Ocean-based Negative Emission Technologies

OCEAN NETs

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Abstract: This study uses an existing perturbed parameter ensemble (PPE) of simulated ocean CO_2 removal (CDR) to better determine sustainable pathways of ocean-based NET deployment and to provide information to constrain the design of subsequent modelling experiments. The results show that ocean alkalinity enhancement (OAE) can only help meet SDG13 (Climate Action) when other ambitious mitigation efforts are taken. This reinforces that OAE is not a substitute for emissions reduction, but could contribute to meeting our climate goals (if other factors suggest OAE is worth doing). For SDG14 (Life Below Water), the results suggest OEA can contribute to limiting or even reversing ocean acidification. Meeting many other SDG14 objectives is closely linked to also meeting SDG13. A key recommendation is therefore, that subsequent simulations in OceanNETs should only use SDG13 compatible baseline scenarios, unless there is some specific need for process understanding at higher levels of climate change. The analysis has also determined that the idealized CDR in the PPE is not suitable for determining many socio-economic constraints and the implications that these have for meeting the SDGs. Another key recommendation is therefore, that subsequent simulations within OceanNETs should use more realistic scenarios of CDR deployment.

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Document History

Date	Version	Description	Name/Affiliation
30.06.2022	1.0	First submitted version	D. Keller / GEOMAR

List of abbreviations, acronyms and definitions

Ocean alkalinity enhancement	OAE
Perturbed parameter ensemble	PPE
Shared Socio-economic Pathway	SSP
Net Primary Productivity	NPP
Carbon Dioxide Removal	CDR
Negative Emission Technology	NET
Earth System Model	ESM
Work Package	WP
Sustainable Development Goal	SDG
Sea Level Rise	SLR

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1. Introduction

1.1 Context

OceanNETs is a European Union project funded by the Commission's Horizon 2020 program under the topic of Negative emissions and land-use based mitigation assessment (LC-CLA-02-2019), coordinated by GEOMAR | Helmholtz Center for Ocean Research Kiel (GEOMAR), Germany.
OceanNETs responds to the societal need to rapidly provide a scientifically rigorous and comprehensive assessment of negative emission technologies (NETs). The project focuses on analyzing and quantifying the environmental, social, and political feasibility and impacts of ocean-based NETs. OceanNETs will close fundamental knowledge gaps on specific ocean-based NETs and provide more in-depth investigations of NETs that have already been suggested to have a high CDR potential, levels of sustainability, or potential co-benefits. It will identify to what extent, and how, ocean-based NETs can play a role in keeping climate change within the limits set by the Paris Agreement.

1.2 Purpose and scope of the deliverable

Work package 4 (Simulations) fills fundamental knowledge gaps in our understanding of how the Earth system responds to NETs and combines new knowledge on biogeochemical processes and potential deployment sites and scenarios, including the social, legal and governance constraints investigated in CT1, with state-of-the-art Earth system models, to investigate the potential of ocean NETs to contribute to climate neutrality in a sustainable way. Task 4.1 contributes to this effort by analyzing an existing perturbed parameter ensemble (PPE) (performed for the Horizon 2020 COMFORT project; grant agreement No. 820989) of simulated ocean alkalinity enhancement (OAE). Note that while the COMFORT PPE will eventually cover ocean-based CDR approaches other than OAE, at the time of this analysis only data on OAE had been prepared enough (by the COMFORT team) to include in this deliverable. The ensemble explores uncertainties, with regards to key processes parameterizations, of emission-driven Shared Socio-economic Pathway (SSP) scenarios with different deployment magnitudes of OAE. Our analyses extend upon the COMFORT results, which focus on avoiding climatic tipping points, by attempting to identify sustainable pathways in regards to the CO_2 drawdown potential of OAE that are consistent with the relevant UN sustainable development goals, as well as the legal, governance, economic and public acceptance constraints that are being investigated by other work packages (noting that only preliminary results are available from other WPs).

1.3 Relation to other deliverables

This information will feed into Earth System Model (ESM) simulations in Task 4.5 by helping to constrain the amount of ocean alkalinity enhancement in the ESM simulations to be both a feasible and desirable amount.

1.4 Limitations of this work

The modelling work presented here relies upon an existing data set that was not explicitly designed to evaluate socio-economic constraints as it simply deploys OAE on top of existing SSP scenarios. Thereby, these simulations do not follow the underlying narrative or the assumptions of the integrated assessment modelling work that generated the SSP scenarios and forcing.

The model output is also most suited for investigating climate and biogeochemical responses to OAE and the uncertainties that arise from key parameterizations. This means that any constraints that come from OceanNETs in regards to the SDGs, economics, governance, legality, or public acceptance can only be used in the analysis so far as they relate to the OAE deployment, which was not determined by OceanNETs, and the model output variables. The analysis also remains at an annual global mean level (e.g., examined variables include indicators such as the global annual mean atmospheric near-surface temperature) as the coarse resolution and intermediate complexity of the models that can perform PPEs cannot well resolve localized perturbations or extreme events.

Given these limitations, this deliverable should not be viewed as an all-encompassing one that will supply every answer in regards to "constraining" the deployment of OAE. Instead, this should be viewed as a novel attempt to exploit the availability of a very large existing Earth system model data set (hundreds of model runs) by confronting it with potential social and sustainability constraints.

2. Analyzing simulated ocean alkalinity enhancement

2.1 Background

Governments worldwide have recognized the risks of climate change and via the COP21 Paris Agreement, have agreed to "hold 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". Many actions must be taken to achieve this goal. In addition to emission reductions (the primary means of mitigation) that are urgently needed to achieve this goal, the IPCC Special Report on Global Warming of 1.5°C (2018) highlighted with *high confidence* that all projected pathways that limit warming to 1.5°C also require use of carbon dioxide removal (CDR) on the order of 100–1000 Gt CO_2 over the 21st century. Pathways that limit warming to 2°C or achieve net zero emissions at some warmer level also require use of CDR (IPCC, 2022). Proposed CDR approaches encompass a range of methods aimed at reducing atmospheric CO_2 levels by either seeking to engineer the removal and subsequent storage of CO_2 or by deliberately enhancing land and ocean carbon sinks to increase the removal of CO_2 from the atmosphere.

Understanding of CDR method potentials, feasibilities, and risks are limited, even though it is now clear that CDR will be needed at scale within very few decades to complement other climate change mitigation activities. To date the majority of research on CDR has focused on terrestrial-based methods. From this research it is already clear that achieving the Paris Agreement goals with land-based CDR alone, will be extremely difficult, if not impossible due to their side effects, trade-offs with U.N. sustainability goals (e.g., loss of biodiversity), competition for land use, limited individual potentials, and/or issues of carbon storage permanence (European Academies' Science Advisory Council, 2018; Fuss et al., 2018; IPCC, 2019; Lawrence et al., 2018; Smith, 2016; Smith et al., 2016). Much less is known about ocean-based CDR approaches, although some of them appear promising, especially with respect to the potential scale of application (Gattuso et al., 2018; GESAMP, 2019; Keller, 2018; Greg H. Rau, 2019).

In this study we focus on ocean alkalinity enhancement (OAE) for ocean-based CDR. Ocean alkalinity enhancement approaches aim to increase the alkalinity of seawater in the surface mixed layer, thereby physio-chemically allowing more CO_2 to dissolve in seawater and be stored as ions such as bicarbonate (HCO_3^-) or carbonate (CO_3^{2-}), i.e., the general methodology increases the carbon uptake and storage capacity of seawater. The idea behind OAE comes from a natural process called chemical weathering, which removes around 0.4 Gt C yr^{-1}. Most of the proposed OAE methods involve using carbonate (lime or limestone) or silicate (olivine) minerals as an alkalizing agent (Kheshgi, 1995; Köhler et al., 2010). It is known that there is a removal of at least 1.5 moles of atmospheric CO_2 for every mole of dissolved magnesium (Mg)- or calcium (Ca)-based minerals (e.g., wollastonite, olivine, and anorthite) and 0.5 mole for carbonate minerals (e.g., calcite and dolomite) (Phil Renforth & Henderson, 2017). However, mineral derivatives or other alkaline materials, such as some industrial waste products could also potentially be used. Alternatively, the alkalinity could be generated electrochemically (Phil Renforth & Henderson, 2017).

Some proposed OAE deployment approaches involve simply mining, grinding, and dumping naturally abundant limestone, olivine rocks, or other minerals into the ocean or on beaches where they will dissolve and increase the alkalinity of seawater (Hangx & Spiers, 2009; Harvey, 2008; Köhler et al., 2013; Meysman & Montserrat, 2017). In more technological OAE approaches a sodium hydroxide (NaOH) solution would be electrochemically (electrodialytically or electrolytically) generated to increase ocean alkalinity (National Academy of Sciences, Engineering, and Medicine, 2021). Electrochemical OAE can be done in several ways with different electrolytes and approaches for dealing with the acid product of electrochemistry. One hybrid OAE approach even combines electrochemistry with the use of an alkaline mineral to neutralize the acid (Caldeira & Rau, 2000; G. H. Rau et al., 2013; Greg H. Rau, 2008).

Idealized modelling studies have shown that increasing the alkalinity of seawater could potentially remove large amounts of CO_2 from the atmosphere (up to 450 ppm) and keep it there even if the additions were stopped (Feng et al., 2017; González & Ilyina, 2016; Ilyina et al., 2013; Keller et al., 2014a; Köhler et al., 2013). However, realistic constraints on OAE deployment are lacking.

One of the main techno-economic constraints on the potential of these methods appears to be the mining, processing, and transportation of the minerals, since sequestering significant amounts of CO_2 requires massive amounts of mineral rock (Hartmann et al., 2013; P. Renforth et al., 2013). For example, to offset assumed mid-century residual emissions amounting to about 10% of current emissions of ~ 34 Gt CO_2 yr^{-1} would require mineral rock on the order of 10 billions tons per year (National Research Council, 2015). For comparison, about 8 billon tons of coal are mined globally per year. Electrochemical approaches are also constrained by infrastructure and energy requirements, as well as disposal of any byproducts (National Academy of Sciences, Engineering, and Medicine, 2021). Current techno-economic feasibility studies of OAE suggest a potential range of >0.1–1.0 Gt CO_2 yr^{-1} for a large country like the USA, with a potential for sequestering >1 Gt CO_2 yr^{-1} if applied globally (National Academy of Sciences, Engineering, and Medicine, 2021).

However, OAE cannot be evaluated and implemented based only on techno-economic feasibility criteria. Other factors must be also considered, including (but not limited to): impacts on marine life, international laws, governance, social acceptance, how the consideration of OAE effects other mitigation efforts, and wider policy goals, that can be best described by the Sustainable Development Goals (SDGs). Unfortunately, most of these factors are currently poorly understood in relation to OAE and have only begun to be investigated in the OceanNETs project and other research efforts around the world.

In this study I analyzed an existing perturbed parameter ensemble (PPE) (performed for the Horizon 2020 COMFORT project; grant agreement No. 820989) of simulated ocean alkalinity enhancement (OAE) to see if by confronting it with potential social and sustainability goals I can better understand constraints on OAE. The ensemble explores uncertainties, with regards to key processes parameterizations, of emission-driven SSP scenarios with different deployment magnitudes of OAE. It was designed to assess how multiple climate targets are related to allowable CO_2 emissions, thereby providing basic information to design policies aimed to minimize severe or irreversible damage from anthropogenic climate change (M. Steinacher & Joos, 2016; Marco Steinacher et al., 2013).

2.2 Methodology

For the COMFORT PPE the UVic model (Mengis et al., 2020) was applied in a Bayesian, probabilistic, observation-constrained approach that is described in detail in Steinacher et al., (2013). Here I briefly describe this approach.

The model used in this study is the University of Victoria Earth System Climate Model (UVic ESCM) of intermediate complexity, version 2.10, described in detail in Mengis et al., (2020). The model consists of three dynamically coupled components: a three-dimensional general circulation model of the ocean that includes an inorganic sediment model and a dynamic-thermodynamic sea ice model, a terrestrial model, and a simple one-layer atmospheric energy-moisture balance model. All components have a common horizontal resolution of 3.6 longitude x 1.8 latitude. The oceanic component has nineteen 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 is based on the Hadley Center model TRIFFID. The soil module includes a 14-layer representation of soil carbon and a representation of soil freeze–thaw processes that includes a permafrost carbon component. 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 (as determined from surface pressure anomalies that are calculated from deviations in pre-industrial surface air temperature) to prescribed NCAR/NCEP monthly climatological wind data. The model has been extensively used in climate change studies and is well validated under pre-industrial to present day conditions (Mengis et al., 2020).

Baseline forcing (scenarios): For each PPE member, the model was spun up for 10,000 years under pre-industrial atmospheric and astronomical boundary conditions and then run from 1765 to 2015 using historical fossil-fuel and land-use carbon emissions forcing protocols for CMIP6 (Eyring et al., 2015). From the year 2015 to 2100 the model was forced with CO_2 and other greenhouse gas emissions, as well as land-use change, following ScenarioMIP protocols (O'Neill et al., 2016), except that the model was run in emission driven-mode, rather than prescribing atmospheric CO_2 as done in ScenarioMIP. Baseline scenarios include *SSP1-2.6, SSP2-4.5, SSP5-3.4-OS*, and *SSP5-8.5* to cover a wide range of climate forcing (Fig. 1) and simulated climate change outcomes (e.g., Figs. 2 and 3).

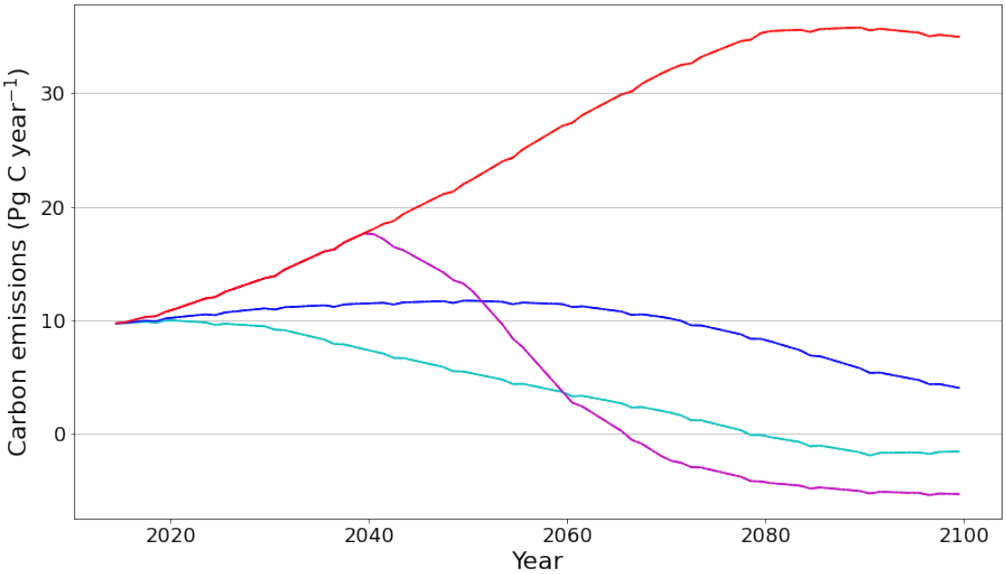

Figure 1. CO_2 emissions forcing for the baseline scenarios SSP1-2.6 (light blue), SSP2-4.5 (dark blue), SSP5-3.4-OS (purple), and SSP5-8.5 (red).

Ocean alkalinity enhancement simulations for each PPE member were done with three deployment magnitudes for each SSP scenario (named *ALK-SSPx-xx* where x follows the SSP baseline name designations). These simulations all start on 01.01.2025 with a 10-year linear ramp up period and then from 01.01.2035 onward constant alkalinity input is simulated until end of simulation. The three constant levels of alkaline mineral addition after 2035 were 0.5, 2.5 and 5 Pg $Ca(OH)_2$ yr^{-1} (for reference 1 Pg $Ca(OH)_2$ yr^{-1} equals ~0.0275 Pmol alkalinity addition per year). These levels were chosen in the COMFORT project to represent low, moderate and high levels of OAE with the highest level corresponding to approximately half of the global shipping capacity. OAE was done in a manner similar to the deployment in Keller et al. (2014a), with the alkalinity addition to the uppermost ice free ocean cells between 70 °N and 60 °S evenly distributed in space and time over the year.

Perturbed parameter ensemble (PPE), Gaussian process (GP) emulation, and validation: To quantify parametric uncertainty, a probabilistic framework was adopted utilizing a perturbed parameter ensemble (PPE) and Gaussian process (GP) emulation (Tran et al., 2020). The ensemble contains over 300-members with 21 perturbed parameters. The analysis provides not only the mean and confident interval of the desirable outputs but also their estimated probability density functions for each scenario.
Parameters to vary were chosen to balance computational costs vs. maximum coverage of the parameter space that is relevant for the model variables of interested in the COMFORT project (see COMFORT project deliverable D5.3 for full details). Once, the choice of perturbed parameters has been made, a training set, or a set of carefully designed simulations, is generated to inform the GP emulators. Because ESMs are computationally expensive, the COMFORT team wanted a design that is capable of exploring interactions between parameters and that is valid across the whole range of the input parameter space using a minimum number of simulations. Thus, a Latin hypercube sampling plan (McKay et al., 1979) with the maximin space-filling criteria (Morris & Mitchell, 1995) was employed.
To ensure that model outputs are meaningful and do not include unphysical climate states, the COMFORT team defined a set of plausibility metrics for comparison with various observed aspects of the Earth system over the historical period (see COMFORT project deliverable D5.3 for full details). The original twenty-six observation-based data sets from Steinacher et al., (2013) were updated for this purpose and used to constrain the PPE.
Then, the COMFORT team calculate the probability (100% confidence) of not exceeding the defined limits for the scenario space (Table 1), considering uncertainties in physical and carbon-cycle parameters. See Steinacher et al., (2013) and Steinacher and Joos., (2016) for a detailed description of this methodology.

Applying criteria from OceanNETs to "constrain" the potential of OAE. In the COMFORT project the analysis utilized a variety of climate and biogeochemical target variable to evaluate the "safe operating space" in future projects (Table 1). My analysis goes beyond this by utilizing further constraints derived from the Sustainable Development Goals and early OceanNETs results. However, it must be recognized that my analysis relies upon an existing data set that was not explicitly designed to evaluate socio-economic constraints as it simply deploys OAE on top of existing SSP scenarios. That is, as these simulations do not follow the underlying narrative or the assumptions of the integrated assessment modelling work that generated the SSP scenarios and forcing, it is not possible to directly infer how this level of OAE effects other mitigation activities, economics, or social dynamics.
Furthermore, the model output is also most suited for investigating climate and biogeochemical responses to OAE and the uncertainties that arise from key

parameterizations. This means that any constraints that come from OceanNETs in regards to the SDGs, economics, governance, legality, or public acceptance can only be used in the analysis so far as they relate to the OAE deployment, which was not determined by OceanNETs, and the model output variables. Furthermore, as these constraints are not explicitly calculated by the model, they cannot be used as targets for a probabilistic calculation. The analysis also remains at an annual global mean level (e.g., examined variables include indicators such as the global annual mean atmospheric near-surface temperature) as the coarse resolution and intermediate complexity of the UVic cannot well resolve localized perturbations or extreme events.

Given these limitations, this research should not be viewed as an all-encompassing endeavor that will supply every answer in regards to "constraining" the deployment of OAE. Instead, this should be viewed as a novel attempt to exploit the availability of a very large existing Earth system model data set (hundreds of model runs) by confronting it with potential social and sustainability constraints.

Table 1. COMFORT project target variables / metrics used in this analysis

Target variable	**Description**	**Target 1**	**Target 2**	**Target 3**	**Target 4**	**Unit**
ΔSAT	Maximum SAT increase until year 2100 relative to 1800	1.5	2	3	4	°C
SLR	Steric sea level rise (2081-2100) relative to (1986-2005)	0.2	0.30	0.6	0.8	m
A_{SO}	Aragonite undersaturation of Southern Ocean surface	5	10	25	50	% of area south of 50ºS
A_{Arctic}	Aragonite undersaturation of Arctic Ocean surface	10	25	50	100	% of area north of 70ºN
$A_{\Omega>3}$	Global loss of surface waters with $\Omega_{arag}>3$	50	70	90	100	% of area in 2005
Subsurface ΔO_2	Change in subsurface dissolved O_2 concentration (average between 100 and 600m)	-4	-6	-8	-12	mmol m^{-3} relative to the 1870-1899 mean
Global ΔO_2	Change in global O_2 content	-1.8	-2.4	-2.6	-3.5	% relative to (1990-1999)

Sustainable Development Goals assessment criteria are determined from the ongoing development of an SDG assessment framework for OceanNETs (Deliverable D7.4, due month 36). This assessment will evaluate the direct and indirect relationships between ocean-based CDR and the SDGs (Table 2), as well as identify areas where there are uncertainties. Then a quantification (approach still in development) will be made to determine how sustainable any particular CDR approach is relative to each goal, and its targets. As the SDG framework development is still in its infancy, I do not provide a full assessment here. Instead, I focus on easy to identify relationships between the SDGs and OAE as deployed in the COMFORT PPE. Note also that I do not look in depth at the relationship between the SDGs and the baseline SSP scenario results as such an analysis is beyond the scope of this task and has been conducted in prior research efforts, e.g., see Zimm et al., (2018). For the analysis here, I have identified SDGs 13 and 14 as having the most relevant criteria (targets) for constraining OAE (as simulated by the COMFORT project).

Table 2. Sustainable Development Goal (SDG) list and selected indicators for SDGs 13 and 14.

Sustainable Development Goals		Highly relevant indicators for SDGs 13 and 14
1) No Poverty		
2) Zero Hunger		
3) Good Health and Well-being		
4) Quality Education		
5) Gender Equality		
6) Clean Water and Sanitation		
7) Affordable and Clean Energy		
8) Decent Work and Economic Growth		
9) Industry, Innovation and Infrastructure		
10) Reducing Inequality		
13) Climate Action		13.2 Integrate climate change measures into national policies, strategies and planning 13.3 Improve education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction and early warning 13.a Implement the commitment undertaken by developed-country parties to the United Nations Framework Convention on Climate Change to a goal of mobilizing jointly $100 billion annually by 2020 from all sources to address the needs of developing countries in the context of meaningful mitigation actions and transparency on implementation and fully operationalize the Green Climate Fund through its capitalization as soon as possible

14) Life Below Water		14.1 By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution 14.2 By 2020, sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and take action for their restoration in order to achieve healthy and productive oceans 14.3 Minimize and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels 14.7 By 2030, increase the economic benefits to small island developing States and least developed countries from the sustainable use of marine resources, including through sustainable management of fisheries, aquaculture and tourism 14.a Increase scientific knowledge, develop research capacity and transfer marine technology, taking into account the Intergovernmental Oceanographic Commission Criteria and Guidelines on the Transfer of Marine Technology, in order to improve ocean health and to enhance the contribution of marine biodiversity to the development of developing countries, in particular small island developing States and least developed countries 14.c Enhance the conservation and sustainable use of oceans and their resources by implementing international law as reflected in the United Nations Convention on the Law of the Sea, which provides the legal framework for the conservation and sustainable use of oceans and their resources, as recalled in paragraph 158 of "The future we want"
15) Life on Land		
16) Peace, Justice, and Strong Institutions		
17) Partnerships for the Goals		

Assessment criteria derived from early OceanNETs research. I aim to use the early findings from other OceanNETs work packages (see project deliverables), as well as socio-economic and governance information available in the literature to understand how the COMFORT PPE can provide information to constrain OAE. This presents a particular challenge due to both the preliminarity of the findings and the question of how easily it is to extrapolate some of the work. For example, how representative are the public perception results from the first focus groups in Norway and Germany? Will these findings hold up in subsequent research efforts? Some types of OAE may be expensive now, but could be cheaper in the future? In order to deal with these uncertainties for some of the work I use a narrative scenario approach to provide a framework for categorizing the results with regards to the OAE deployment as 1) pessimistic, 2) moderate, and 3) optimistic. This will allow me to compare these hypothetical scenarios (and how we see the initial OceanNets results) to the model data set results and to discuss what this would mean for the climate and meeting mitigation targets, as well as constraining if the OAE simulations are reasonable or unlikely.

Table 3. OAE deployment scenario narratives, constraints, and preliminary findings from OceanNETs.

Narrative scenario with regards to OAE deployment	**Constraints**			
	Economic	**Public Acceptance**	**Governance / Legal**	**Biogeochemical / ecological**
Pessimistic, likely no OAE because:	OAE is expensive	No acceptance	Not governable or legal to do	Not effective or safe for marine life
Moderate, likely limited OAE because:	OAE is mid-priced compared to other CDR	Acceptable in some countries or cultures, but not others	Is allowed and governed in some countries, but not others	Effective and safe up to a certain scale
Optimistic, likely much OAE because:	OAE is cheap or even pays for itself	Accepted everywhere	Internationally legalized and governed	Very effective with only benefits or low impacts on marine life
Preliminary OceanNETs results suggest the:	Moderate and pessimistic scenarios, depending on the type of OAE	Moderate scenario	Moderate scenario	Moderate scenario

2.3 Results and Discussion

One of the first findings came early in the COMFORT analysis process. This was that the two lowest levels of OAE did not have enough of an effect on the Earth system to allow for differences to readily be distinguishable from the base line simulations in a probabilistic manner (i.e., when parametric uncertainties were taken into account the range of uncertainty in the OAE simulations fell well within that of the baseline scenario). That is, probabilities of meeting targets with limited OAE deployments cannot be distinguished from baseline scenario results without OAE. Only the 5 Pg $Ca(OH)_2$ yr^{-1} addition had enough of an impact for a readily distinguishable probabilistic analysis, and even here the mean of the PPE OAE simulations was mostly well within one standard deviation of the uncertainty range of the baseline scenarios (e.g., see Figs. 2 and 3). For this reason, the lower level OAE simulations are not further analyzed or presented here with regards to the probability analysis. Note that this does not mean that lower levels of OAE are not worth investigating or simulating, but that this particular model is not the proper tool to use for such study. This finding has important implications for detecting and attributing OAE using global-scale observation capabilities, such as atmospheric CO_2 or temperature measurements in that detection would be very difficult and attribution uncertain – especially given the natural variability of the real world. Furthermore, this implies that carbon accounting would need to be done at a much more local level as distinguishing any effect of OAE on atmospheric CO_2 would be difficult, even with a massive deployment.

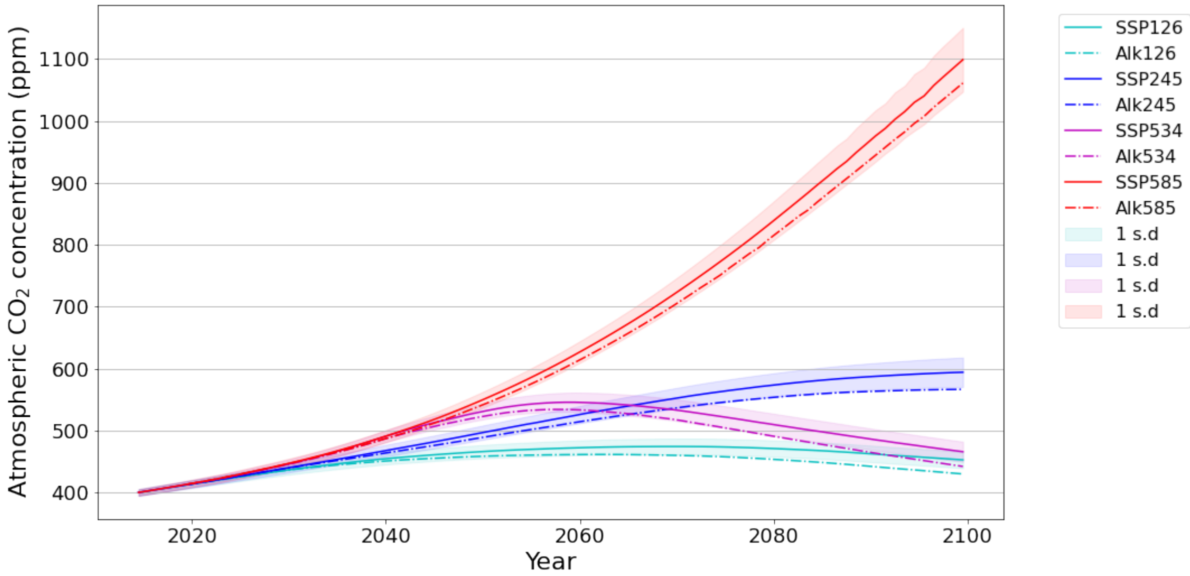

Figure 2. Simulated atmospheric CO_2 for the baseline scenarios (solid lines), SSP1-2.6 (SSP126), SSP2-4.5 (SSP245), SSP5-3.4-OS (SSP534), and SSP5-8.5 (SSP585) and the same scenarios where ocean alkalinization ($5\ Pg\ Ca(OH)_2\ yr^{-1}$) has been done (dash-dotted lines; in legend this corresponds to Alk + the SSP numbers). The colored shaded areas show 1 standard deviation of the parametric uncertainties for each of the baseline scenarios. The Alk standard deviations are of a similar magnitude, but not shown for clarity due to the overlap.

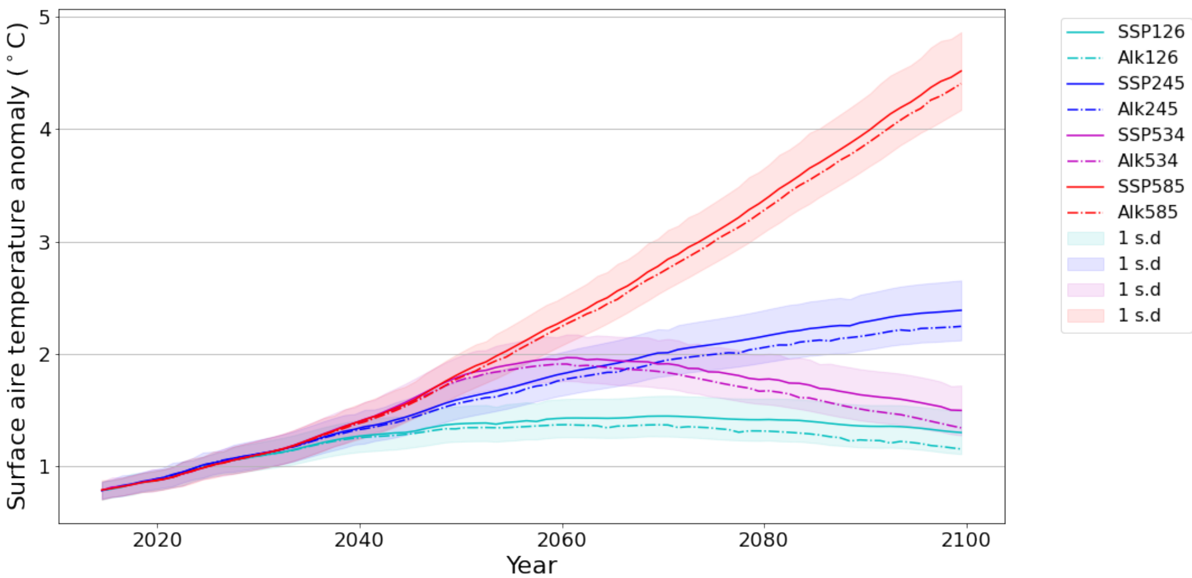

Figure 3. Simulated near surface air temperature anomalies for the baseline scenarios (solid lines), SSP1-2.6 (SSP126), SSP2-4.5 (SSP245), SSP5-3.4-OS (SSP534), and SSP5-8.5 (SSP585) and the same scenarios where ocean alkalinization ($5\ Pg\ Ca(OH)_2\ yr^{-1}$) has been done (dash-dotted lines; in legend this corresponds to Alk + the SSP numbers). The colored shaded areas show 1 standard deviation of the parametric uncertainties for each of the baseline scenarios. The Alk standard deviations are of a similar magnitude, but not shown for clarity due to the overlap.

The next key finding relates to SDG 13 (Climate Action). This can be considered in two ways. The simplest is to evaluate if the goal is reached by the mean of the ensemble and the second is to use the ensemble to derive probabilities of meeting a target/goal. Using the mean of the ensemble is certainly the less powerful approach as it does not fully take into account parameteric uncertainties, but this is analagous to what is typically done when modelling CDR, doing one simulation with your best model version and basing the analysis entirely on that. For the 1[st] approach, OAE helps to meet the ambitious 1.5° C climate goal for the *ALK-SSP1-2.6* and *ALK-SSP5-3.4-OS* scenarios with a cooling that is up to 0.2° C beyond that achieved in the baseline *SSP1-2.6* and *SSP5-3.4-OS* scenarios, which also achieve this goal by the year 2100. Although in the *SSP5-3.4-OS* scenario there is of course an overshoot that reaches almost 2° C around mid-century.
For the 2nd approach, if we consider target 1 (table 1) to meet very ambitions climate goals and target 2 to meet less ambitious climate goals (e.g., the 1.5 degree target vs. the 2 degree target) then it is possible to say which scenarios with OAE achieve SDG 13 with a high liklihood. Only the overshoot and low emission scenarios have higher probabilites of meeting the less ambitious targets (2). Parametric uncertainties mean that there is a low <30% probability of meeting the 1.5° C target and limiting sea level rise (SLR) even in the *ALK-SSP1-2.6* PPE simulations. Many scenarios can meet targets 3 and 4 (see appendix figures 9 and 10). However, these targets are not compatible with SDG 13.

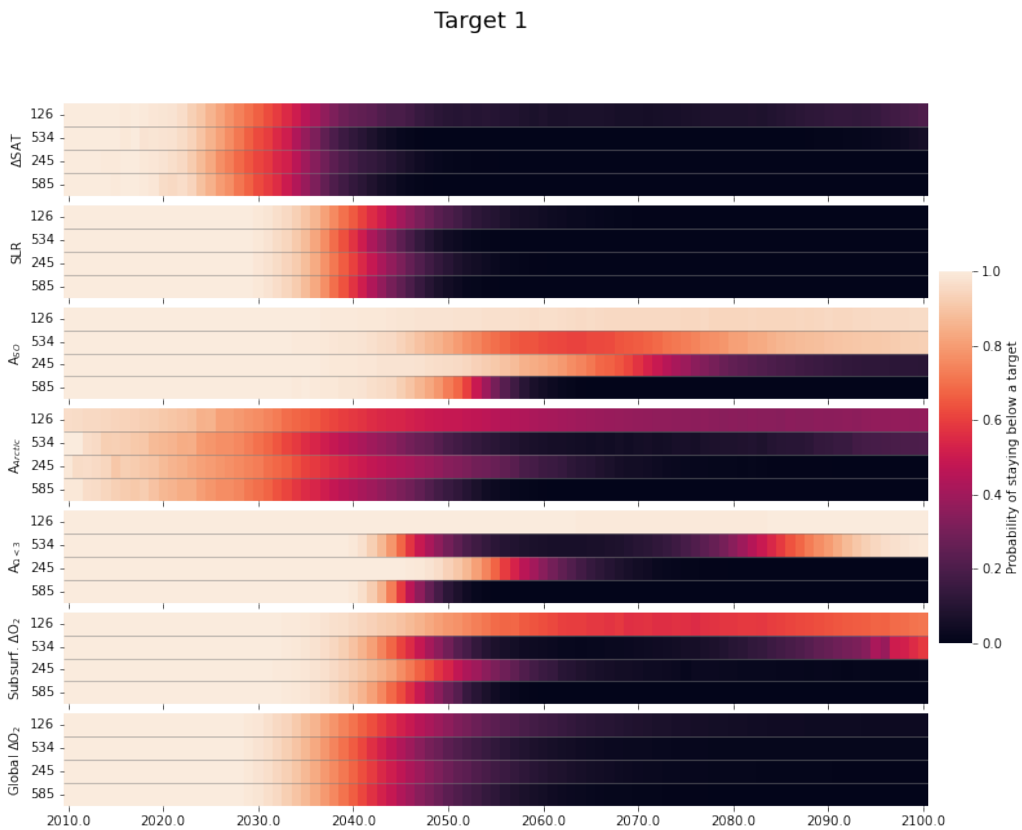

Figure 4. Probability of each 5 Pg $Ca(OH)_2\ yr^{-1}$ alkalinity enhancement scenario (y-axis of each heat plot with the baseline SSP scenario upon which OAE is deployed indicated by the numbers) to stay below target 1 values as defined in Table 1. For simplicity, target 1 can be thought of as meeting very ambitious climate goals and limiting warming to 1.5 deg. C.

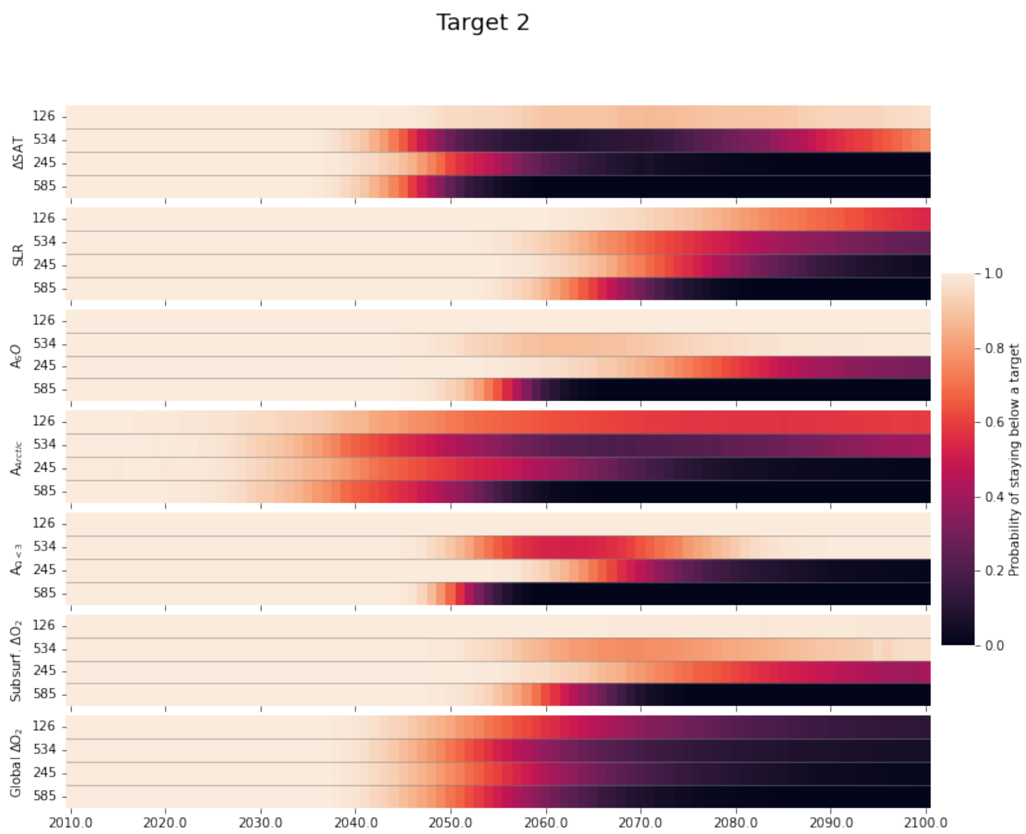

Figure 5. Probability of each 5 Pg $Ca(OH)_2$ yr^{-1} alkalinity enhancement scenario (y-axis of each heat plot with the baseline SSP scenario upon which OAE is deployed indicated by the numbers) to stay below target 2 values as defined in Table 1. For simplicity, target 2 can be thought of as meeting less ambitious climate goals such limiting warming to 2 deg. C rather than 1.5 deg. C.

The next key finding relates to SDG 14 (Life Below Water). Again, many (but not all) results can be considered in two ways, looking at the mean or the probabilities derived from the PPE.

The first model output that I will consider is phytoplankton net primary productivity (NPP; Fig. 6). NPP is the key output for the marine ecosystem as simulated by UVic since it relates to phytoplankton growth and carbon fixation, as well as providing information on how productive the base of the food chain is. While UVic does not have higher trophic levels like fish (a zooplankton state variable is the highest tropic level), I can infer that if NPP decreases, then there would be less food for higher trophic levels (e.g., some fish stocks would likely be negatively effected). In the PPE, the response of NPP to climate change is highly uncertain and can both increase of decrease, making it difficult to determine meaningful probabilies of change (e.g., as in Figs. 4 and 5). In the scenario with the highest level of climate change SSP5-8.5, uncertainties are especially high (see standard deviation range). In the low emission scenarios that are most compatible with SDG13, mean (of the PPE) NPP mostly decreases with climate change. This is a response commonly seen in other models (Bopp et al., 2013; Séférian et al., 2020). There is little difference between simulations with and without OAE, which is not surprising as the UVic model does not simulate impacts of carbonate chemistry changes on phytoplankton. Therefore, the only differences are due to climatic effects. Overall, the model PPE response still leaves high uncertainies in how NPP is impacted by OAE and climate change, although there appears to be a trend towards decreasing NPP of a few % due to climate change in the baseline scenarios that best meet SDG13.

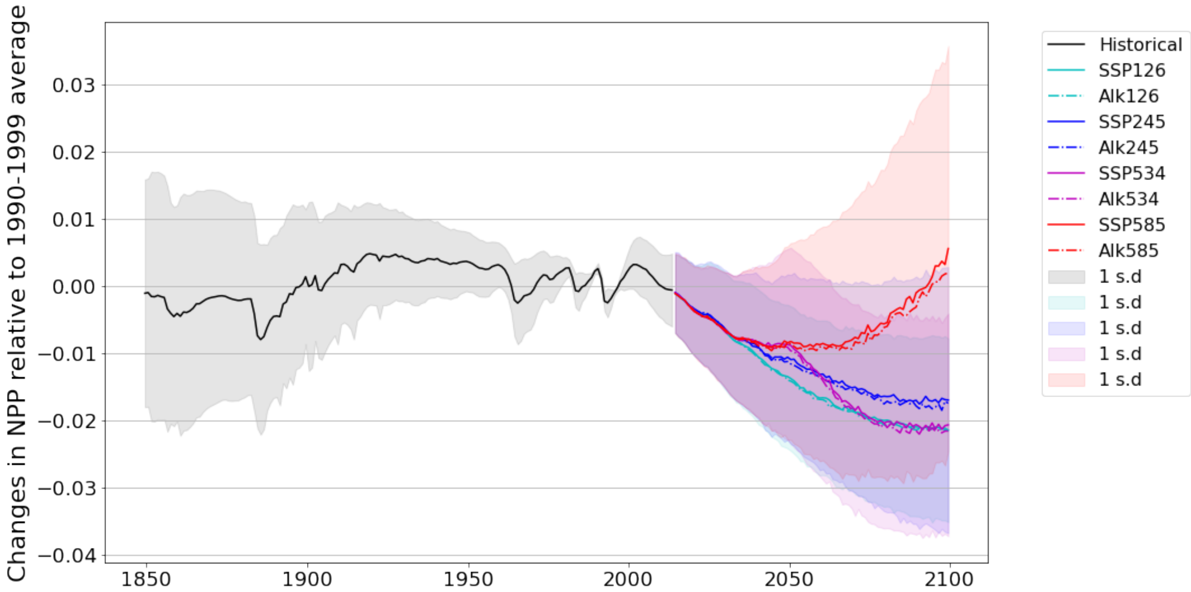

Figure 6. Changes (%) in globally integrated annual phytoplankton net primary productivity (NPP) relative to a 1990-1999 average for the historical period (black line; grey shading), baseline scenarios (solid lines), SSP1-2.6 (SSP126), SSP2-4.5 (SSP245), SSP5-3.4-OS (SSP534), and SSP5-8.5 (SSP585) and the same scenarios where ocean alkalinization (5 Pg $Ca(OH)_2$ yr^{-1}) has been done (dash-dotted lines; in legend this corresponds to Alk + the SSP numbers). The colored shaded areas show 1 standard deviation of the parametric uncertainties for each of the baseline scenarios. The Alk standard deviations are of a similar magnitude, but not shown for clarity due to the overlap.

The next model outputs that will be considered in relation to SDG 14 are ocean carbonate chemistry variables, e.g., surface ocean pH and aragonite saturation, because they allow to determine if ocean acidification becomes worse or better in response to mitigation – something that would have an impact upon many species, especially calcifying organisms like corals (Hurd et al., 2018). In ocean biogeochemistry, aragonite saturation Ω is widely adopted as a metric to characterize the saturation state of seawater with respect to aragonite ($CaCO_3$) mineral and levels below 3 (the chosen target for low latitude waters) fall below the range in which most coral reefs evolved (3.4 in the pre-industrial period) or are at today (Rockström et al., 2009; Steffen et al., 2015; Marco Steinacher et al., 2013). In arctic waters aragonite saturation is typically lower and can approach undersaturation, at which point $CaCO_3$ can begin to dissolve (Steinacher et al., 2013).

As OAE has a direct effect on pH and aragonite saturation, there is clearly a difference between the baseline scenarios and the OAE simulations. OAE limits and even partially reverses ocean acidification in the low emission scenarios (Figs. 4, 5, 7 and 8). There is a high probability of meeting the most ambitious targets for *ALK-SSP1-2.6* simulations, except in the Arctic. The *ALK-SSP1-2.6* and *ALK-SSP5-3.4-OS* simulations also have a high probability of meeting the less ambitious mitigation targets (Target group 2; Fig. 5), except in the Arctic for the overshoot scenario. Overall, this suggests that OAE can help to achieve SDG 14, especially in regards to indicators 14.2 and 14.3 (Table 2), if done in conjunction with ambitious greenhouse gas emission reductions as in the baseline scenarios.

In regards to oxygen loss, which is another important factor for life underwater, none of the simulations is able to meet the recommended targets and prevent continued losses (Figs. 4 and 5). This is imporant because much of the ocean is already geochemically quite close today to the 'edge of anoxia' and deoxygenation is likely to lead to the growth of hypoxic and anoxic 'dead zones', with probable effects on ecosystems, and the production of biogenic and radiatively active gases (like N_2O) (Shepherd et al., 2017). Much of the oxygen loss is directly related to ocean warming (Gruber, 2011; Oschlies et al., 2018), thereby closely linking this aspect of SDG14 with SDG13. This suggests that SDG14 will be difficult to meet without mitigation that goes beyond the pathways needed to reach SDG13 and the Paris Agreement climate targets, i.e., perhaps warming needs to be limited to even much less than 1.5 degrees.

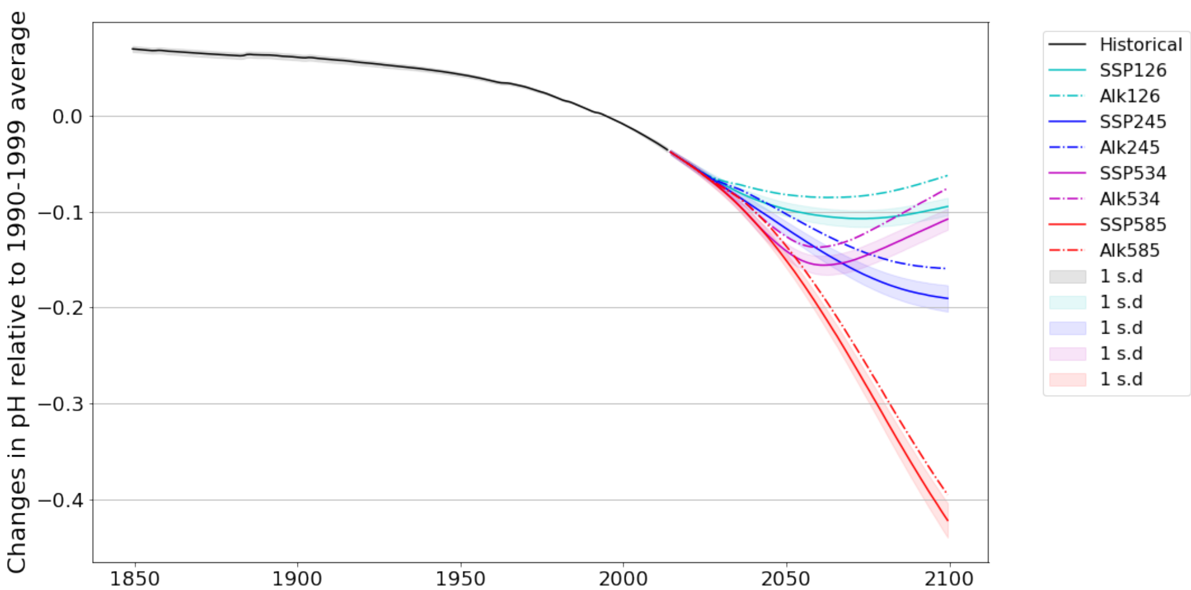

Figure 7. Changes (%) in global annual mean surface pH relative to a 1990-1999 average for the historical period (black line; grey shading), baseline scenarios (solid lines), SSP1-2.6 (SSP126), SSP2-4.5 (SSP245), SSP5-3.4-OS (SSP534), and SSP5-8.5 (SSP585) and the same scenarios where ocean alkalinization ($5\ Pg\ Ca(OH)_2\ yr^{-1}$) has been done (dash-dotted lines; in legend this corresponds to Alk + the SSP numbers). The colored shaded areas show 1 standard deviation of the parametric uncertainties for each of the baseline scenarios. The Alk standard deviations are of a similar magnitude, but not shown for clarity due to the overlap.

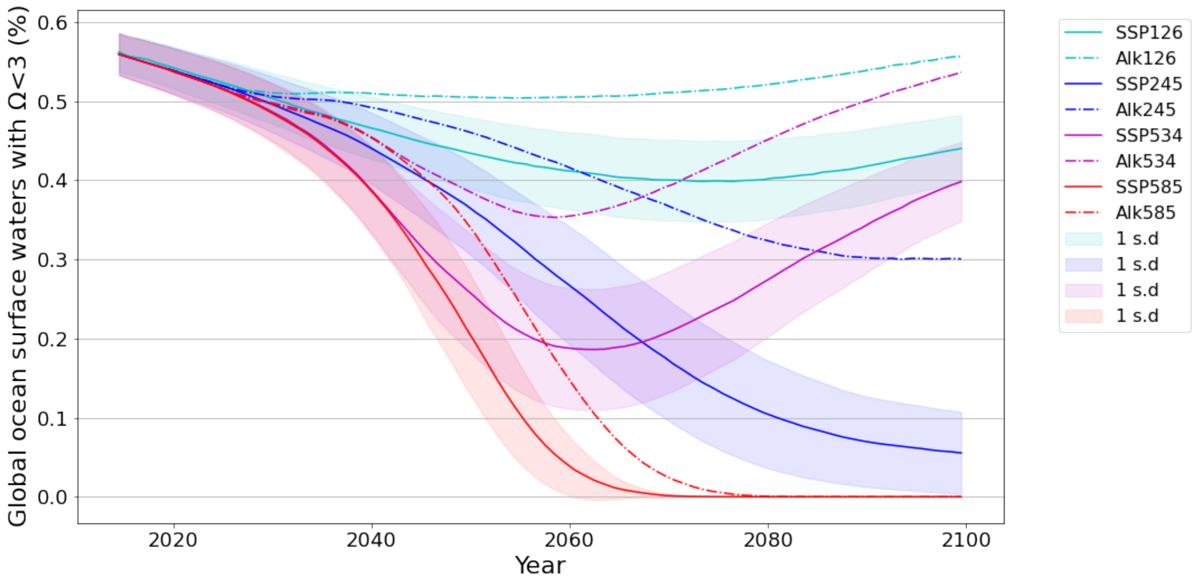

Figure 8. Changes (%) in global ocean surface waters with an aragonite saturation level lower than 3, relative to a 1990-1999 average, for the historical period (black line; grey shading), baseline scenarios (solid lines), SSP1-2.6 (SSP126), SSP2-4.5 (SSP245), SSP5-3.4-OS (SSP534), and SSP5-8.5 (SSP585) and the same scenarios where ocean alkalinization (5 Pg $Ca(OH)_2$ yr^{-1}) has been done (dash-dotted lines; in legend this corresponds to Alk + the SSP numbers). The colored shaded areas show 1 standard deviation of the parametric uncertainties for each of the baseline scenarios. The Alk standard deviations are of a similar magnitude, but not shown for clarity due to the overlap.

So far, this analysis has looked at simulated output variables that are easy to link directly to SDGs 13 and 14. Now I turn to the less easily quantified impacts, relationships, and constraints; keeping in mind the idealized design of the simulated OAE PPE. First, are the economic implications of the simulated OAE. The high level of OAE in the simulations, implies that a massive OAE industry has been created. Such a wide-scale industry would certainly have many impacts upon people and their livelihoods, as well as natural systems, given that massive mining would most likely have to take place (electrochemical weathering and ocean liming via spare capacity in the cement industry likely cannot be scaled up to provide alkalinity at this scale but could contribute; see OceanNETs deliverables from WP6). Second, there would likely have to be widespread public acceptance or significant autocratic rule for OAE to be done at this scale as no portion of the ocean would not see the impacts of OAE. Third, widespread legalization and governance would likely have to be in place for this level of OAE to take place. While it is possible that a few coastal countries would not participate in OAE, the scale of deployment suggests that OAE is occurring off most coastlines and throughout the open ocean (even in a modified scenario that does not add alkalinity as homogenously as the COMFORT one). Furthermore, even coastal countries that do not participate in OAE, would see the effects due to cross-boundary transport of alkaline waters (i.e., alkaline waters transported into their exclusive economic zones). This suggest that some international agreements would be in place to deal with these cross-boundary effects. Finally, for this level of OAE to be done it would be desirable/necessary to have few biogeochemical or ecological side effects as severe impacts would feedback upon the economics, governance, and public

perception of OAE. So far the OceanNETs mesocosm studies and other ongoing work (Ferderer et al., 2022) has suggest that biological impacts of OAE are low to moderate. As the simulations widely distribute OAE over the ocean there is no reason to suggest that this would not be the case. Recent OceanNETs studies have, however, suggested that OAE may need to be carefully done to avoid secondary precipitation of CaCO3, which would end up lowering alkalinity instead of increasing it (Hartmann et al., 2022). These results also suggest that highly technical engineered approaches may be needed for successful OAE, something that could drive up the costs and have an impact upon how much is done. Therefore, it is not clear if a 5 Pg yr^{-1} deployment of OAE is techno-economically feasible. When combined with the socio-political impacts suggested by the simulations, this further suggests that OAE could not be achieved at the level in the simulations (at least early in the century). Preliminary OceanNETs results (Table 3) also suggest that a more moderate level of deployment is likely – at least up until mid-century, but we will have to revisit this towards the end of the project when more information is available.
So, can any further constraints be derived from the SDG implications of the simulations? Aside from for SDGs 13 and 14 as detailed above, for most SDGs I could only speculate on the implications of the idealized OAE simulations, especially given the many interactions between the SDGs (Horvath et al., 2022). Such speculation is likely not helpful as the simulated OAE deployment is simply too idealized. However, perhaps it is worth briefly commenting on the overall implications of the pathways (scenarios) with OAE. Clearly, high emission scenarios, even with OAE, meet few SDG goals. For more highly ambitious and optimistic pathways, such as *SSP1-2.6*, research has suggest so far that they too do not meet all SDGs and fail to provide information on some of them (Zimm et al., 2018). Thus, by adding idealized OAE to these scenarios we should not expect them to fulfill all SDGs, but instead that OAE will both contribute to and also interfere with achieving some of the SDGs. The SDG assessment framework for ocean-based CDR that is under development in OceanNETs aims to clarify these relationships towards the end of the project.

3. Conclusion

The objective of the task that this deliverable contributes to, is to better constrain and determine sustainable pathways of ocean-based NET deployment. I have been partially successful in this task for OAE in regards to SDGs 13 and 14, but have determined that the COMFORT PPE is not suitable for addressing many socio-economic constraints and the implications that these have for meeting the SDGs. This is due to the idealized design of the simulated OAE, uncertainties in the parameterization of Earth system processes, and the limitations of the model (e.g., in regards to output variables).
According to the simulations, OAE can only help meet SDG 13 (Climate Action) when added on top of the most ambitious mitigation scenarios (*SSP1-2.6, SSP5-3.4-OS*). This reinforces a conclusion that has been found many times before - CDR is not a substitute for emissions reduction (Keller et al., 2014b), but can contribute to meeting our climate goals (ideally if other sustainability criteria are met). As a constraint for further ESM simulations in OceanNETs this suggests that only these low emission or overshoot

scenarios should be used (e.g., as a baseline and to add OAE too), unless there is some specific need for process understanding at higher levels of climate change.

For SDG14 (Life Below Water) the results suggest that OEA can help to limit or even reverse ocean acidification. Other direct effects of OAE on marine life are unclear as they are not parameterized in the UVic model. In addition to the direct effects of OAE, the results did show that low emission scenarios, with or without OAE, trend towards meeting SDG14 related targets. Although for some criteria like oxygen even the most ambitious mitigation scenario with OAE did not meet the targets of limiting oxygen loss. These results highlight the well-known interlinkages between SDG14 and SDG13, making it clear that SDG13 must be achieved to also achieve SDG14.

Overall, these results suggest that forthcoming ESM simulations within OceanNETs should use SDG13 compatible baseline scenarios with more realistic scenarios of deployment and levels of CDR for the remaining WP4 tasks. The only exception would be if there is some specific need for process understanding at higher levels of climate change or CDR. However, even with more realistic OAE simulations by state-of-the-art ESMs, it may be difficult to discern impacts that can be attributable to CDR with only global scale aggregated analyses (e.g., annual mean surface air temperature). Therefore, subsequent analysis will need to investigate CDR impacts at higher spatial and temporal scales to better determine SDG compatibility.

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5. Acknowledgements

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6. Appendix

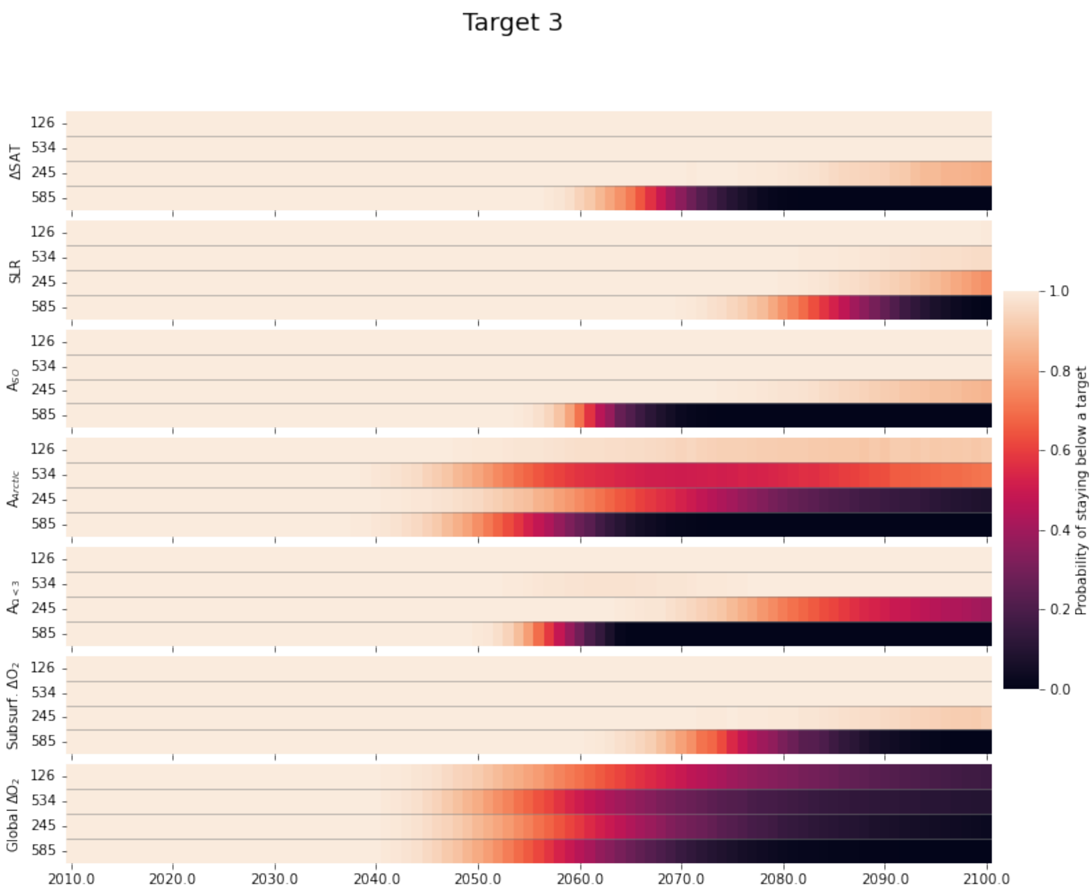

Figure 9. Probability of each $5\ Pg\ Ca(OH)_2\ yr^{-1}$ alkalinity enhancement scenario (y-axis of each heat plot with the baseline SSP scenario upon which OAE is deployed indicated by the numbers) to stay below target 3 values as defined in Table 1. For simplicity, target 3 can be thought of as missing our climate goals and with mitigation efforts limiting warming to only 3 deg. C.

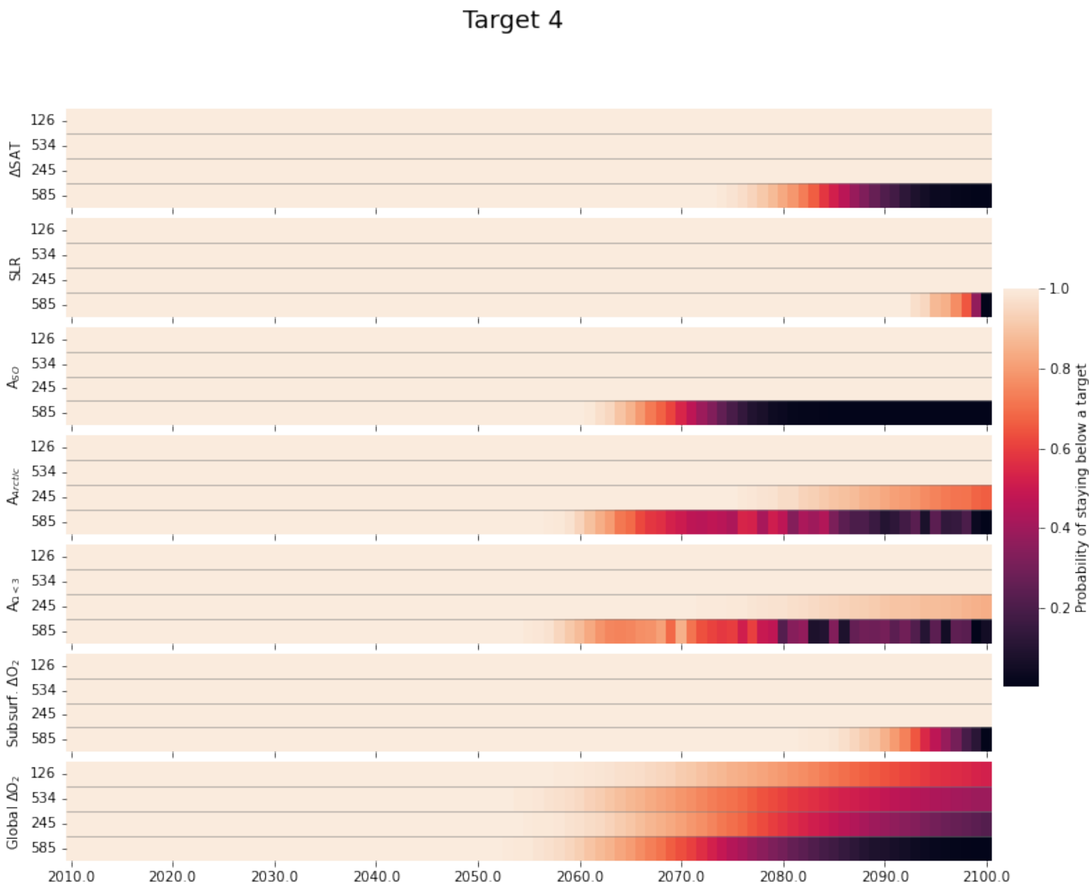

Figure 10. Probability of each 5 Pg $Ca(OH)_2\ yr^{-1}$ alkalinity enhancement scenario (y-axis of each heat plot with the baseline SSP scenario upon which OAE is deployed indicated by the numbers) to stay below target 4 values as defined in Table 1. For simplicity, target 4 can be thought a worst-case scenario where all fossil fuels are burned and warming is not limited.

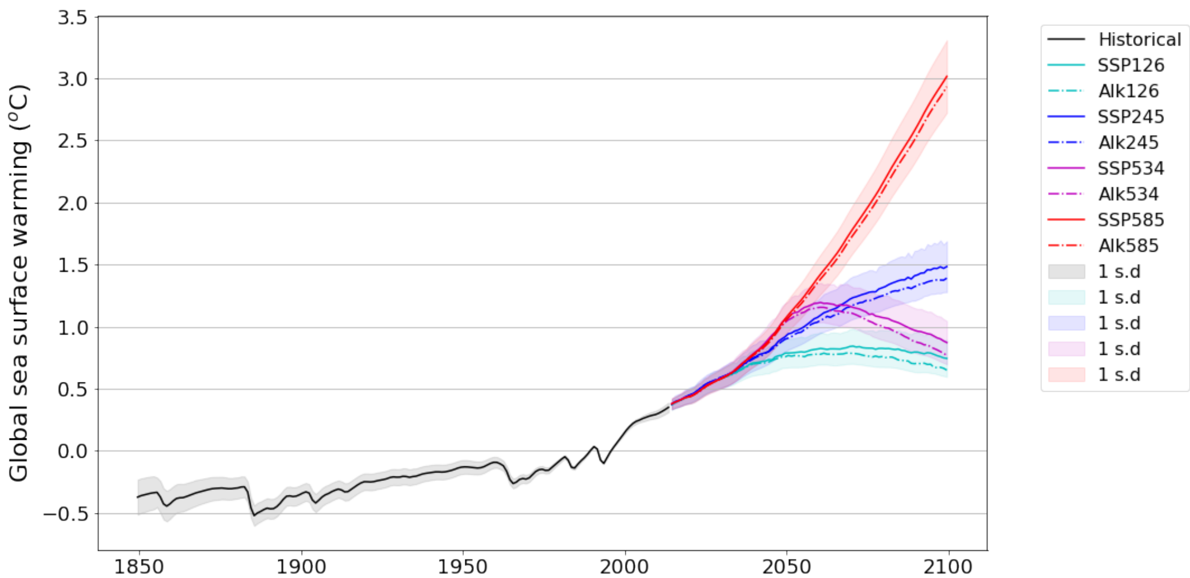

Figure 11. Simulated sea surface temperature anomalies for the historical (black line; grey shaded area), baseline scenarios (solid lines), SSP1-2.6 (SSP126), SSP2-4.5 (SSP245), SSP5-3.4-OS (SSP534), and SSP5-8.5 (SSP585) and the same scenarios where ocean alkalinization has been done (dash-dotted lines; in legend this corresponds to Alk + the SSP numbers). The colored shaded areas show 1 standard deviation of the parametric uncertainties for each of the baseline scenarios. The Alk standard deviations are of a similar magnitude, but not shown for clarity due to the overlap.