



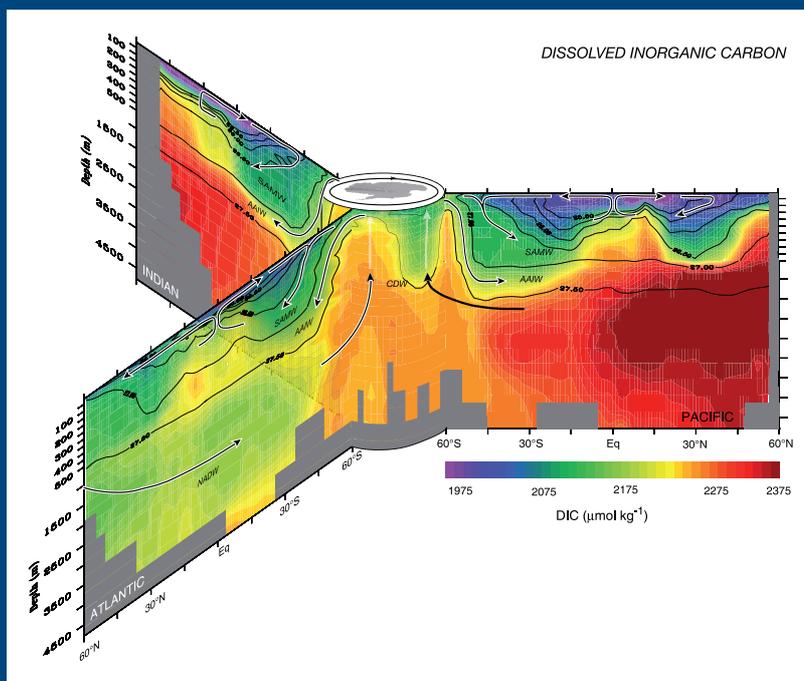
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## Deglacial Changes in Ocean Dynamics and Atmospheric CO<sub>2</sub>

Michael Sarnthein and Gerald H. Haug (Eds.)



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## Mitigation Potential, Risks, and Side-Effects of Ocean Alkalinity Enhancement

Miriam FERRER-GONZALEZ and Tatiana ILYINA (Hamburg)

With 2 Figures

Increasing atmospheric carbon dioxide ( $\text{CO}_2$ ) levels due to human activities leads to climate change and ocean acidification (decline in ocean pH). In order to tackle these issues and due to the lack of effective mitigation actions, a great variety of geo-engineering techniques have been suggested, however, knowledge about their effectiveness and collateral effects remains sparse (*Royal Society* 2009). In 1995, KHESHGI proposed the carbon dioxide removal (CDR) method of artificial ocean alkalization (AOA) (KHESHGI 1995). This is one of the ocean-based CDR methods that aims at enhancing the natural and slow (geological timescales of tens to hundreds of thousands of years) process of weathering by which  $\text{CO}_2$  is taken out of the atmosphere. Alkalinity is the charge balance of ions in water and it determines the  $\text{CO}_2$  oceanic uptake and storage as well as the buffering capacity of the seawater to inhibit changes in pH. It has been claimed that ocean alkalinity might have played a key role in glacial-interglacial cycles. For instance, BROECKER and PENG (1989) proposed an increase in the alkalinity of polar surface waters as driver of the last glacial to interglacial atmospheric  $\text{CO}_2$  changes. Ocean alkalinity might be artificially increased by injecting the dissolution products of alkaline minerals into the seawater (e.g. calcium hydroxide). This geo-engineering technique would not only tackle climate change, but also ocean acidification, which has been found to accelerate climate change (SIX et al. 2013) and it possess a serious risk for marine organisms (DONEY et al. 2009). Ocean acidification not only leads to changes in physiology and reproduction of living organisms, it also threatens ocean biota due to the decrease of the mineral saturation state of calcium carbonate ( $\text{CaCO}_3$ ), commonly known as omega.

Few studies exist that address the method of alkalinity enhancement. KHESHGI (1995) proposed this geo-engineering technique and carried out a preliminary analysis of its potential and limitations. He concluded that ocean alkalization might enhance marine storage of atmospheric  $\text{CO}_2$  but its implementation would be an energy-intensive process. Using the carbon-cycle model LOSCAR, PAQUAY and ZEEBE (2013) studied the impact of this method on ocean pH and atmospheric  $\text{pCO}_2$  during the time span 2020 to 2400. From this study, they came to the conclusion that large scale implementation of ocean alkalization might stabilize ocean acidification but  $\text{CO}_2$  atmospheric levels would remain higher than pre-industrial levels. ILYINA and colleagues also carried out research on this matter using HAMOCC (ILYINA et al. 2013), they implemented and examined different alkalinity enhancement scenarios. In these scenarios, alkalinity was added to the ocean in proportional amounts to  $\text{CO}_2$  emissions. They show that this method, under the scenario where two moles of alkalinity per mol of emitted  $\text{CO}_2$  are dis-

tributed widely into the ocean, does have the potential to stabilize (at current levels) ocean pH and the saturation state of carbonate minerals. Regarding the atmospheric CO<sub>2</sub> concentration, this method under the same scenario would only lead to a reduction of 300 ppm with respect to the unmitigated scenario by 2100. The novelty of our research relies on the fact that none of previous studies have addressed this topic with a fully coupled Earth system model of such a level of complexity. Fully coupled set-ups (*versus* box-models or forced subsystems) hold the potential of revealing new features within the Earth system dynamics. Coupled models provide a more complete approach because box models are limited by simplified formulations of the underlying processes. Besides, since climate engineering research is a new scientific field, many aspects of ocean-based carbon dioxide removal methods remain still unanswered. Our research might bring new insights into the link of deglacial changes with ocean dynamics and atmospheric CO<sub>2</sub> through a better understanding of the underlying mechanisms. This project belongs to the German Research Foundation (DFG) priority program (SPP) 1689 that examines the risks and side-effects of different climate engineering technologies from a multidisciplinary perspective. Thus, it will be part of a comparative assessment of potential impacts, side-effects and uncertainties of different climate engineering measures.

We use the Max Planck Institute Earth System Model (MPI-ESM) based on the Coupled Model Intercomparison Project Phase 5 version with low-resolution (MPIOM: 1.5. horizontal resolution and 40 vertical layers; ECHAM: 1.9. horizontal resolution and 47 levels) (GIORGETTA et al. 2013). Fossil fuel CO<sub>2</sub> emissions follow the pathway of scenario RCP8.5. Model scenarios of alkalinity enhancement (from 2006 until 2100) are designed to keep the atmospheric CO<sub>2</sub> concentrations similar to values of the stabilization scenario RCP4.5, whilst fossil

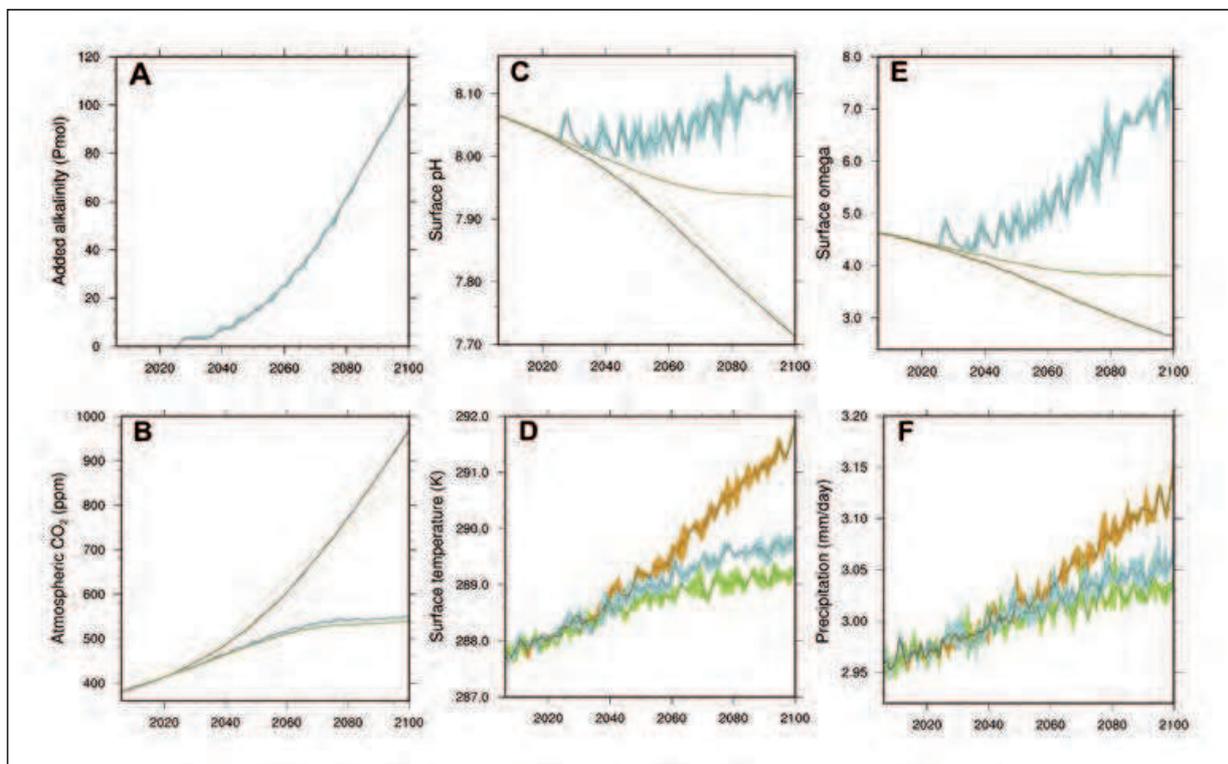


Fig. 1 Time series of globally averaged annual means for scenarios: RCP8.5, AOA and RCP4.5. Coloured area is model internal variability based on 3 ensemble members. Solid lines show 5-year-running means.

fuel emissions follow the pathway of the scenario RCP8.5. Alkalinity is added globally into the upper 12 meters of the ocean in different seasons and years. Note that this CE method addresses only atmospheric CO<sub>2</sub> reduction, therefore, land use, air pollutants, and other greenhouse gases (GHGs) remain unchanged with the values of the RCP8.5 emission scenario.

In order to maintain atmospheric CO<sub>2</sub> at RCP4.5 levels under the high emission scenario RCP8.5 (Fig. 1B), alkalinity was added in the upper ocean (Fig. 1A). In total, approximately 105 Petamol would be needed until the year 2100. Compared to the unmitigated scenario (RCP8.5) this AOA scenario leads to a reduction in the annual global mean of air surface temperature of around 1.5 K (Fig. 1D), following more closely the RCP4.5. The slightly higher temperature (0.5 K) of AOA compared to RCP4.5 is due to the radiative forcing effect of other GHGs (e. g. N<sub>2</sub>O, CH<sub>4</sub> and halogenated GHGs). AOA strongly mitigates ocean acidification leading to higher pH and omega (calcite) values than those associated with the RCP4.5 scenario and preindustrial values over the whole period (Fig. 1C and E). Largest changes of pH occur in the Arctic ocean where values higher than 8.4 are reached (see Fig. 2). This AOA

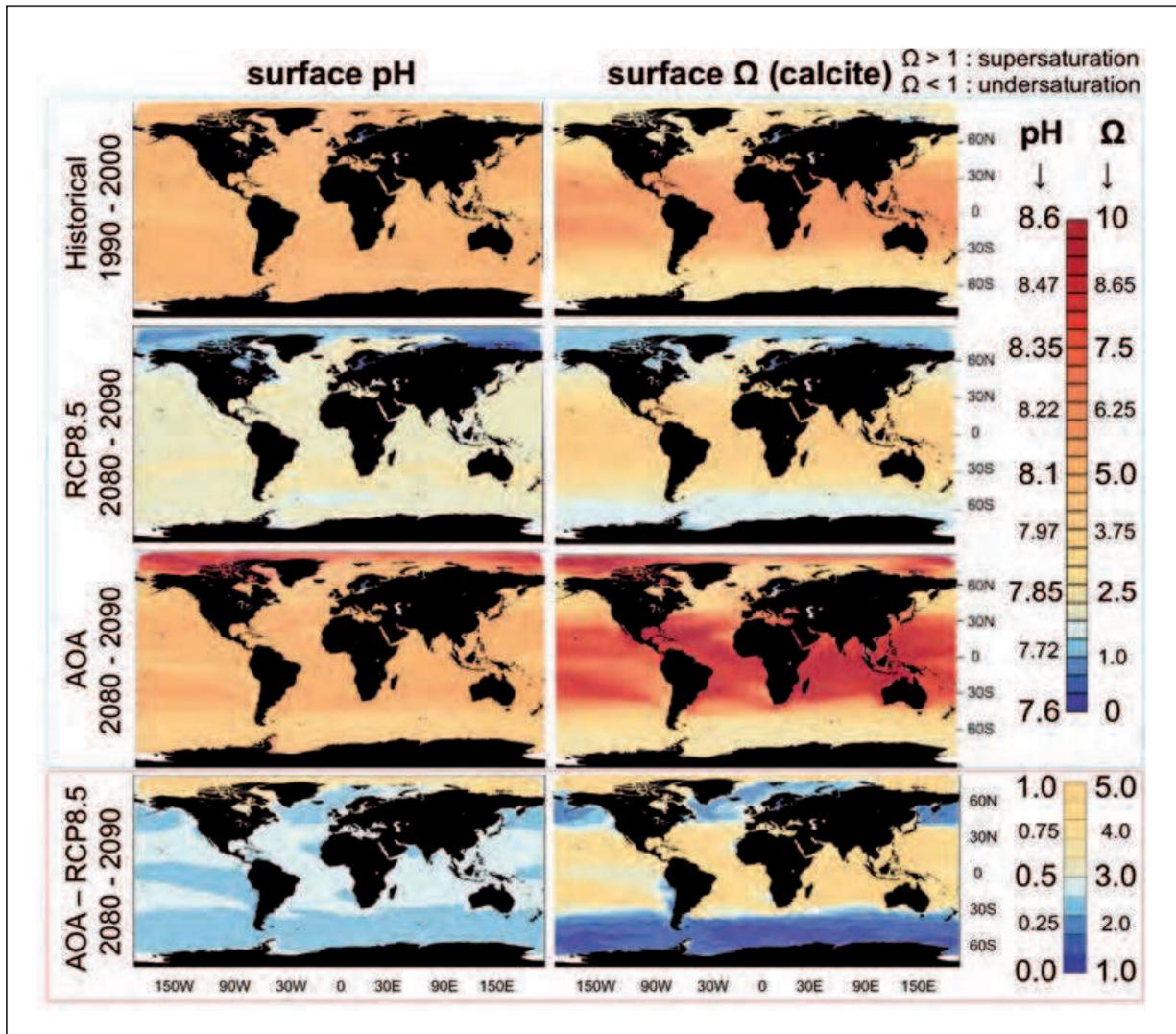


Fig. 2 Averages of 10-year periods of pH (*left*) and the saturation state of carbonate minerals ( $\Omega$ , calcite) (*right*) for different time intervals.

scenario leads to changes in different properties of the climate system which are noticeable within centennial timescale. For instance, in global precipitation (Fig. 1F). Despite model internal variability, it is clear that state of the Earth system is similar to the RCP4.5 scenario. However, mitigating atmospheric CO<sub>2</sub> alone does not lead to an identical climate state.

Averages of a 10-year period of pH (*left*) and the saturation state of carbonate minerals ( $\Omega$ , calcite) (*right*) for different time intervals are shown in Figure 2. By the end of this century, whilst global values of pH (see Fig. 1C) would be similar to preindustrial levels, regional values would differ and that has a strong impact on the ocean biogeochemistry. This AOA implementation scenario would prevent the extreme ocean acidification projected for the unmitigated scenario (RCP8.5); however, high pH and  $\Omega$  values would be reached leading to a potential impact on marine biota (CRIPPS et al. 2013).

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Miriam FERRER-GONZALEZ  
Max Planck Institute for Meteorology  
Bundesstraße 53  
B117  
20146 Hamburg  
Germany  
Phone: +49 40 41173193  
Fax: +49 40 41173298  
E-Mail: miriam.ferrer-gonzalez@mpimet.mpg.de

Dr. Tatiana ILYINA  
Max Planck Institute for Meteorology  
Bundesstraße 53  
B218  
20146 Hamburg  
Germany  
Phone: +49 40 41173164  
Fax: +49 40 41173298  
E-Mail: tatiana.ilyina@mpimet.mpg.de