCC, 2021), has demanded mankind to devote considerable attention to combat such a challenge. Facing this pressing threat, the willingness to mitigate climate change is formulated into series of international and domestic laws, from which specific carbon emission mitigation goals are proposed (Ayres and Walter, 1991; Longo *et al.*, 2012). Currently, the most legal-binding and likely effective climate action accord internationally is Paris Agreement, signed in year 2015 and ratified by 194 contracting parties so far (UNFCCC, 2015). The drafted articles from Paris Agreement demand signatories altogether for 'holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change' (UNFCCC, 2015). It is anticipated that to prevent above 2 °C warming target from being crossed, only 1150 Gt CO_2 carbon budget allowed for emissions during the rest of this century (IPCC, 2022). Such calculation is delivered by assuming the global warming rate falling into a range of 67% chance (IPCC, 2022).

To achieve Paris Agreement, a feasible roadmap is needed to guide emission sectors from sovereign states for planning their allowed emission budget. Hereby, a more specific plan to realize such course is proposed by United Nations (UN) to achieve carbon emission neutrality by year 2050 (UN, 2020). Carbon neutrality goal, *i.e.*, net-zero goal, is a rhetoric to characterize the climate action goal of developing a social state in which the net-emitted CO_2, measured by the net sum of gross emissions and possible land and ocean CO_2 absorption, maintains ap-

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proximately zero (Fankhauser *et al.*, 2022). Scientific evidence indicates the later mankind reach the net-zero emission goal, the more harm climate change will impose, underlining the necessities to timely implement climate mitigation (Boucher *et al.*, 2012). If the net-zero emission goal can be achieved, meaning approximately 527 Gt CO_2 are allowed to be emitted to atmosphere, consisting around half of the 21st century carbon emission budget for 2 °C target. Therefore, achieving net-zero emission goal introduces a good chance for mankind to avoid warming over 2 °C by the end of the 21st century (Geden, 2016; Tanaka and O'Neill, 2018).

The most straightforward and intuitive option to achieve net-zero emission goal lies within decisive and substantial efforts to decarbonize the human society. Such attempt encompasses solid and rapid transformations in energy supply systems towards low-carbon patterns from both supply chain and end-use perspectives. However, the decarbonation alone cannot achieve net-zero emission goal for two reasons. First, there are certain emission sectors, *e.g.*, construction and husbandry industries, will always leave residual CO_2 or other greenhouse gas (GHG) emissions even if emission-free energy supply and infrastructures are adopted (Martin *et al.*, 2010; Hart and Pomponi, 2021). Second, demanding all CO_2 emission sectors to reduce their emissions to zero within merely 30 years' time window imposes enormous challenges in social, economic, political and even cultural lens, hence highly difficult to fully comply (Shove and Walker, 2010; Victor, 2011; Davis *et al.*, 2018).

1.2 Carbon Dioxide Removal

To fill in decarbonation's insufficiency gap, the carbon dioxide removal (CDR) is proposed as a supplementary and indispensable option. CDR functions by uptaking atmospheric CO_2 through natural and engineered means into permanent carbon reservoirs like ocean and land carbon sinks (Keller *et al.*, 2014; Wang and Zhang, 2020). Scientific consensus regarding the role of CDR in the net-zero emission goal asserts around 80%–90% of carbon budget-allowed CO_2 emissions can be avoided by decarbonation, while the remaining 10%–20% requires CDR (Iyer *et al.*, 2021; IPCC, 2022; Jordaan *et al.*, 2022). However, even for such minor proportion, there are disputes regarding the scalability and feasibility to remove 10 Gt CO_2 annually with the CDR portfolio (Hepburn *et al.*, 2019). The major challenges to implement CDR in large scale, are subjected to specific CDR technologies (Mace *et al.*, 2021). For example, some typical nature-based CDR options, such as afforestation, already approach their scale limits given their competitive nature in land space against agriculture (Calvin *et al.*, 2014). Meanwhile, many technology-based CDR options, are either not maturely developed for large-scale practices in a cost-effective manner, *e.g.* direct air capture (DAC) (Desport *et al.*, 2023), or lack robust carbon accounting framework to measure its carbon removal effectiveness complying to measurement, reporting and verification (MRV) principles, *e.g.* ocean alkalinity enhancement (Feng *et al.*, 2016, 2017).

Therefore, many research efforts from CDR study community concentrate on enhancing CDR's scalability and feasibility. One of the initiatives to boost the expansion of CDR implementation is through carbon pricing mechanisms (Hickey *et al.*, 2023). This is particularly meaningful to technologies like DAC, in which sequestrated carbon referenced to the baseline emission level, is treated as a priced commodity for trading profits (Song and Oh, 2023). In most climate mitigation future scenarios, CDR technologies are by default included without additional carbon pricing to drive their expansion (Hilaire *et al.*, 2019). Therefore, it is reasonable to argue, CDR technology driven by carbon pricing mechanisms can further promote climate mitigation effectiveness for the rest of 21st century beyond our current climate mitigation projections.

1.3 Research Question

The net-zero emission target constructs a scenario in which combined efforts from decarbonation and CDR jointly reduce atmospheric CO_2 level. In particular, ambitious 2050 net-zero target will inevitably utilize CDR strategies, making it both technologically and operationally ready long before 2050. But whether those CDR technologies should still be operated subsequently after net-zero emission year, remains an open question rarely discussed:

1) On one hand, it is reasonable to continue CDR because the net-zero emission goal only promises a chance of avoiding 1.5 or 2 °C warming threat, insufficient for ridding climate change-induced harm completely (Solomon *et al.*, 2009; IPCC, 2021).

2) On the other hand, the negative of above judgement can also be reasoned. As the emission gap quickly diminishes, *i.e.*, the anthropogenic carbon emission between ongoing years and net-zero emission year, it will not be attractive enough to economically maintain many CDR practices according to carbon pricing mechanisms (Anderson and Peters, 2016). As a result, it is anticipated the CDR deployment scale and operation will have to face evident decline and even be ceased after 2050.

Therefore, our research goal in this study concentrates on investing how different CDR policies impact future climate and suggest CDR policies in particular after 2050 net-zero target is achieved. By employing Earth-system modelling simulations, the impact of hypothetically implemented CDR policies can be analyzed through model output such as global average surface air temperature (SAT), sea level change, and sea surface pH change. Those three variables are chosen as metrics to detect and determine the habitable level of Earth climate for mankind, as they are strongly associated with proposed planetary boundary thresholds (Rockström *et al.*, 2009). We in this study choose DAC as the representative CDR strategy for research convenience. We anticipate by performing CDR modelling simulations designed for the next

200 years, and we are able to find out whether CDR technologies are still necessary to prevent harmful climate impacts, and figure out the evidences to adjust and optimize the design of any needed CDR policies in particularly after 2050 net-zero year.

2 Methods

2.1 UVic Model Description

The numerical climate modelling tool used in this paper is the Earth System Climate Model version 2.10 (UVic-ESCM). As a representative member of the Earth-system Model of Intermediate Complexity (EMIC) framework (Weaver *et al.*, 2001), this model has shown unique cost-effectiveness in long-term (millennium to 10000-year) global climate system simulation (Weber, 2010). The system architecture consists of three major components: an energy-moisture equation-governed atmosphere (Fanning and Weaver, 1996), a land component with soil and vegetation carbon pools (Meissner *et al.*, 2003; Avis *et al.*, 2011; MacDougall *et al.*, 2012), and a 3D-ocean coupled with Nutrients, Phytoplankton, Zooplankton, Detritus (NPZD) biogeochemical modules (Simmons *et al.*, 2004; Wanninkhof, 2014). The recent development of Version 2.10 updates UVic's marine biogeochemical cycle and land carbon dynamics (Avis *et al.*, 2011), in addition to the inclusion of a new permafrost module (MacDougall and Knutti, 2016). UVic is able to generate modelling results subjected to Coupled Model Intercomparison Project Phase 6 (CMIP6) protocol and forcing files, and it can also describe climate states regulated by carbon cycle feedback under sophisticated physical and biogeochemical perturbations (Meinshausen *et al.*, 2017). Given its capacity in tracing and tracking carbon flows within modeled Earth climate system, UVic is particularly effective in simulating CDR-engineered Earth climate, resulting into a series of CDR modelling studies for almost all discussed CDR technologies (Keller *et al.*, 2014).

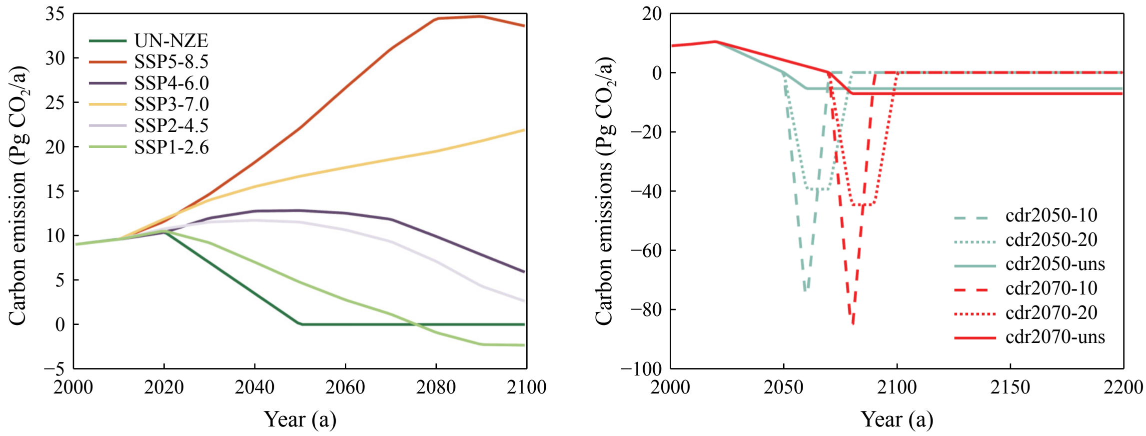
2.2 Modelling Setup

In this study, we perform two sets of modelling simulation with UVic to investigate the impacts of the net-zero emission goal and subsequent CDR policies thereafter.

In the first modelling group (hereafter named as 'Non-CDR group'), we use the historical CO_2 record-prescribed climatological initial condition from year 2000, and simulate climate change driven by some specific CO_2 forcing scenarios till year 2100. The five of all six chosen CO_2 forcing scenarios, namely SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP4-6.0 and SSP5-8.5 (Table 1), are derived from shared social-economic pathway (SSP) ensembles that are generated and assimilated from Integrated Assessment Models (IAMs) by assuming different human society development conditions. Among them, SSP1-2.6 describes a future pathway that mankind prepares adaption and mitigation sufficiently, leading to a low CO_2 world, while in SSP5-8.5 climate adaption and mitigation are deployed to the least degree hence a high CO_2 world. The rest three SSP scenarios are supposed to reach atmospheric CO_2 to the levels between SSP1-2.6 and SSP5-8.5 (Fig.1). Besides above SSP scenarios, the UN-suggested 2050 net-zero emission goal scenario, named as 'UN-NZE', defines a unique situation where the net emission is gradually reduced to zero in year 2050. In this scenario, we assume such reduction follows a linear trend each year, while leaving the emission after 2050 still zero, so that the UN-NZE scenario in format of time series can be established and used to drive mitigated climate change in

Table 1 Description of model run setups

	Model run name	Start year	End year	Description
Non-CDR group	UN-NZE	2000	2100	The UN-suggested net-zero emission scenario, has linear emission reductions from now on to net-zero emission in year 2050.
	SSP1-2.6			A strict scenario, with temperature rising by 1.5–1.7 °C, moves toward a green economy and enhances international cooperation.
	SSP2-4.5			A medium pathway, with temperature rising by about 2 °C, relies on some emissions reductions but is slow to act.
	SSP4-6.0			A medium pathway, with temperature rising significantly higher than 2 °C, reflects the 'dual-track' world.
	SSP3-7.0			A high emission pathway, with temperature rising close to 4 °C, depicts a highly divided and fragile future.
	SSP5-8.5			A high emission pathway, with temperature rise exceeding 4 °C, assumes that fossil fuels continue to dominate in the future.
CDR-group	cdr2050_10	2000	2200	After achieving net-zero emission in year 2050, CDR implements for 10 years to remove anthropogenic CO_2 accounted since pre-industrial.
	cdr2050_20			After achieving net-zero emission in year 2050, CDR implements for 20 years to remove anthropogenic CO_2 accounted since pre-industrial.
	cdr2050_uns			After achieving net-zero emission in year 2050, CDR implements till year 2200 to remove anthropogenic CO_2 accounted since pre-industrial.
	cdr2070_10			After achieving net-zero emission in year 2070, CDR implements for 10 years to remove anthropogenic CO_2 accounted since pre-industrial.
	cdr2070_20			After achieving net-zero emission in year 2070, CDR implements for 20 years to remove anthropogenic CO_2 accounted since pre-industrial.
	cdr2070_uns			After achieving net-zero emission in year 2070, CDR implements till year 2200 to remove anthropogenic CO_2 accounted since pre-industrial.



(a) Net carbon emissions (b) Net carbon emissions, CDR

Fig.1 Time series of net carbon emissions (a) in different scenarios (UN-NZE, SSP5-8.5, SSP4-6.0, SSP3-7.0, SSP2-4.5, and SSP1-2.6), and (b) with using CDR. In (b) the dashed lines represent the results of short-term rapid CDR, and the solid lines represent the results of long-term CDR, with blue representing the scenario for achieving net-zero emissions by year 2050 and red representing the scenario for achieving net-zero emissions by year 2070.

UVic. In UN-NZE scenario, technology-based CDR such as DAC is integrated within the emission profile, and thus the net-zero emission is achievable in theory. Given the absence of specific CDR technology outlined in the report, we assume a linear reduction pathway to net-zero emissions from year 2020 to 2050.

The other modelling group (hereafter named as 'CDR-group'), focuses on comparing different CDR policies after the net-zero goal is achieved. The aim of subsequent CDR is to prevent climate change-induced anomalies to the least impact. Thus, it is ideal to restore the atmospheric CO_2 level to pre-industrial state for coming centuries. In this group, six different CDR policies are designed to remove all accumulative anthropogenic CO_2 emissions since industrial revolution till the net-zero emission year into permanent carbon reservoirs (Table 1). The six types of prepared CDR activities are commenced in parallel immediately after the net-zero emission goal is achieved in year 2050 and 2070 (model run name with _2050 and _2070 suffix respectively), which is equivalent to 2962.42 Gt CO_2 and 3355.62 Gt CO_2 for net-zero emissions of year 2050 and 2070, respectively. To achieve such huge amount of CO_2 removal, CDR needs to be designed following suitable time and magnitude scale. Unlike 2050 net-zero emission goal with clear pledge currently, 2070 goal is a hypothetical case in which UN-demanded mitigation pledge is not met hence procrastination. For each CDR policy, we assume the removed carbon is a constant value each year with interpolations to the initial and ending time points, and CDR lasts for 10, 50 and 150 years if net-zero target is reached in year 2050, and 10, 50 and 130 years when net-zero year is reached in year 2070 (Fig.1).

3 Results

3.1 Non-CDR Group Results

We first investigate the results from the Non-CDR group comparing UN-NZE and SSP scenarios. In year 2100, the business-as-usual high emission scenario *i.e.* SSP5-8.5 causes atmospheric CO_2 concentration to reach 1086.52 ppm, resulting that global average atmospheric SAT approaches 17.68 °C in year 2100, sea level increases by 36.94 cm, and sea surface pH decreases by 0.39 in a century. Compared to SSP5-8.5, the gradually expanded climate mitigation measures, characterized by SSP4-6.0, SSP3-7.0, SSP2-4.5 and SSP1-2.6, reduce atmospheric CO_2 concentration by 450.21 ppm, 257.87 ppm, 500.59 ppm and 642.85 ppm in year 2100, while for global average SAT, the values are 1.41 °C, 0.74 °C, 1.62 °C and 2.39 °C respectively. The global average sea level is raised by 27.53 cm, 32.00 cm, 26.18 cm and 20.56 cm in a century and sea surface pH difference for those four scenarios remains at 0.20, 0.10, 0.23, and 0.32 in year 2100 compared to SSP5-8.5, which demonstrate mitigated ocean acidification compared to SSP5-8.5 case (Fig.2).

In this modelling group, pre-industrial global average SAT is 13.5 °C. Therefore, climate state characterized by SSP1-2.6 makes to prevent Paris Agreement 1.5 °C target goal from being crossed, while SSP5-8.5, SSP4-6.0, SSP3-7.0, and SSP2-4.5 even cannot safeguard the future climate from crossing 2 °C target set by the accord. UN-NZE scenario turns to be the most ambitious climate mitigation measure, with only 1.59 °C warmer being reached by year 2100 compared to pre-industrial level, accompanied by 31.61 cm raised sea level and pH reduction by 0.14. Such outcome formatted in time series indicates much lesser environmental harm to mankind compared to other SSP scenarios like SSP5-8.5 and even SSP1-2.6. Compared to SSP5-8.5 case, climate mitigation efforts in SSP1-2.6 accumulatively reduce by 488.29 Gt CO_2, while for NZE such value is only 5.67% higher. But the outcome in global average SAT increase, sea level rise, and pH decrease is mitigated by 8.37%, 13.19% and 5.31% in a century. SSP1-2.6 reaches net-zero target in the year around 2076, therefore the results between SSP1-2.6 and NZE reaffirm achieving net-zero emission goal sooner will provide the better climate mitigation effectiveness

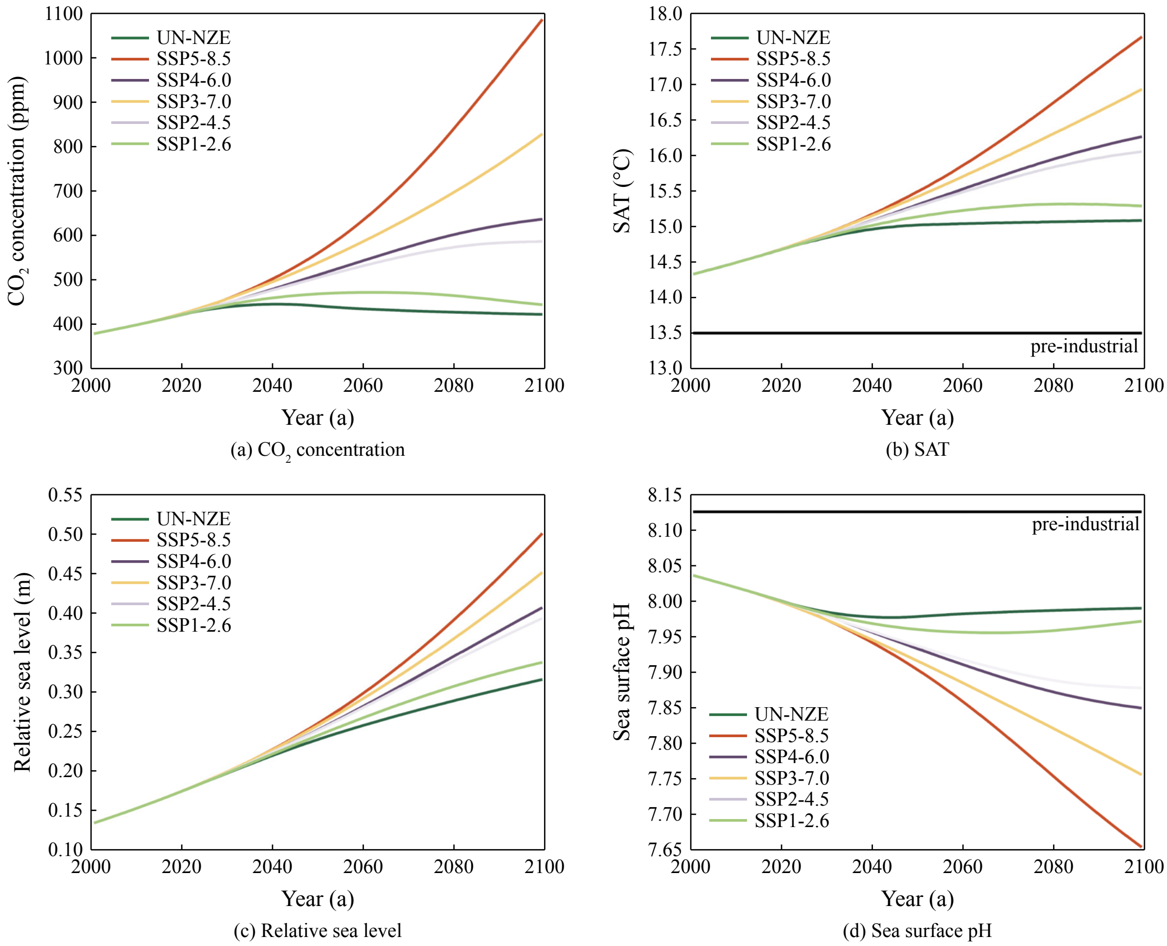


Fig.2 Time series of (a) CO_2 concentration, (b) SAT, (c) relative sea level, and (d) sea surface pH in different scenarios (UN-NZE, SSP5-8.5, SSP4-6.0, SSP3-7.0, SSP2-4.5, and SSP1-2.6).

(Fig.2).

For NZE scenario, the hotspots of warming since year 2000 are identified mostly at high latitudes, while itself experiences much lesser warmer in those areas compared to high emission counterpart SSP5-8.5 scenario. The globally distributed sea surface pH profile shows strongest ocean acidification induced by climate change happens at mid-high latitudes, and NZE reduces its overall acidification magnitude compared to SSP5-8.5 case. Some individual spatial grid boxes in regions for example like Laptev Sea and Kara Sea, can still experience warming by 2.19 °C, and acidification by pH of 0.17 (Fig.3). Therefore, although NZE prevented negative climate consequences in most locations globally, individual spots may still suffer from SAT and sea surface pH anomalies. Therefore, subsequent climate actions posting a net-zero emission goal to limit the harmful impacts are still necessary.

3.2 CDR-Group Results

We next turn to investigate the results from the CDR-group. It is specifically designed to remove the cumulative anthropogenic CO_2 emissions from the pre-industrial era to the net-zero emission year. Two types of CDR implemented till the end of the next century scenarios *i.e.*, 'cdr2050-uns' and 'cdr2070-uns' cause atmospheric CO_2 concentration to reach 252.76 ppm and 246.52 ppm, respectively, resulting that global average SAT approaches 13.63 °C and 13.66 °C in year 2200, sea level increases by 3.2 cm and 0.88 cm, and sea surface pH increases by 0.17 and 0.19 from the net-zero emission year to year 2200. Compared to 'cdr2050-uns' and 'cdr2070-uns', the rapid removal measures in a short term, characterized by 'cdr2050_10', 'cdr2050_20', 'cdr2070_10', and 'cdr2070_20', result that atmospheric CO_2 concentration approaches 274.57 ppm, 274.05 ppm, 272.41 ppm, and 271.72 ppm in year 2200, while for global average SAT, the values are 13.62 °C, 13.62 °C, 13.63 °C and 13.63 °C. The global average sea level decreases by 3.62 cm, 3.25 cm, 6.39 cm, and 5.92 cm, and sea surface pH change remains at 0.15, 0.15, 0.17, and 0.17 from the net-zero emission year to year 2200 (Fig.4). Figure 4 reveals two notable results: First, atmospheric CO_2 concentrations in year 2200 are significantly different depending on the CDR implemented; second, short-term rapid CDR exhibits superior efficacy in mitigating sea-level rise.

In order to investigate the reason for different atmospheric CO_2 concentrations in year 2200, we analyze global total carbon. Two CDR implemented till the end of the next century scenarios *i.e.*, 'cdr2050-uns' and 'cdr2070-uns' results that the global total land carbon decreases by 30.62 Gt and 31 Gt, and the global total ocean

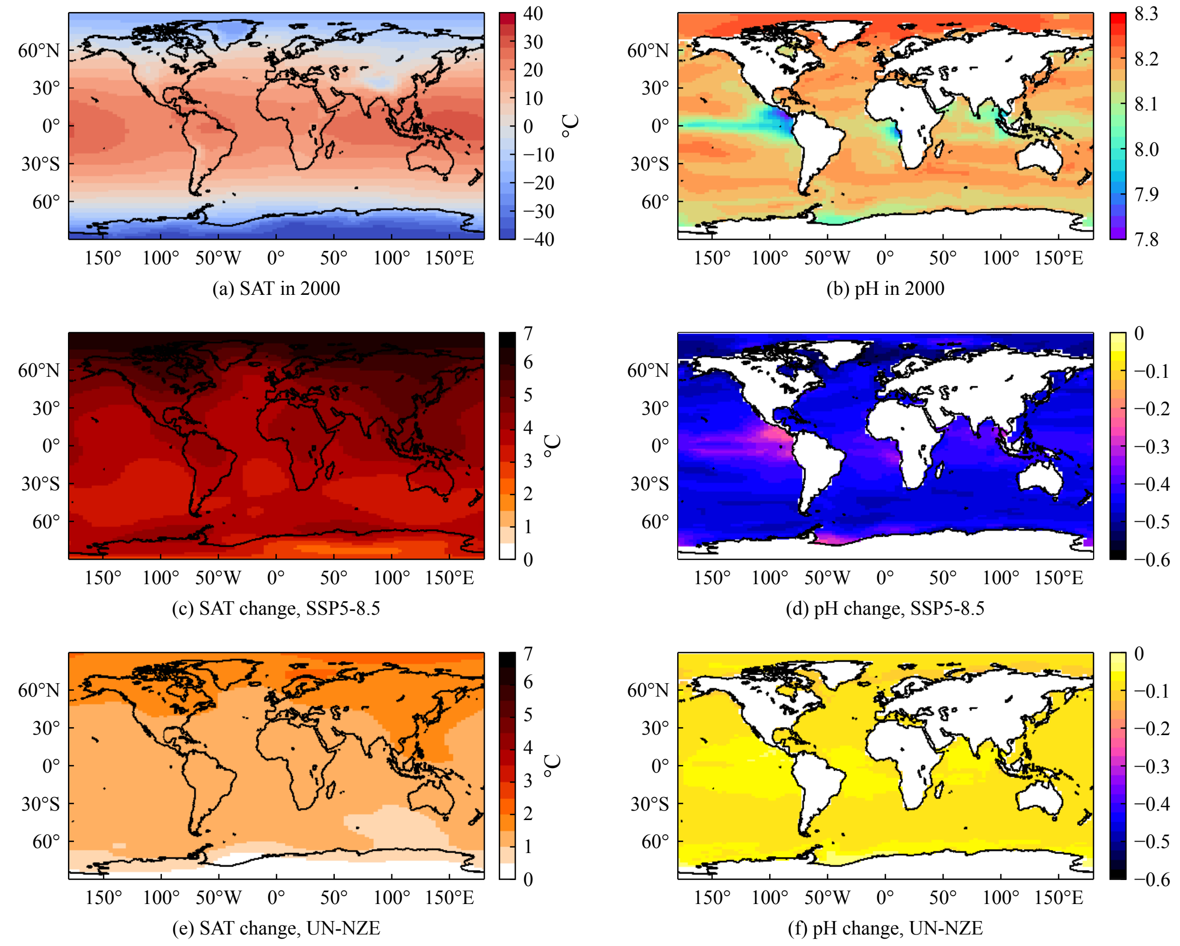


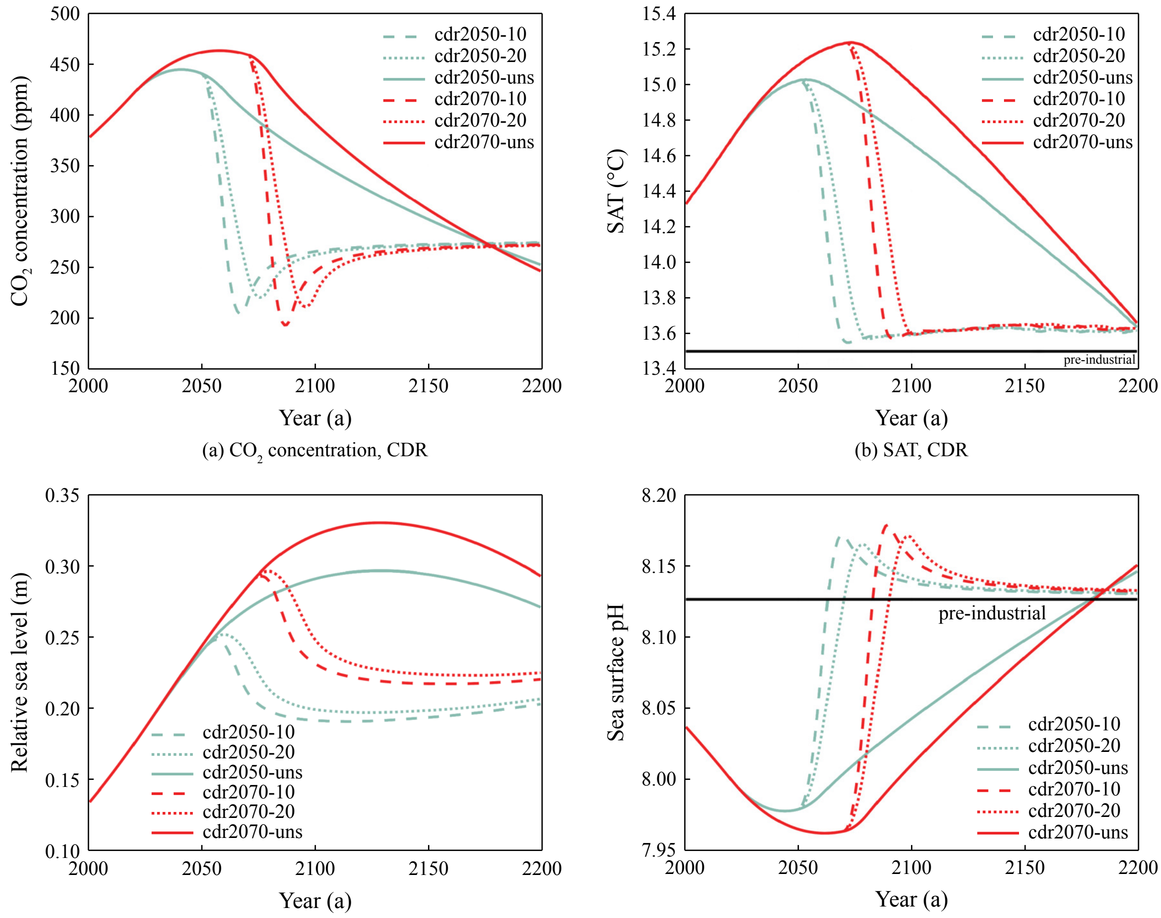
Fig.3 Spatial distribution of (a) SAT in 2000, (b) pH in 2000, (c) SAT change in SSP5-8.5 scenario from 2000 to 2100, (d) pH change in SSP5-8.5 scenario from 2000 to 2100, (e) SAT change in UN-NZE scenario from 2000 to 2100, and (f) pH change in UN-NZE scenario from 2000 to 2100.

carbon increases by 95.06 Gt and 109.57 Gt. Compared to 'cdr2050-uns' and 'cdr2070-uns' cases, there are similar results on global total land carbon, while evident difference on global total ocean carbon, for other four CDR measures. The 'cdr2050_10', 'cdr2050_20', 'cdr2070_10', and 'cdr2070_20' result that global total land carbon decreases by 26.27 Gt, 27.42 Gt, 31.91 Gt and 33.46 Gt, and the global total ocean carbon increases by 41.61 Gt, 43.89 Gt, 51.85 Gt, and 54.86 Gt (Fig.5). These findings suggest that the difference in atmospheric CO_2 concentrations by year 2200 is linked to variations in oceanic carbon sequestration.

In order to investigate the reason for different efficacy in mitigating sea-level rise, we analyze surface albedo, sea surface temperature (SST) and ocean temperature. The 'cdr2050-uns' and 'cdr2070-uns' result that the land surface albedo reduces by 0.21% and 0.22%, and the ocean surface albedo reduction remains at 0.08% and 0.09%. The 'cdr2050_10', 'cdr2050_20', 'cdr2070_10', and 'cdr2070_20' result that the land surface albedo of these four CDR all decreases by 0.2%, and the ocean surface albedo reduction remains at 0.07%, 0.07%, 0.08% and 0.08%. All six CDR measures achieve mitigation of SST to a warming margin within 0.1 °C compared to preindustrial levels. However, different CDR measures exhibit different results about ocean temperature. 'cdr2050-uns' and 'cdr2070-uns' result that the ocean temperature increases by 0.09 °C and 0.05 °C from the net-zero emission year to year 2200. The 'cdr2050_10', 'cdr2050_20', 'cdr2070_10', and 'cdr2070_20' result that ocean temperature decreases by 0.02 °C, 0.03 °C, 0.06 °C and 0.05 °C from the net-zero emission year to year 2200 (Fig.5). These findings suggest that short-term rapid CDR induces an immediate reduction of atmospheric CO_2 concentration, leading to a subsequent decrease in both SAT and SST, and decreasing ocean temperature. The decrease in ocean temperature reduces thermal expansion in the upper ocean, mitigating sea-level rise. Concurrently, the combined effects of temperature reduction and surface albedo increase establish a positive feedback loop, amplifying thermal reductions.

4 Conclusions and Discussion

In this paper, we use UVic-ESCM to perform two modelling simulation groups, *i.e.*, Non-CDR group and CDR-group, and we investigate the mitigation ability of 2050 net-zero target and effects of CDR policies thereafter. The main conclusions are as follows: Compared to the business-as-usual high emission scenario, *i.e.*, SSP5-

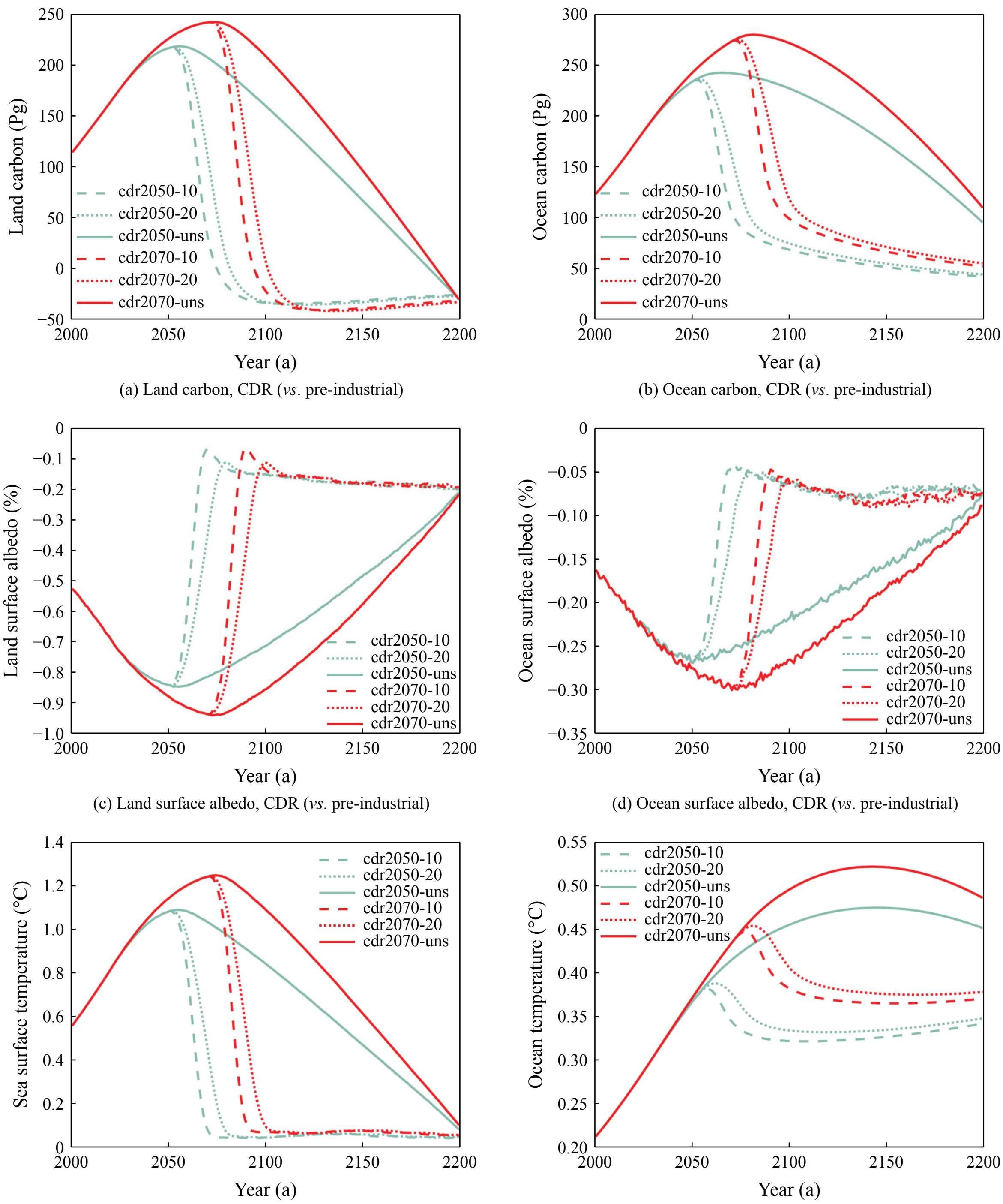


(a) CO_2 concentration, CDR (b) SAT, CDR (c) Relative sea level, CDR (d) Sea surface pH, CDR

Fig.4 Time series of (a) CO_2 concentration, (b) SAT, (c) relative sea level, and (d) sea surface pH with using CDR. The dashed lines represent the results of short-term rapid CDR, and the solid lines represent the results of long-term CDR, with blue representing the scenario for achieving net-zero emissions by year 2050 and red representing the scenario for achieving net-zero emissions by year 2070.

8.5, other gradually expanded climate mitigation SSP scenarios demonstrate varying degrees of mitigation ability. The ambitious 2050 net-zero emission target ensures achievement of the Paris Agreement 2 °C goal, and approaches the threshold of the 1.5 °C goal. Compared to SSP1-2.6, 5.67% higher reduction of carbon emissions can result in more decreases of SAT and sea level, therefore achieving net-zero emission goal sooner provides the better climate mitigation effectiveness. Compared to SSP5-8.5, UN-NZE reduces SAT and mitigates ocean acidification to a substantial extent in a century. While SAT warming hotspots are concentrated in the Northern Hemispheres high-latitude areas and severe ocean acidification zones predominantly span global mid-high latitudes, these regions demonstrate greater climate mitigation potential compared to high-emission pathway scenarios.

The net-zero goal is insufficient for ridding climate change-induced harm completely according to our findings, and it is necessary to continue CDR. There are some discussions on the reversibility of CDR, with relevant studies from the Carbon Dioxide Removal Model Intercomparison Project (CDRMIP) indicating that climate models exhibit certain discrepancies in simulating the mitigation effects of atmospheric CO_2 concentrations (Keller *et al.*, 2018). Our results demonstrate CDR is not the inverse process of carbon emissions, because the allocation relations of carbon in the atmosphere, ocean, and land systems in year 2200 are different from the pre-industrial cases. The dynamics of these allocation relations are also modulated by the acceleration of CDR implementation. Besides a reduction in atmospheric CO_2 concentrations induces CO_2 release from the ocean and terrestrial biosphere (Cao *et al.*, 2023). Our findings reveal the earlier CDR implemented, the lesser atmospheric CO_2 reduced, as short-term rapid CDR triggers premature release of ocean carbon into the atmosphere. Because the ocean exhibits a slow response to the reduction of atmospheric CO_2 concentrations (Li *et al.*, 2020), this case counteracts the reduction of atmospheric CO_2, hence diminishing CDR efficiency. Among the variables in the climate system, there are significant differences in their reversibility potential. After atmospheric CO_2 concentrations return to lower levels, SAT can revert to the pre-industrial level (Keller *et al.*, 2018), while sea level remains significantly higher than the pre-industrial level (Cao *et al.*, 2023). Our results agree with these, and we find that short-term rapid CDR is more effective in mitigating sea-level rise. Be-



(a) Land carbon, CDR (*vs*. pre-industrial)
(b) Ocean carbon, CDR (*vs*. pre-industrial)
(c) Land surface albedo, CDR (*vs*. pre-industrial)
(d) Ocean surface albedo, CDR (*vs*. pre-industrial)
(e) Sea surface temperature, CDR (*vs*. pre-industrial)
(f) Ocean temperature, CDR (*vs*. pre-industrial)

Fig.5 Time series of (a) land carbon, (b) ocean carbon, (c) land surface albedo, (d) ocean surface albedo, (e) sea surface temperature, and (f) ocean temperature compared to pre-industrial levels with using CDR. The dashed lines represent the results of short-term rapid CDR, and the solid lines represent the results of long-term CDR, with blue representing the scenario for achieving net-zero emissions by year 2050 and red representing the scenario for achieving net-zero emissions by year 2070.

cause it can rapidly enhance the atmospheric CO_2 concentrations, and a subsequent decrease in temperatures led by the reduction of atmospheric CO_2 concentration reduces thermal expansion in the upper ocean. Therefore, there are important values for both long-term and short-term CDR implementation. Short-term rapid CDR appears imperative for sea level decline, although the abrupt temperature drop induced by such cases may trigger much harm to ecosystems. When considering CDR efficacy or impacts on carbon cycle dynamics, long-term CDR becomes necessary.

In conclusion, we assess the mitigation effects of a net-zero emission goal, finding it can achieve Paris Agreement target goals, and mitigate ocean acidification. It is necessary to continue CDR after the net-zero emission year, and CDR-group results demonstrate that both long-term and short-term CDR implementation have their values. Obviously, the CDR policies in this study are hypothetical, the specific design should be adjusted and optimized in practical progress.

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Author Contributions

All authors contributed to the study conception and design. Xin Cui: formal analysis, methodology, validation, visualization and writing. Jianping Li: supervision and funding acquisition. Yuming Ellias Feng: supervision and conceptualization. All authors read and approved the final manuscript.

Data Availability

The data and references presented in this study are available from the corresponding author upon reasonable request.

Declarations

Ethics Approval and Consent to Participate

This article does not contain any studies with human participants or animals performed by any of the authors.

Consent for Publication

Informed consent for publication was obtained from all participants.

Conflict of Interests

The authors declare that they have no conflict of interests.

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