Project: **1258**

Project title: **RETAKE—Carbon Dioxide Removal by Alkalinity Enhancement: Potential, Benefits and Risks**

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In the past year, we have completed eight alkalinity enhancement (AE) scenarios under the present day conditions (based on the hindcast simulation) with the aim to investigate the efficacy and potential side effects of various application concepts. The scenarios are grouped into three sets:

1) The first set of simulations involved adding only alkalinity to the seawater surface across various deployment sites (as shown in Fig. 1a). To achieve a 5 Mt CO2 removal target per year for Germany, 134 Gmol/year of alkalinity was added as a continuous flux across the surface boundary of the selected sites. We also doubled the amount of alkalinity added to the European coast (scenario AE_EUCoast x2). Furthermore, we branched out scenario AE_EUCoast to AE_EUCoast_termin at the end of 2008, which continued for the years 2009 and 2010 without alkalinity addition. This branching provided insight into how the ocean system would recover after the AE's termination.

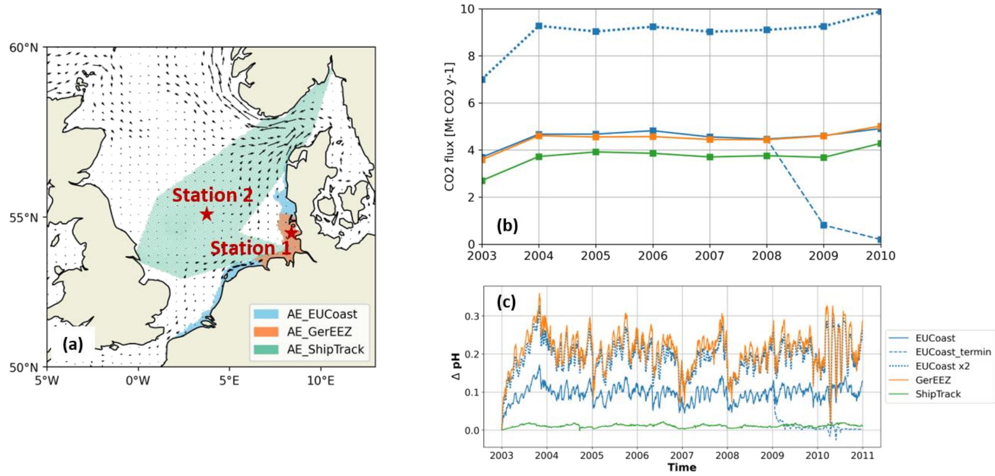

Fig.1 (a) Sites of the AE deployments, parts of the sites are overlapped. Red stars are selected stations where the time series of pH change are displayed in (c). (b) AE-induced CO_2 uptake over the model domain. (c) Time series of pH changes in Station 1 except for the scenario ShipTrack, in which the time series is plotted for the Station 2 as shown in (a).

The AE induced CO_2 uptake began to take place in the first year and reached a steady state from the second year (Fig.1b), suggesting that the North Sea system adjusted quickly to the continuous AE intervention. When the same amount of alkalinity is added into different sites, less CO_2 is removed from the atmosphere when the deployment site is constrained in the ship track area, as compared with the cases that alkalinity was spread over the other two coastal areas. A good scalability of the AE effect is evidenced by the proportional increase of CO_2 uptake when the amount of alkalinity is doubled in AE_EUCoastx2. Following the termination of AE, the CO_2 uptake due to the enhanced AE gradually diminishes and eventually returns to the unperturbed level within two years, implying a quick response of the North Sea system to the AE perturbation, also because Alkalinity additions and the systems adaptation is transported out of the system.

We use pH as an indicator to illustrate the potential environmental changes. The time series of the pH change due to AE in the scenarios illustrate no long-term trend but significant seasonal and interannual variability (Fig.1c). Therefore, potential side effects can be evaluated within a short time scale of several years. Over the simulation period, the largest changes in pH occur when the alkalinity is added to a limited area (AE_GerEEZ) and when the amount of added alkalinity is doubled. On the other hand, the addition of alkalinity over the ship track area causes the smallest pH changes.

2) For the second set of simulations, olivine was added to the sediment surface of the entire Southern Bight (map shown in Fig. 2a) following the results of mesocosm experiments conducted near Ostend by the DE-HEAT project (directed by Sebastiaan van de Velde; Royal Belgian Institute of Natural Sciences & Université Libre de Bruxelles). The weathering rate of olivine is determined by the ambient temperature and pH, olivine grain size, and available olivine mass.

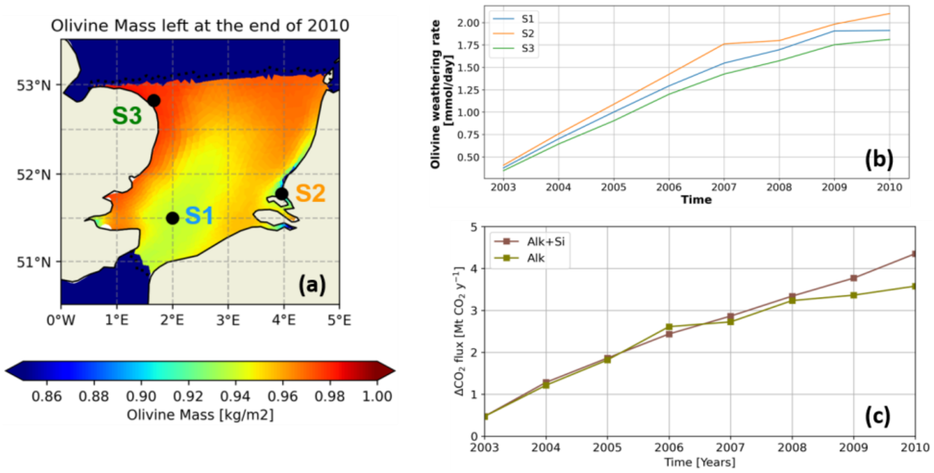

Fig.2 (a) Map of the olivine distribution. Color pattern shows the available olivine mas at the end of the year 2010. (b) The time series of the olivine weathering rate at the three stations which locations are illustrated in (a). (c) The olivine-weathering induced CO_2 uptake over the entire model domain. Alk+Si stands for the scenario considering both the alkalinity addition and silicate release effect. Alk stands for the scenario only considering the alkalinity addition due to the olivine weathering.

The olivine weathering rate varies over the deployment sites because of the heterogeneous distribution of temperature and pH (Fig.2a-b, pH and temperature distribution not shown). As a result, S2 emerges the highest weathering rate due to its low pH level while S3 is characterized by the lowest weathering rate because of its high pH and low temperature conditions (Fig.2b).

The CO_2 uptake is increasing over time (Fig.2c), mainly in accordance with the increasing of the weathering rate (Fig.2b) because of the accumulated available olivine in the system. The difference of the two parallel scenarios, one considering both the alkalinity and silicate additions from the olivine weathering and the other only considering the alkalinity addition, provides us an estimation of the contribution of the nutrient enrichment to the total AE effect, which accounts for approximately 15% of the total CO_2 removal by the end of the simulation (in the year 2010).

3) Another additional scenario, keeping the olivine weathering assumptions consistent with the second set of simulations, was implemented at the discrete dumping sites of the European countries instead of assuming an evenly distributed olivine addition over the Southern Bight (Fig.3a).

In this scenario, the dumping sites are point sources of alkalinity and silicate. After 8 years' simulation, the increased alkalinity propagated along the coast and spread into the offshore areas (Fig.3b), resulting the drawn-down of pCO2 mainly in the southern Bight and the German Bight (Fig.3c).

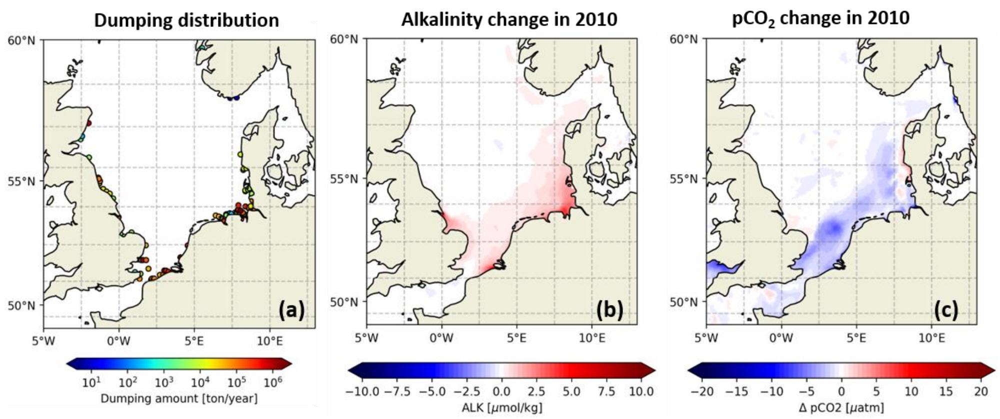

Fig.3 (a) Map of the olivine addition at the dumping sites. The amount of olivine added at each dumping point was scaled by its dumping amount shown by colours. (b-c) The surface alkalinity and pCO2 change due to the olivine dumping by the end of the simulation.

In summary, the eight scenarios provide us a comprehensive assessment of the different choices of AE methods. It also helps to determine the optimal scenarios which sustainability should be further tested under different climate change conditions over the 21st century (high emission SSP3-7.0 and low emission SSP1-2.6).