

Supplementary Information for

Marine Carbon Dioxide Removal under Overshoot Conditions: A Multi-Model Assessment of Efficiency and Carbon Cycle Responses

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1. Introduction

This file contains a short description of each ESM used in this study (section 2) and supplementary figures (Figs. S1-S6; section 3).

2. Models

2.1. The Norwegian Earth System Model version 2 (NorESM2-LM)

The Norwegian Earth system model (NorESM2, Seland et al., 2020) is based on the Community Earth System Model (CESM2.1, Danabasoglu et al., 2020). NorESM2 keeps the original land (CLM5) and sea ice (CICE5) components of CESM2.1, but uses a modified version of CAM6 as the atmospheric component. The isopycnic Bergen Layered Ocean Model (BLOM) is the physical ocean component of NorESM2, while the ocean biogeochemistry is based on the HAMBURG Ocean Carbon Cycle model (HAMOCC). The isopycnic HAMOCC implementation (Schwinger et al., 2016; Tjiputra et al., 2020) has a Nutrient-Phytoplankton-Zooplankton-Detritus (NPZD) - type ecosystem model and inorganic seawater carbon chemistry following Dickson (2007). Total alkalinity (TA) is defined as including contributions of boric acid, phosphoric acid, hydrogen sulfate, hydrofluoric acid, and silicic acid. The Community Land Model version 5 prognostically simulates the carbon and nitrogen cycles, which include natural vegetation, crops, and soil biogeochemistry. The carbon and nitrogen budgets comprise leaf, live-stem, dead-stem, live-coarse-root, dead-coarse-root, fine-root, and grain pools. In addition to the vegetation pools, CLM includes a series of decomposing carbon and nitrogen pools as vegetation successively breaks down into coarse woody debris and/or litter and subsequently into soil organic matter. Details on the CLM5 models are available in Lawrence et al. (2019). Here, we use NorESM2 in its “LM” configuration with 1° resolution in the ocean component and ~2° resolution in the atmosphere-land component (NorESM2-LM), and in emission driven mode to simulate the SSP5-3.4 scenario. We use an updated version of BLOM/iHAMOCC with the capabilities to simulate OAE deployment.

2.2. AWI-ESM

The Alfred Wegener Institute Earth System Model (AWI-ESM) is based on the AWI Climate Model (AWI-CM1, Semmler et al., 2020) but includes a representation of the carbon cycle between land, ocean, and atmosphere. Ocean and sea ice are represented by the Finite Element Sea Ice-Ocean Model FESOM (FESOM1.4, Danilov et al., 2004; Wang et al., 2014). Ocean biogeochemistry is described by the Regulated Ecosystem Model REcoM (REcoM2, Schourup-Kristensen et al., 2014; Hauck et al., 2013). The coupled ocean-only model FESOM-REcoM is discretized on an unstructured mesh, allowing variable grid resolution (12-147 km, mean 76 km, median 41 km) with higher resolutions in highly dynamic regions (e.g., equatorial region, North Atlantic, regions of deep-water formation) and lower resolution elsewhere. The carbonate system in REcoM is computed across the entire water column by the mocsy 2.0 routine (Orr and Epitalon, 2015). Next to carbon, REcoM2 models the cycling of nitrogen, iron, silicon, and oxygen in the ocean. The ecosystem is represented by two phytoplankton and one zooplankton functional groups. The atmospheric component of AWI-ESM is represented by the spectral atmospheric model ECHAM (version 6.3, Stevens et al., 2013; Giorgetta et al., 2013). Land dynamics are modelled by the land surface model JSBACH version 3.20 including the soil carbon model Yasso (Reick et al., 2021).

2.3. FOCI

We used the Flexible Ocean and Climate Infrastructure (FOCI, Matthes et al., 2020) Earth system model coupled to the ocean biogeochemistry model MOPS (Model of Oceanic Pelagic Stoichiometry, (Kriest and Oschlies, 2015; Chien et al., 2022). FOCI is a fully coupled Earth system model and combines the ECHAM6.3 atmosphere (Stevens et al., 2013) and the JSBACH land models (Reick et al., 2013) with

the NEMO3.6 ocean (Madec, 2016) and LIM2 sea-ice models (Fichefet and Maqueda, 1997), using the coupler OASIS3-MCT (Valeke, 2013). The atmospheric model has a T63 (1.9°) grid with 95 vertical levels reaching up to 0.01 hPa. Ocean and sea-ice models run on the ORCA05 grid (0.5°) with 46 vertical levels. MOPS is a biogeochemistry model that includes two plankton functional types (phytoplankton and zooplankton) and enables simulation of the full marine carbon cycle. When coupled within the FOCI Earth system model, this includes interactions with the atmospheric and land carbon reservoirs. MOPS also simulates the biogeochemical cycles of key ocean elements, including phosphorus, nitrogen, oxygen, and carbon, which allows us to simulate alkalinity addition.

2.4. EC-Earth3

We used the carbon cycle variant of the EC-Earth3 model (EC-Earth3-CC; Döscher et al., 2022) which incorporates the atmosphere model IFS (Integrated Forecast System) from ECMWF, LPJ-GUESS land model (Lund Potsdam Jena-General Ecosystem Simulator; Smith et al., 2014) and NEMO (Nucleus for European Modelling of the Ocean) ocean model including PISCES (Pelagic Interactions Scheme for Carbon and Ecosystem Studies) ocean biogeochemistry (Aumont et al., 2015) with TM5MP providing transport of CO₂ in the atmosphere (Tracer Model 5 Massively Parallel; Williams et al., 2017). The atmospheric model uses T_L255 horizontal resolution with 91 levels yielding approximately 80 km grid spacing at the equator. The land model is run on the same horizontal grid as the atmosphere; NEMO ocean model is run on the ORCA1 1° grid with 75 layers and CO₂ transport is done on a 3° × 2° grid with TM5MP. The PISCES code was modified to incorporate the ocean liming experiments, and the annual normalization of alkalinity was removed with a correction to limit the drift in alkalinity. Simulations were started at the end of CMIP6 historical simulation.

3. Supplementary Figures

Comparison of flux of TA into the surface ocean layer due to OAE

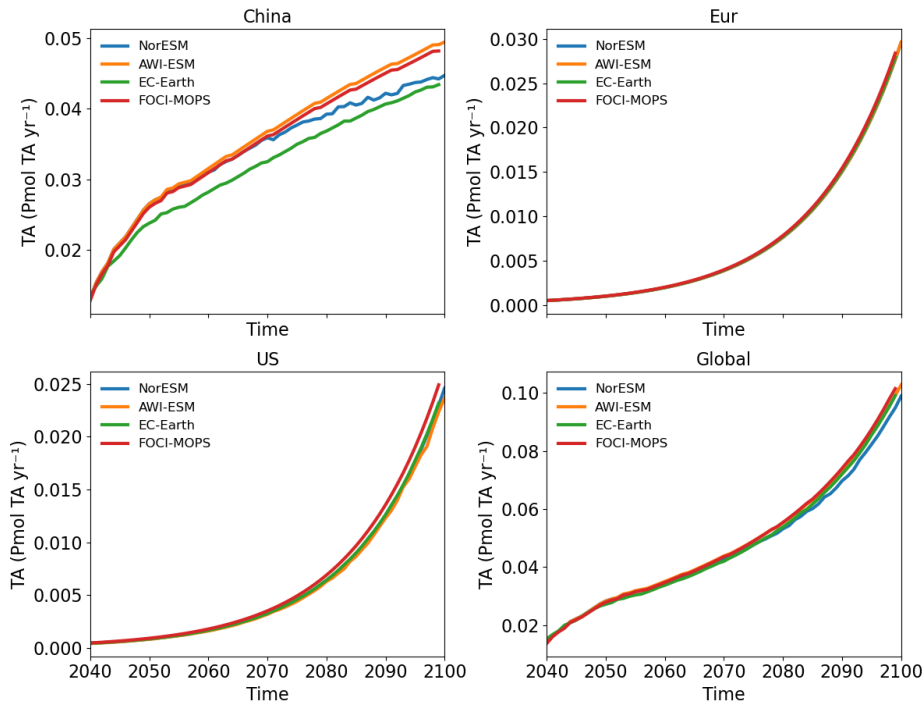


Figure S1: Total flux of TA [Pmol yr⁻¹] added to the surface ocean layer due to OAE in each region for each model. The plotted fluxes represent the realized TA addition for each model, which may differ slightly from the target TA addition from the ocean liming LCA due to model-specific implementation differences (see main text).

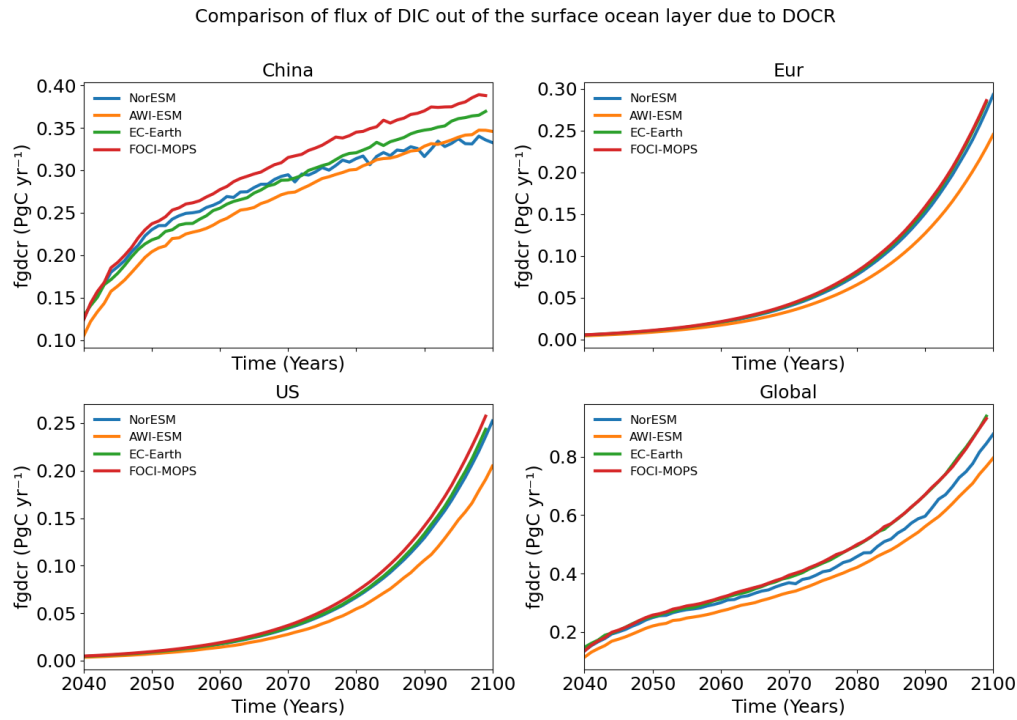


Figure S2: Total flux of DIC [Pg C yr⁻¹] removed from the surface ocean layer due to DOCR for each region and each model.

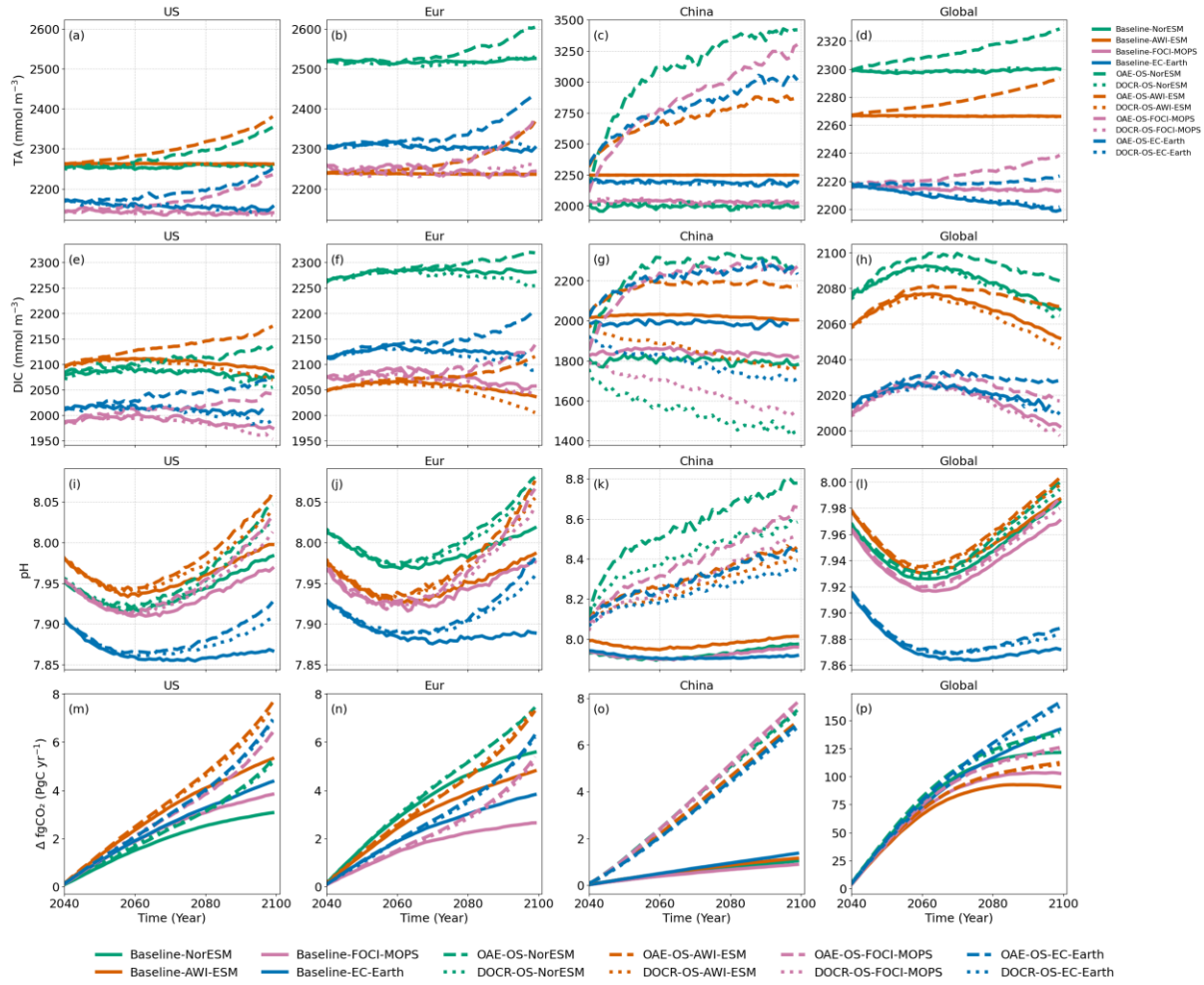


Figure S3: Timeseries of (a-d) alkalinity, (e-h) DIC (i-l) pH, and (m-p) cumulative air-sea carbon fluxes; shown for deployment regions (column 1-3) and globally (column 4).

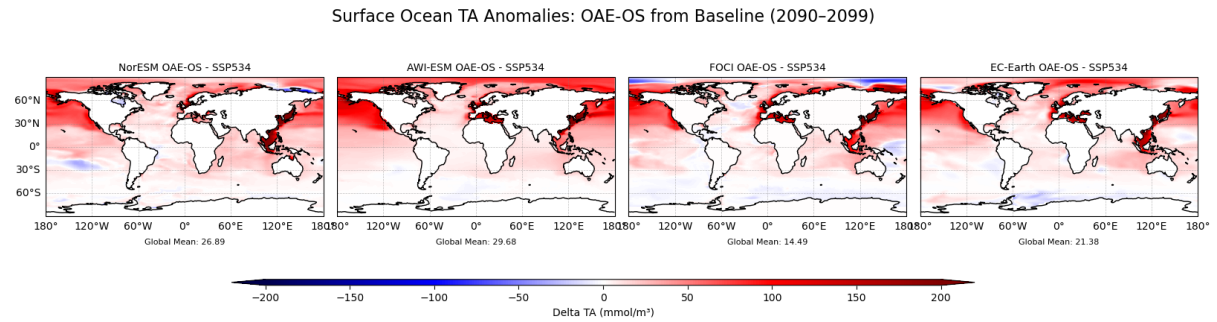


Figure S4: Spatial maps of surface TA anomalies in the OAE-OS simulation, averaged over the last 10 years (2090-2099), for each individual model used in this study.

Surface Ocean DIC Anomalies: OAE-OS and DOCR-OS from Baseline (2090-2099)

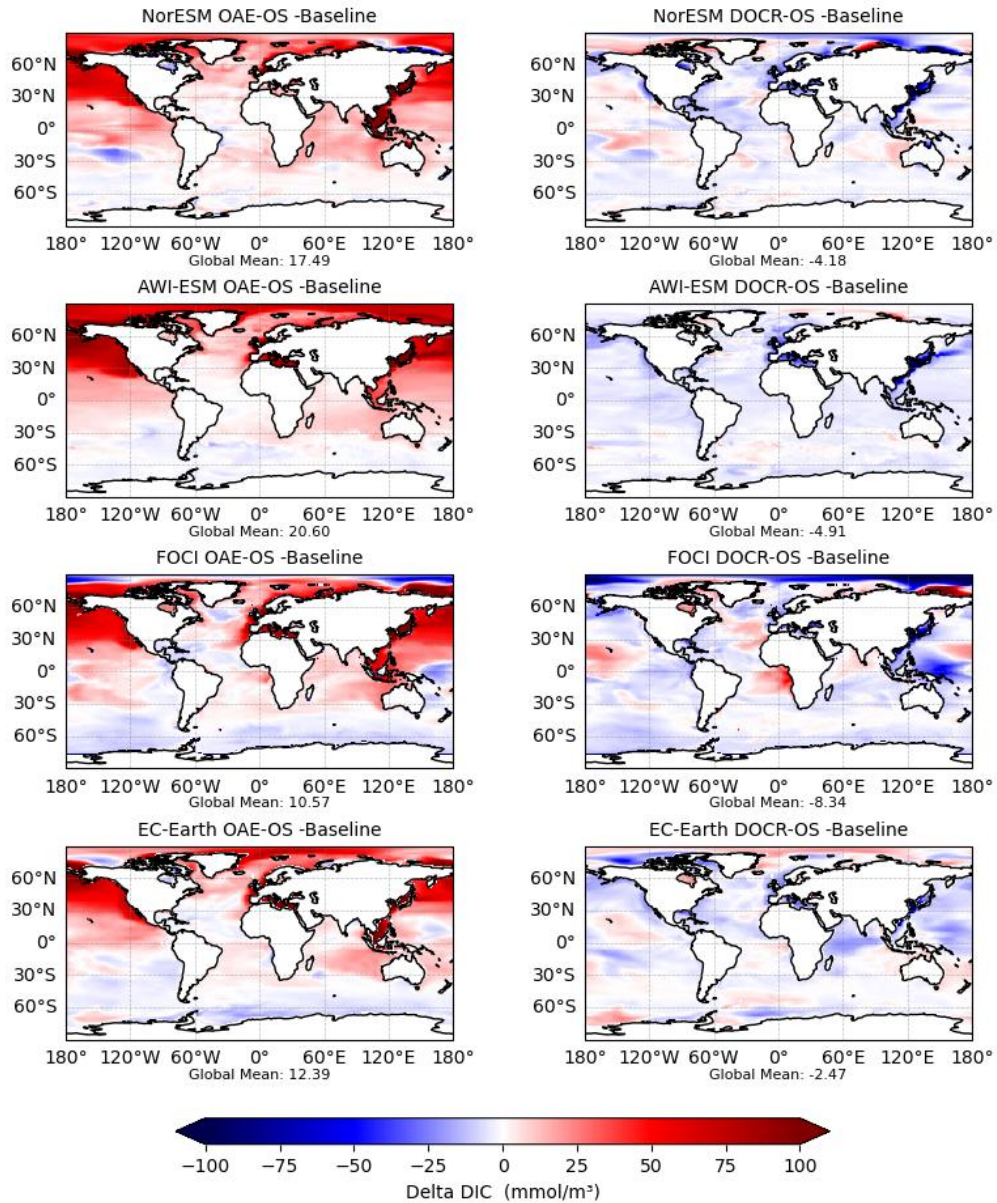


Figure S5: Spatial maps of surface DIC anomalies, averaged over the last 10 years (2090-2099) of the OAE-OS (left column) and DOCR-OS (right column) simulations for each individual model used in this study.

Surface Ocean pH Anomalies: OAE and DOCR from Baseline (2090-2099)

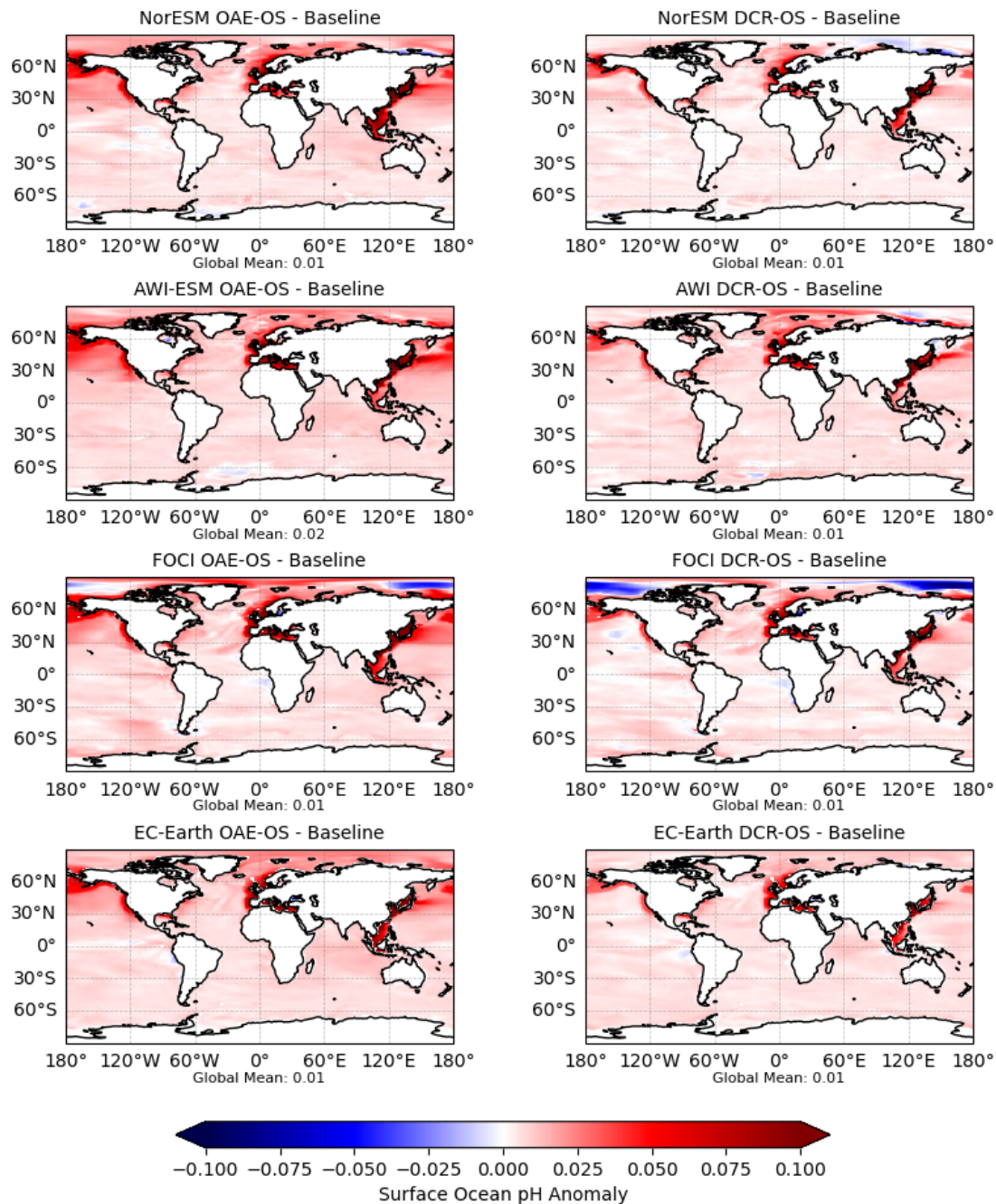


Figure S6: Spatial maps of surface pH anomalies, averaged over the last 10 years (2090-2099) of the OAE-OS (left column) and DOCR-OS (right column) simulations for each individual model used in this study.

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