Deliverable 5.3: Report on parameterizing seasonal response patterns in primary- and net community production to ocean alkalization	
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Author(s)	Jan Taucher, Markus Schartau
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Abstract: We applied a 1-D plankton ecosystem-biogeochemical model to assess the impacts of ocean alkalinity enhancement (OAE) on seasonal changes in biogeochemistry and plankton dynamics. Depending on deployment scenarios, OAE should theoretically have variable effects on pH and seawater $p\text{CO}_2$, which might in turn affect (a) plankton growth conditions and (b) the efficiency of carbon dioxide removal (CDR) via OAE. Thus, a major focus of our work is how different magnitudes and temporal frequencies of OAE might	

affect seasonal response patterns of net primary productivity (NPP), ecosystem functioning and biogeochemical cycling.

With our study we aimed at identifying a parameterization of how magnitude and frequency of OAE affect net growth rates, so that these effects could be employed for Earth System Modell applications. So far we learned that a meaningful response parameterization has to resolve positive and negative anomalies that covary with temporal shifts. As to the intricacy of the response patterns, the derivation of such parameterization is work in progress. However, our study readily provides valuable insights to how OAE can alter plankton dynamics and biogeochemistry. Our modelling study first focuses at a local site where time series data are available (European Station for *Time series* in the Ocean Canary Islands ESTOC), including measurements of pH, concentrations of total alkalinity, dissolved inorganic carbon (DIC), chlorophyll-a and dissolved inorganic nitrogen (DIN). These observational data were made available by Andres Cianca (personal communication, PLOCAN, Spain), Melchor Gonzalez and Magdalena Santana Casiano (personal communication, Universidad de Las Palmas de Gran Canaria). The choice of this location was underpinned by the fact that the first OAE mesocosm experiment was conducted on the Canary Island Gran Canaria, which will facilitate synthesizing our modelling approach with experimental findings.

For our simulations at the ESTOC site in the Subtropical North Atlantic we found distinct, non-linear responses of NPP to different temporal modes of alkalinity deployment. In particular, phytoplankton bloom patterns displayed pronounced temporal phase shifts and changes in their amplitude. Notably, our simulations suggest that OAE can have a slightly stimulating effect on NPP, which is however variable, depending on the magnitude of OAE and the temporal mode of alkalinity addition. Furthermore, we find that increasing alkalinity perturbations can lead to a shift in phytoplankton community composition (towards coccolithophores), which even persists after OAE has stopped. In terms of CDR, we found that a decrease in efficiency with increasing magnitude of alkalinity addition, as well as substantial differences related to the timing of addition.

Altogether, our results suggest that annual OAE during the right season (i.e. physical and biological conditions), could be a reasonable compromise in terms of logistical feasibility, efficiency of CDR and side-effects on marine biota.

With respect to transferability to global models, the complex, non-linear responses of biological processes to OAE identified in our simulations do not allow for simple parameterizations that can easily adapted. Dedicated future work is required to transfer the observed responses at small spatiotemporal scales to the coarser resolution of global models.

Background:

The major aim of the work presented here was to assess the ecological and biogeochemical impacts of ocean alkalization approaches on natural pelagic ecosystems, particularly regarding ecological risks and side effects. These may theoretically arise due to expected changes in seawater carbonate chemistry in response to ocean alkalization.

Different biomes, e.g. Arctic/Antarctic high latitude systems, temperate ecosystems and, tropical/subtropical ocean ecosystems can be expected to display different sensitivities.

A major potential bottleneck in the application of ocean alkalization is considered to be the dispersion of added alkalinity (in the form of mineral powder or in aqueous solution) at the site of deployment. Depending on the degree of vertical and lateral mixing, added alkalinity might generate substantial out-of-equilibrium conditions of the carbonate system (pH, $p\text{CO}_2$) that could theoretically affect plankton communities on local and short-term scales. In this regard, subtropical open-ocean ecosystems can be considered the potentially most vulnerable, as these regions usually display a strong thermal stratification of the water column with a relatively low degree of vertical mixing (compared to higher latitude waters). Therefore, we chose to prioritize our modeling work for such subtropical ocean ecosystems.

A suitable location is the “European Station for Time Series in the Ocean” (ESTOC), which is operated since 1994 (Neuer et al., 2007). It is located about 100 km North of the Canary Islands (29°N, 15°W) at the Eastern boundary of the North Atlantic subtropical gyre and characterized by mostly oligotrophic waters. Data on environmental conditions (physical and biogeochemical) were retrieved from various data sources (PLOCAN, PANGAEA, World Ocean Atlas) in order to allow for accurate calibration of our 1-D ecosystem model. Some additional data were provided by Andres Cianca (personal communication, PLOCAN, Spain), and from Melchor Gonzalez and Magdalena Santana Casiano (personal communication, Universidad de Las Palmas de Gran Canaria).

We used the OPPLA model (OPTimality-based PLAnkton ecosystem model; developed by Markus Pahlow at GEOMAR, see e.g. Pahlow et al. (2020; 2013) for simulating biotic and biogeochemical responses to ocean alkalization. This model has been applied and analysed in several studies, including global applications (Chien et al., 2020; Pahlow et al., 2020) and simulations of mesocosm experiments (Krishna et al., 2019). The optimality-based approach accounts for a high level of physiological detail, which is relevant when considering responses to changing environmental conditions. Such detail remains unresolved by most Earth System Models, but specific simulation effects to OAE could possibly be simulated by some meaningful parameterization, e.g. changes in relative growth rates of the phytoplankton.

Physical forcing data for our simulations are based on the FOCI (Flexible Ocean and Climate Infrastructure) model, operated at GEOMAR. Forcing data for the local ESTOC site were made available by Chia-Te Chien (personal communication), covering a thirty years period, from 1990 though 2020.

How will OAE alter carbonate chemistry and environmental conditions for phytoplankton?

The temporal frequency of ocean alkalization is a crucial factor in the context of potential ecological risks and side effects. An increase in alkalinity enhances the capacity of seawater to take up CO_2 from the atmosphere, thereby eventually leading to higher concentrations of dissolved inorganic carbon (DIC) and a relatively slight increase in pH. Such conditions may theoretically favor photosynthesis by phytoplankton (due to higher availability of bicarbonate, HCO_3^- , a substrate for photosynthesis) and favor calcifying organisms (due to higher pH and saturation state of calcium carbonate). These conditions occur once the $p\text{CO}_2$ of seawater after alkalinity enhancement is in equilibrium with the atmosphere (see Fig. 1, green area).

However, reaching such an equilibrium takes some time, depending on the velocity of air-sea gas exchange, which in turn is controlled by a variety of environmental factors (Jones et al., 2014). Previous studies have shown, that it can take weeks to months, until a $p\text{CO}_2$ equilibrium between atmosphere and ocean is reached. Accordingly, alkalinity enhancement can be expected to temporarily result in non-equilibrated $p\text{CO}_2$ conditions, which are accompanied by a strong increase in pH and a sharp decline in $p\text{CO}_2$ (see red area in Fig. 1). Such conditions may exceed thresholds beyond which photosynthesis by phytoplankton is inhibited due to CO_2 limitation and/or pH effects. For instance, previous studies have found that $p\text{CO}_2$ conditions $<100\text{--}150\text{ }\mu\text{atm}$ had negative impacts on productivity of phytoplankton communities (Rost et al., 2003; Taucher et al., 2015). As can be seen in Fig. 1, such conditions can already be reached at alkalinity enhancement of $\sim 500\text{ }\mu\text{mol kg}^{-1}$ under non-equilibrated conditions.

equilibrated				non-equilibrated		
TA [$\mu\text{mol kg}^{-1}$]	DIC [$\mu\text{mol kg}^{-1}$]	pH	$p\text{CO}_2$ [μatm]	DIC [$\mu\text{mol kg}^{-1}$]	pH	$p\text{CO}_2$ [μatm]
2400	2090.8	8.04	413	2135.9	8.06	400.2
2700	2334.1	8.09	413	2135.9	8.44	149.8
3000	2574.9	8.12	413	2135.9	8.69	71.9
3300	2813.2	8.16	413	2135.9	8.91	36.9
3600	3049.4	8.19	413	2135.9	9.10	18.8
3900	3283.4	8.22	413	2135.9	9.31	9.0
4200	3515.6	8.24	413	2135.9	9.52	3.9
4500	3745.9	8.27	413	2135.9	9.76	1.5
4800	3974.6	8.29	413	2135.9	10.00	0.5

Fig. 1: Example calculations for the difference between equilibrated (green) and non-equilibrated (red) states of the carbonate system in response to different degrees of alkalinity enhancement. Lower panel: Visualization of pH (left) and $p\text{CO}_2$ (right) for different degrees of alkalinity enhancement under equilibrated (green) and non-equilibrated (red) conditions.

Consequently, the interplay between (a) the magnitude of alkalinity enhancement and (b) the time-scale of CO_2 equilibration between ocean and atmosphere determine whether ecological risks and side effects (due to transient changes in carbonate chemistry) can theoretically be expected.

Methodology - OAE scenarios

Following these considerations, one major focus of our 1-D model experiments was to test how different temporal modes of alkalinity deployment may affect short- to medium-term responses of carbonate chemistry and assess associated implications for net primary production and ecosystem state in the subtropical oligotrophic ocean.

Such temporal factors of alkalinity enhancement have so far not been considered in global modeling studies, which are not capable of resolving the required small temporal and spatial

scales, and therefore usually assume a constant and steady increase in alkalinity over time (González and Ilyina, 2016; Keller et al., 2014; Köhler et al., 2013).

To test the effect of the temporal mode of alkalinity enhancement, we simulated addition of a given amount of alkalinity over a wide range of temporal frequencies, ranging from continuous (daily) addition (which can be considered analogous to the approach in the aforementioned global studies), over weekly, monthly, seasonal and annual addition, and also including a scenario, in which the entire amount of alkalinity is deployed at once.

Note that we add pure alkalinity in our simulations due to the current uncertainties about possible applications of OAE, particularly with respect to the mineral used. For instance, addition of olivine would also add silicate and trace metals, which both could potentially modify the responses of marine biota.

Within the scope of these simulations, OAE was carried out over a period of 3 years in the different temporal modes. To reach target alkalinity required for different levels of CDR (see Table 1 and explanations below), these various OAE deployment scenarios would need to continue until the end of the century. In terms of logistical effort and cost-efficiency, this poses a massive challenge based on the current infrastructure. In theory, it would also be possible to add the entire alkalinity for a give target level in one single deployment. We call this “all-at-once” OAE here.

The total amount of alkalinity enhancement was chosen according to previous modeling studies and describes the global average change in surface ocean alkalinity between present-day conditions and end-of-the-century. Idealized modeling studies suggest that OAE could increase surface seawater alkalinity by about 100 to $>2,000 \mu\text{mol kg}^{-1}$ by the year 2100 (Bach et al., 2019) although the upper estimates are based on extreme, likely unrealistic, application scales (González and Ilyina, 2016; Ilyina et al., 2013; Keller et al., 2014; Köhler et al., 2013; Lenton et al., 2018). Thus, we separated the possible range of OAE into three scenarios, “moderate”, “high”, and “extreme”.

The “moderate” OAE scenario is based on considerations regarding the current technological infrastructure (e.g. mining capacities, transport capacity of cargo ships) following Keller et al. 2014 and Lenton et al. 2018, resulting in a max. increase in TA by $100\text{--}200 \mu\text{mol kg}^{-1}$ by the year 2100.

The “high” OAE scenario is based on the required amount of carbon dioxide removal (CDR) to maintain atmospheric CO_2 concentrations following a RCP4.5 pathway, but under emissions following a RCP8.5 scenario (sensu Gonzalez and Ilyina, 2016). This results in a surface ocean alkalinity increase of $700\text{--}1000 \mu\text{mol kg}^{-1}$ by the year 2100.

Note that numbers for both “moderate” and “high” scenarios (and the global modeling studies that these numbers are based on) assume a globally uniform application of alkalinity enhancement. However, in reality OAE may be applied only in certain regions or in a spatially non-uniform way. The “extreme” OAE scenario accounts for this, thereby following the study of Ilyina et al. 2013, in which they simulated application of OAE in certain oceanic regions, e.g. in the North Atlantic and North Pacific. Local alkalinity changes in this study reached $1000\text{--}4000 \mu\text{mol kg}^{-1}$. According to the described scenarios regarding the temporal frequency and magnitude of alkalinity enhancement, we developed the scenarios shown in Table 1. Note that alkalinity is added only to the uppermost box in our simulations, thus assuming alkalinity deployment to the surface ocean. In our simulations, we let the model spin up for 2 years, then simulate a period of alkalinity enhancement of 3 years (according to the scenarios in Table 1) and then follow the system after perturbation for another 2 years, until a new equilibrium is reached.

	# of deployments during 80 years (assuming OAE from 2020 to 2100)	moderate	high	extreme	
		200	800	2000	[mmol m ⁻³]
daily (continuous)	29200	0.01	0.03	0.07	[mmol m ⁻³ d ⁻¹]
weekly	4160	0.05	0.19	0.48	[mmol m ⁻³ wk ⁻¹]
monthly	960	0.21	0.83	2.08	[mmol m ⁻³ mon ⁻¹]
seasonal (4x)	320	0.63	2.50	6.25	[mmol m ⁻³ 3 mon ⁻¹]
annual	80	2.50	10.00	25.00	[mmol m ⁻³ yr ⁻¹]
all at once	1	200.00	800.00	2000.00	[mmol m ⁻³]

Table 1: Scenarios for temporal frequency of alkalinity enhancement: Number of alkalinity deployments for different scenarios of temporal frequency, assuming a period of 80 years (year 2020 to 2100). Average increase in seawater alkalinity concentration in the mixed layer [mmol m⁻³] for different scenarios of alkalinity enhancement (moderate, high, and extreme; see text for explanations), broken down into theoretically expected changes for the different temporal modes of deployment (i.e. change in alkalinity after each deployment).

Results for present-day conditions (reference baseline)

The reference model solution was determined by visual comparisons between observational data and their simulated counterparts. A more rigorous scheme for parameter optimization has not been employed, but is planned for the near future during the duration of the OceanNETs project. Simulated nitrate concentrations and chlorophyll are slightly too high, and chlorophyll is overestimates typical winter concentrations. Finding a good balance between carbon uptake by phytoplankton, calcification, alkalinity changes together with pH could only be achieved by maintaining rates of calcification low, which turned out to be particularly tricky given the interannual variations in mixing and the associated changes in nitrate concentration. The reason is likely that winter mixing is sometimes overestimated by the physical model forcing, which is also connected to large interannual variability (Fig. 2 E) , and enhanced growth conditions may easily lead to an overestimation of carbon fixation. Such situations become worse for DIC being used for the formation of particulate inorganic carbon (PIC) by the model's calcifiers. The latter introduces a severe drawdown in alkalinity as well.

Overall, the annual cycle of the biogeochemical quantities in the reference solution is well resolved (Fig. 2), and the absolute values and intra-annual variability of pH and alkalinity are captured well by the model (Fig. 2 F), thus providing a solid basis for simulations of ocean alkalinity enhancement.

Fig. 2: Comparison between simulation results and observational data for nitrate (A, B), chlorophyll (C, D) and carbonate chemistry parameter (F: pH and alkalinity) at the ESTOC site in the subtropical North Atlantic (29°N, 15°W). Panel E shows the simulated vertical turbulent diffusivity and comparison to observational data of mixed layer depths (white line; derived from Argo-floats temperature measurements, see Yumruktepe et al., (2020))

Results of alkalinity enhancement simulations: Physico-chemical conditions

The physical features at the ESTOC site are typical for subtropical open ocean conditions, with a relatively stable thermal stratification that separates the upper 100–200 m from deeper waters below. Periods of deeper mixing occur regularly due to winter storms and eddies. Our simulations show that these physical properties are an important factor in distributing the enhanced alkalinity across the water column (Fig. 3).

Fig. 3: Vertical changes in alkalinity (top) and DIC (bottom) in response to seasonal alkalinity enhancement, exemplary for the “extreme” scenario. Note the profound effect of winter mixing in vertically distributing alkalinity, thereby dampening the short-term alkalinity peaks in the surface layer.

These results demonstrate that physical mixing determines the temporal and spatial scales, for which (potentially unfavorable) non-equilibrated conditions of the carbonate system may occur. Accordingly, the simulation of different temporal modes of alkalinity enhancement show a distinct pattern, in which a decrease in the temporal frequency leads to an increase in maximum alkalinity changes in the surface ocean (Fig. 4).

Fig. 4: Effects of different temporal modes of alkalinity enhancement (“extreme” scenario) for the amplitude of alkalinity concentrations in the surface layer. Note the distinct difference between alkalinity addition during winter or summer due to seasonal differences in vertical mixing.

Results: Oceanic uptake of atmospheric CO₂, biotic responses and consequences

CDR: Oceanic carbon uptake under different OAE scenarios

Addition of alkalinity to the surface ocean results in a swift increase in oceanic carbon uptake, as expected from changes in seawater carbonate chemistry due to OAE (Fig. 5 A). The efficiency of carbon dioxide removal (CDR), given as the relative increase in DIC per increase in alkalinity scales with the total amount of added alkalinity, as well as its temporal frequency (Fig. 5 B). Notably, we found a profound difference between OAE during summer or winter for the annual addition, with higher efficiencies for summer conditions. The variability in CDR

between summer and winter OAE was even higher than the variability among the magnitude of alkalinity additions. Surprisingly, CDR efficiency for the “annual, summer” addition were consistently higher than those for more continuous (i.e. higher temporal frequency) additions.

Figure 5: (A) Development of carbon dioxide removal under different temporal mode of alkalinity addition (here under the extreme OAE scenario), calculated as the depth-integrated difference in the DIC inventory (relative to the control simulation). (B) Influence of the temporal mode of OAE addition on CDR efficiency (calculated as DIC/ALK change in %), including differences between summer and winter.

Primary productivity responses to OAE

The different magnitudes and temporal modes of alkalinity enhancement have very variable effects on carbonate chemistry (Fig. 6), which in turn are an important physiological parameter for phytoplankton growth. Generally, there is a pronounced shift from dissolved CO_2 and bicarbonate (HCO_3^-) towards carbonate (CO_3^{2-}) due to the increase in alkalinity and the corresponding increase in pH, which drives the shifts in carbonate chemistry.

Figure 6: Changes in speciation of dissolved inorganic carbon (relative) and pH (absolute) under different magnitudes and temporal mode of alkalinity addition. Note that bicarbonate (HCO_3^-) reaches net positive changes only towards the end of the simulation, thus illustrating the long timescale of equilibration with the atmosphere.

The response of net primary production to these changes depends on the magnitude and temporal mode of OAE due to the seasonal cycle of phytoplankton growth. Under ambient conditions, simulated net primary production displays a distinct seasonal pattern at the ESTOC site (Fig. 7A). The largest portion of NPP is driven by non-calcifying phytoplankton, although the contribution of coccolithophores slightly increases towards the end of the simulation, probably due to interannual variability.

The temporal mode of OAE has a profound impact on the seasonal cycle of NPP, leading to phase shifts and changes in the amplitude that reach up to ~15% change due to OAE (Fig. 7B). Notably, on annual average (last 3 years of the simulation), NPP under different OAE scenarios is consistently higher than in control simulation (Fig. 7C). For annual OAE, differences between summer or winter addition were substantial, with larger positive effects on NPP for winter conditions. The reason is likely the larger alkalinity perturbation during summer (because of lower vertical mixing and thus slower distribution of alkalinity across the water column; see Fig. 4), which leads to stronger physiological effects on phytoplankton than during winter conditions (during which the alkalinity perturbation is diluted much faster). However, as Fig. 6B shows, the period of higher NPP after winter addition also shows some time lag, indicating complex, non-linear responses throughout the seasonal cycle.

Figure 7: (A) seasonal pattern of NPP in the control simulation, (B) seasonal pattern of the response of NPP to different temporal modes of alkalinity addition (here under the extreme OAE scenario), (C) response of NPP to moderate, high and extreme OAE (see text) and different temporal modes of alkalinity addition. Response of NPP in (B) and (C) is given as the relative difference [%] to the control simulation.

The seasonal response patterns to OAE display a higher temporal variability of NPP with increasing OAE, as well as larger NPP variability for winter addition than during summer (for annual OAE) (Fig. 8A). This response is linked to distinct phase shifts and changes in NPP amplitude in response to summer vs. winter addition (Fig. 8B).

This result is somewhat surprising, as the alkalinity perturbation during summer is larger and theoretically has stronger physiological effects. A possible explanation for this result is that during summer, the alkalinity perturbation does not reach the layer of highest NPP (deep chlorophyll maximum), while during winter, the alkalinity perturbation directly affects near-surface NPP.

Figure 8: (A) Influence of the temporal mode of OAE addition on the temporal variability of NPP (calculated as the standard deviation) relative to the control simulation (relative difference in %), including differences between summer and winter. (B) Differences in NPP temporal phase shifts and magnitudes between summer and winter addition (annual), shown as the relative difference [%] to the control simulation.

The changes in total NPP are also accompanied by shifts in phytoplankton community composition. In response to OAE, the relative contributions of coccolithophores and other phytoplankton to NPP change over the course of the simulation, with a sharp increase in coccolithophores (Fig. 9A). Interestingly, the shift occurs most strongly during the last 2 years of the simulation, after OAE has stopped. The shift towards coccolithophores scales with OAE magnitude, and also displays a strong difference between summer and winter addition (for the annual OAE case), with winter addition benefitting coccolithophores more strongly (Fig. 9B). The most likely explanation for these results is that the OAE-driven shifts in carbonate chemistry, particularly the increase in pH (i.e. decrease in H^+) and carbonate (CO_3) have positive physiological effects on coccolithophore growth.

A

B

Figure 9: (A) ratio of coccolithophore/phytoplankton in NPP under extreme OAE and (B) its dependence on the temporal mode of OAE addition, including differences between summer and winter.

→ increase in Cocco/Phyto NPP ratio at increasing OAE, and for annual: larger effect for winter addition

Physiological responses to pH and CO₂ and the role of alkalinity intrusion to depth

Relative changes in pH of the extreme event approach 1.2 %, with a gradual decline during years of no alkalinity addition (Fig. 10). The pH changes at the end of 2020 differ only by the amount of alkalinity added and hardly by the frequency of addition.

Figure 10: (A) Changes in pH, relative to the reference solution, for the different scenarios (alkalinity added), (B) changes in relative growth rate (RGR) of phytoplankton, including coccolithophores.

Equilibrated pH at the end of the simulation period remains insensitive to the timing and frequency of alkalization (Fig. 10A). While changes in pH are mainly sensitive to the magnitude of perturbation any superimposed variations due to primary production remain negligible. Clearly, the response patterns in algal growth reveal an enhanced signal, being more sensitive to the frequency of alkalization events (Fig. 10B). The anomalies, induced by the alkalisation, show a delay in bloom development, indicated by negative anomalies at times of the blooms in the reference solution. The negative are followed by positive anomalies, but we do not find a clear relationship that determines the switching from negative

to positive anomalies, which complicates the entire picture and is one reason for why we could not come up with a meaningful parameterization of the responses on RGR, yet. We will therefore consider various (diagnostic) models, possibly artificial intelligence (AI) approaches. So far, we realized that after the years of alkalinization the response patterns of the different scenarios converge again, being only sensitive to the amount of alkalinity added.

The convergence behaviour in RGR after the years of alkalinization becomes clear when looking at the CO₂ concentrations (Fig. 11). This example shows similar CO₂ concentrations in the second year after alkalinization stopped, although the annual alkalinisation differs with respect to the timing, summer versus winter addition. Since the CO₂ concentrations in the years 2019 and 2020 are similar we find similar responses in RGR, provided that the imposed RGR sensitivity of RGR to CO₂ is realistic.

Figure 11: (A) CO₂ concentration of the reference solution and for annual additions of alkalinity in summer (B, middle panel) and winter (C, lower panel).

Responses to “all-at-once” addition of alkalinity

Above sections describe responses to OAE over an extended period of time (3 years of alkalinity addition in the model simulations here). As described above, it would also be possible to add the entire alkalinity for a given CDR target level in one single deployment (all-at-once” OAE) to maximize cost-efficiency. This results in substantial changes in alkalinity concentrations in the surface ocean, reaching up to 5-fold higher concentrations than under

present conditions (Fig. 12A). Over the simulation period, CDR efficiency for “all-at-once” alkalinity addition increases over time, but at lower rates for higher OAE magnitudes (Fig. 12 B). Addition during winter results in significantly higher CDR efficiency than addition during summer, thus showing the opposite winter/summer difference than annual OAE (see Fig. 5B).

Fig. 12: (A) Amplitude of alkalinity changes in the surface layer in the all-at-once deployment (here for the extreme OAE scenario). Note the distinct difference between alkalinity addition during winter or summer due to seasonal differences in vertical mixing. (B) changes in pH and dissolved CO_2 and (C) CDR efficiency (calculated as DIC/ALK change in %) under different “all-at-once” OAE scenarios.

NPP is substantially affected by “all-at-once” alkalinity addition, displaying an almost 100% decrease for the high and extreme scenarios (Fig. 13A). Over the simulation period, NPP recovers, and displays distinct seasonal patterns under the different magnitudes and the timing (winter/summer) of alkalinity addition. The recovery period (defined as the time until NPP reaches a net positive difference compared to the control simulation), is prolonged at larger OAE magnitude, but displays a large difference depending on summer or winter addition (i.e. a reversal of the OAE vs. NPP recovery relationship; Fig. 13B). Furthermore, NPP in the high and extreme OAE scenario increases sharply towards the end of our simulations. This “overshoot” NPP reaches 2- to 3-fold higher levels compared to the control simulation.

Figure 13: “all-at-once” OAE impact on (A) total NPP and (B) the time-scale of NPP recovery after alkalinity addition, including differences between summer and winter.

The responses in NPP are also linked to underlying changes in community composition after alkalinity addition. While under moderate “all-at-once” OAE, phytoplankton remain dominant, a major regime shift occurs under high and extreme “all-at-once” OAE (Fig. 14). Here, coccolithophores almost completely replace other phytoplankton. However, it should be noted that under extreme OAE conditions, absolute values of coccolithophore NPP are much reduced compared to high OAE.

Whether these patterns remain needs to be explored in future simulations, in which a multi-decadal period after “all-at-once” OAE will be monitored.

Figure 14: “all-at-once” impact on NPP of (A) “generic” phytoplankton and (B) coccolithophores → at moderate OAE, phytoplankton remains dominant. Under high and extreme OAE, a regime shift occurs, with coccolithophores taking over completely

Conclusion and outlook

Our model experiments revealed that the sensitivity of phytoplankton productivity to OAE displays a non-linear behavior, which also varies with the magnitude and temporal frequency of alkalinity addition. Frequency of alkalinization events hardly alter the overall increase in DIC as well as how alkalinity becomes vertically distributed. In contrast to this, the seasonal cycling of phytoplankton growth and subsequent response in grazing are significantly altered. This is well expressed in variability patterns, in biomass as well as nutrient concentrations within the upper 140 m.

In a next step, we will conduct extended (multi-decadal) model simulations in order to compare long-term effects of OAE on NPP with natural seasonal variability. In this regard, it will also be important to account for a larger number of phytoplankton species, as it can be expected that other important taxonomic groups display variable sensitivities to changing carbonate chemistry in response to OAE. So far, we have only considered two types of phytoplankton, coccolithophores and other (non-calcifying) phytoplankton. Future model experiments will include additional functional groups that might have different sensitivities to changing carbonate chemistry, e.g. diatoms and nitrogen-fixers. This will also allow us to account for different scenarios of future technological OAE implementations, which might be based on different minerals that may contain silicate and/or trace metals (and thereby further affect various phytoplankton taxa to a different extent). Furthermore, such an extended model setup will also allow us to conduct similar model experiments for temperate and high-latitude ecosystems. It can be expected that differences in the physical environment (e.g. vertical mixing) and taxonomic composition and seasonality of phytoplankton might lead to very different responses to OAE than in the subtropical ocean.

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