# Ocean biogeochemical responses to AMOC variability in a changing climate

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## I. Rationale: AMOC impact on simulated equilibrium interior oxygen

One of the key questions related to future climate prediction is the stability of the ocean overturning (THC) and how it responses to the ongoing anthropogenic climate change. The functioning of ocean biogeochemistry and distributions of biogeochemical tracers are tightly coupled with the THC. Doney et al. (2004) show that the representation of ocean transport and dynamics directly affects the predicted ocean carbon cycle variables. Thus, changes in THC will influence ocean biogeochemical processes through altering the carbon sources and sinks, which then could feedback to the climate. Using a single coupled biophysical ocean model (HAMOCC-MICOM, Tjiputra et al., 2013) configured for different setups, we show that different AMOC strengths lead to different equilibrium states of ocean biogeochemical tracers (e.g., dissolved oxygen, Figs. 1 and 2).

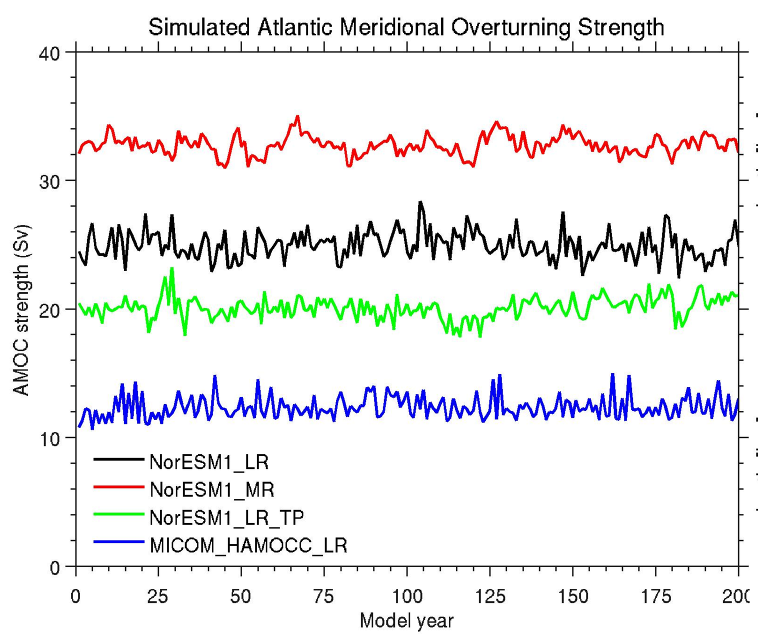


**Figure 1.** Time series of annual mean Atlantic Meridional Overturning Circulation Strength (AMOC) simulated by the NorESM ocean component based on different configurations (coupled or forced offline) and spatial resolutions: LR (3°), MR (1°), TP (Tripolar grid).

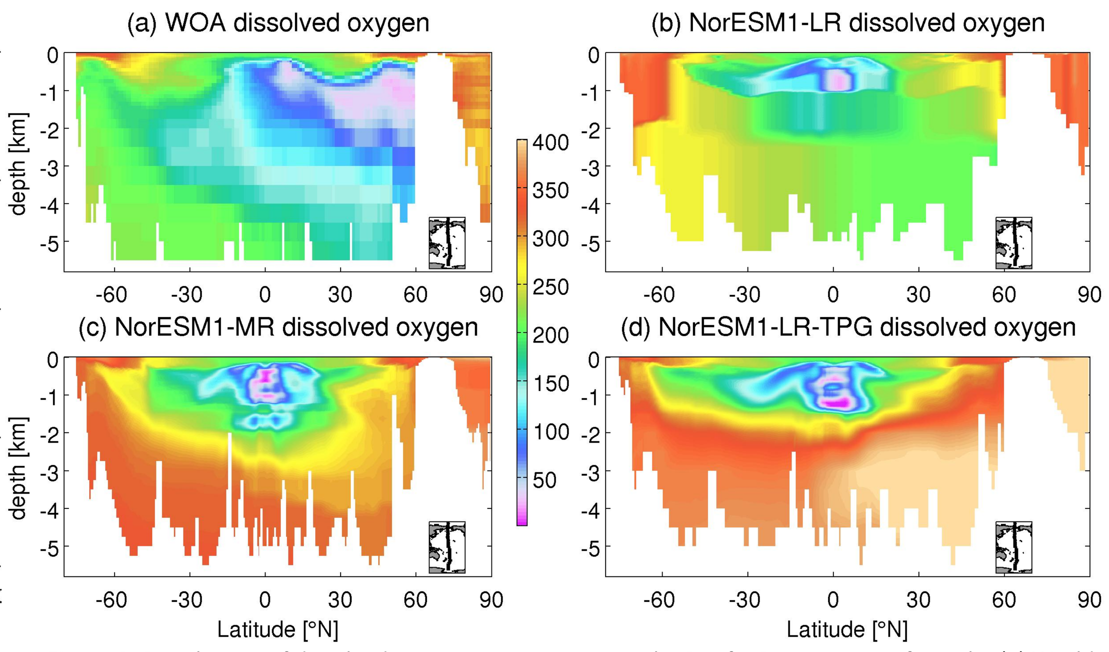


**Figure 2.** Distribution of dissolved oxygen concentration in the Pacific Ocean section from the (a) World Ocean Atlas and preindustrial states simulated by the (b) NorESM1-LR, (c) NorESM1-MR, and NorESM1-LR-TPG models. Unit in µmol $L^{-1}$. See also Fig. 1 for the different model configurations. All configurations was spun up for at least 1000 model years.

## II. AMOC-induced changes in North Atlantic oxygen and phosphate

We simulated climate change under the RCP8.5 scenario with NorESM and to illustrate the sensitivity of interior biogeochemical tracers to AMOC, additional scenario with strong climate engineering based on stratospheric aerosol injection on top of the RCP8.5 (RCP8.5+CE, Tjiputra et al., 2015) was performed. A termination simulation where CE is stopped abruptly in 2100 is also simulated and resulted in rapid decrease in AMOC over the subsequent decade (Fig. 3). Figure 4 shows that climate change reduces interior oxygen and phosphate concentrations. Signals in the intermediate depth up to 2000m emerge relatively fast, within few years after AMOC perturbation (see simulation with CE termination), whereas in deeper layer, changes also occur but at a slower pace.

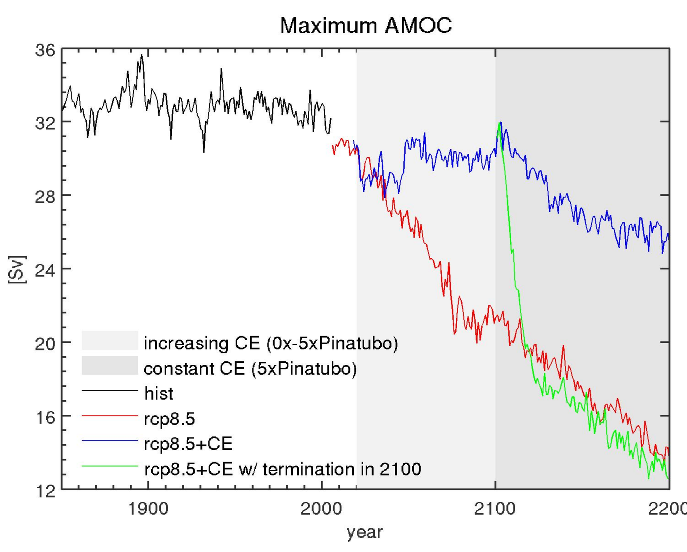


**Figure 3.** Time-series of AMOC as simulated by NorESM1-ME for various CMIP5 scenario and with additional climate engineering forcing

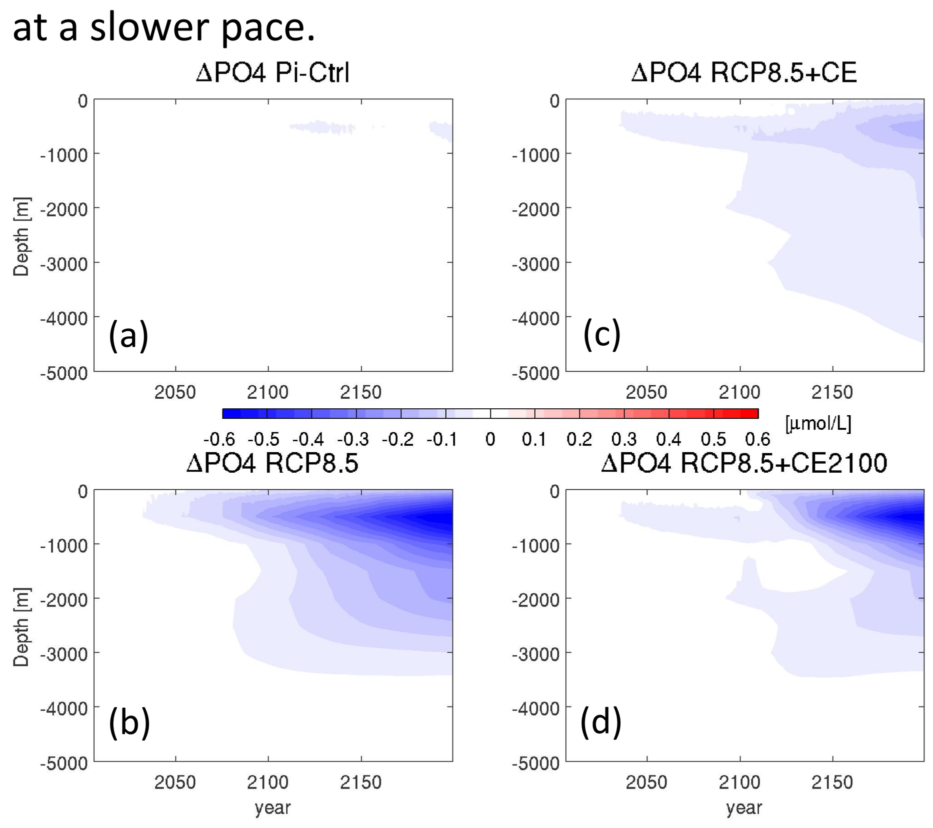


**Figure 4.** Change in vertical mean profile phosphate in the North Atlantic up to year 2200 relative to year 2005 for experiments (a) preindustrial control, (b) RCP8.5, (c) RCP8.5 plus climate engineering, (d) RCP8.5 plus climate engineering until 2100.

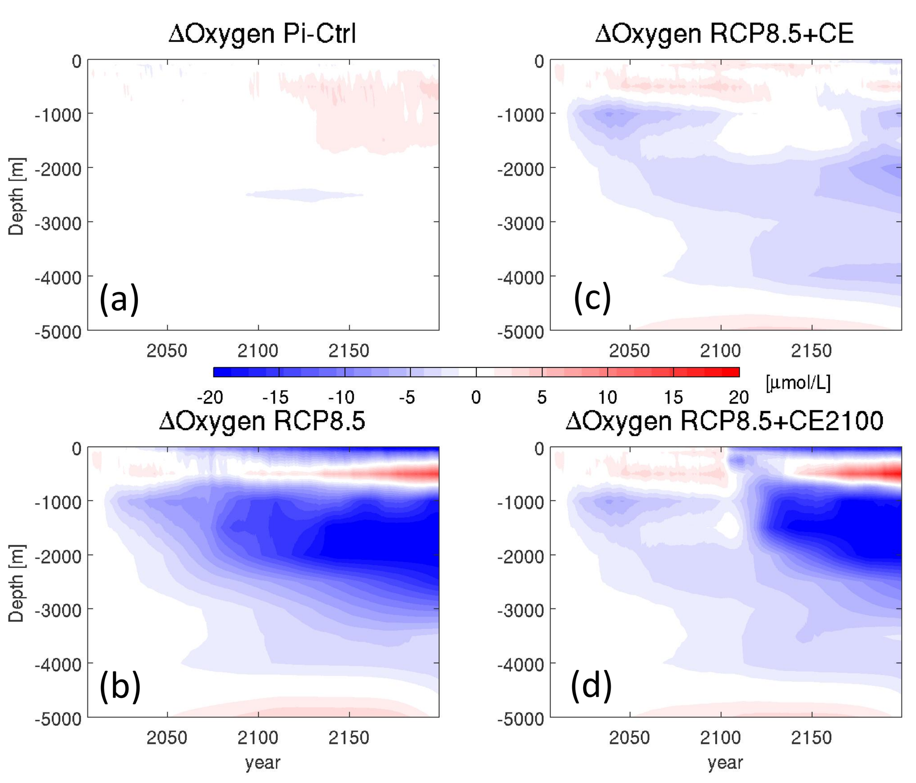


**Figure 5.** Same as Fig. 4 but for Oxygen.

## III. Biological vs. physical contribution of oxygen changes

Change in the interior phosphate projected in the future (e.g., Fig. 4) reflects, to some extent, the change in large scale overturning circulation. This is not obvious for the interior oxygen. Figure 6 shows that weaker overturning circulation leads to a broad, but mostly in the upper 1000m, reduction in the North Atlantic Oxygen.

Increased preformed oxygen at 1000m depth south of Iceland could indicate a shallower overturning cell in the future. AMOC-induced reduction in surface nutrient also leads to reduction in biological production, and consequently reduction in remineralization (oxygen consumption, AOU in Fig. 6) in the interior ocean. Fig. 6 also indicate that biological remineralization in the future is projected to occur at more shallow depth.

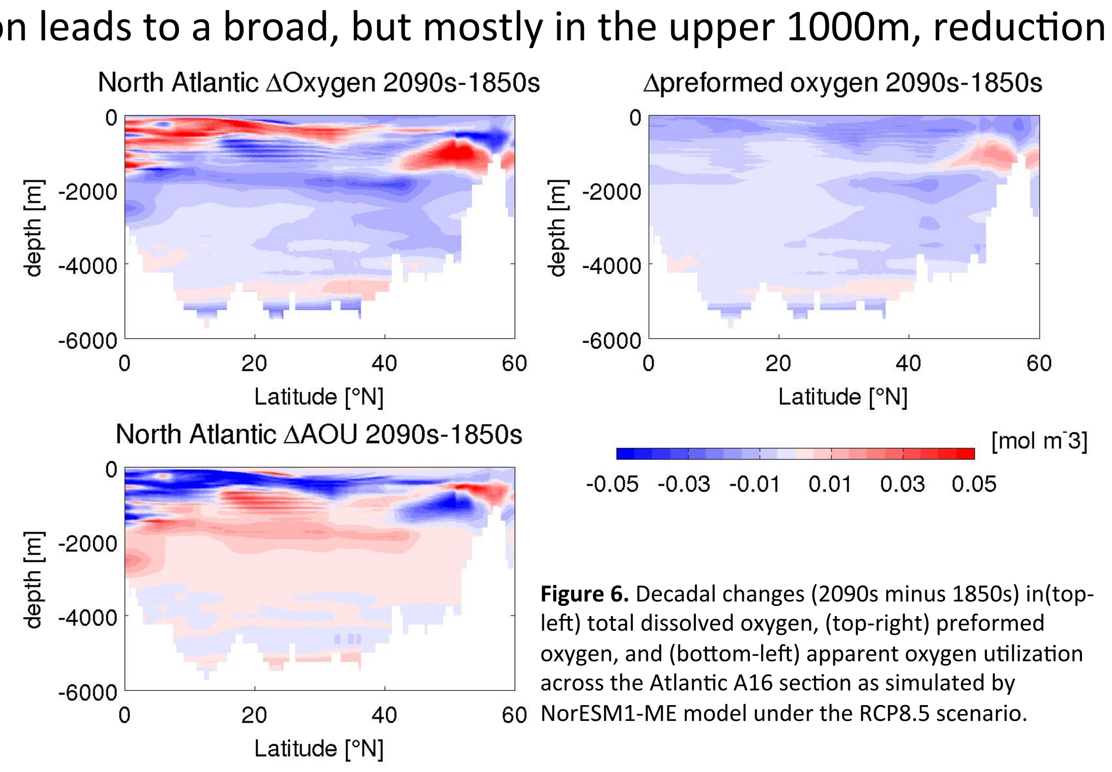


**Figure 6.** Decadal changes (2090s minus 1850s) in(top-left) total dissolved oxygen, (top-right) preformed oxygen, and (bottom-left) apparent oxygen utilization across the Atlantic A16 section as simulated by NorESM1-ME model under the RCP8.5 scenario.

## IV. Time of Detectable Change (ToDC)

Here, we explore the detectability of biogeochemical tracer changes in response to the projected climate change. We define Time of Detectable Change (ToDC) as the year where the seasonal cycle exceeds twice of the natural standard deviation for five continuous years. The ToDC is calculated relative to the present day period, i.e., mean over 2006-2015 period. In the North Atlantic, Fig. 7 shows that ToDC for temperature, alkalinity, and oxygen would emerge earlier in the subtropical and earliest in the North Atlantic drift region. In the Labrador Sea, oxygen ToDC will occur earlier than temperature.

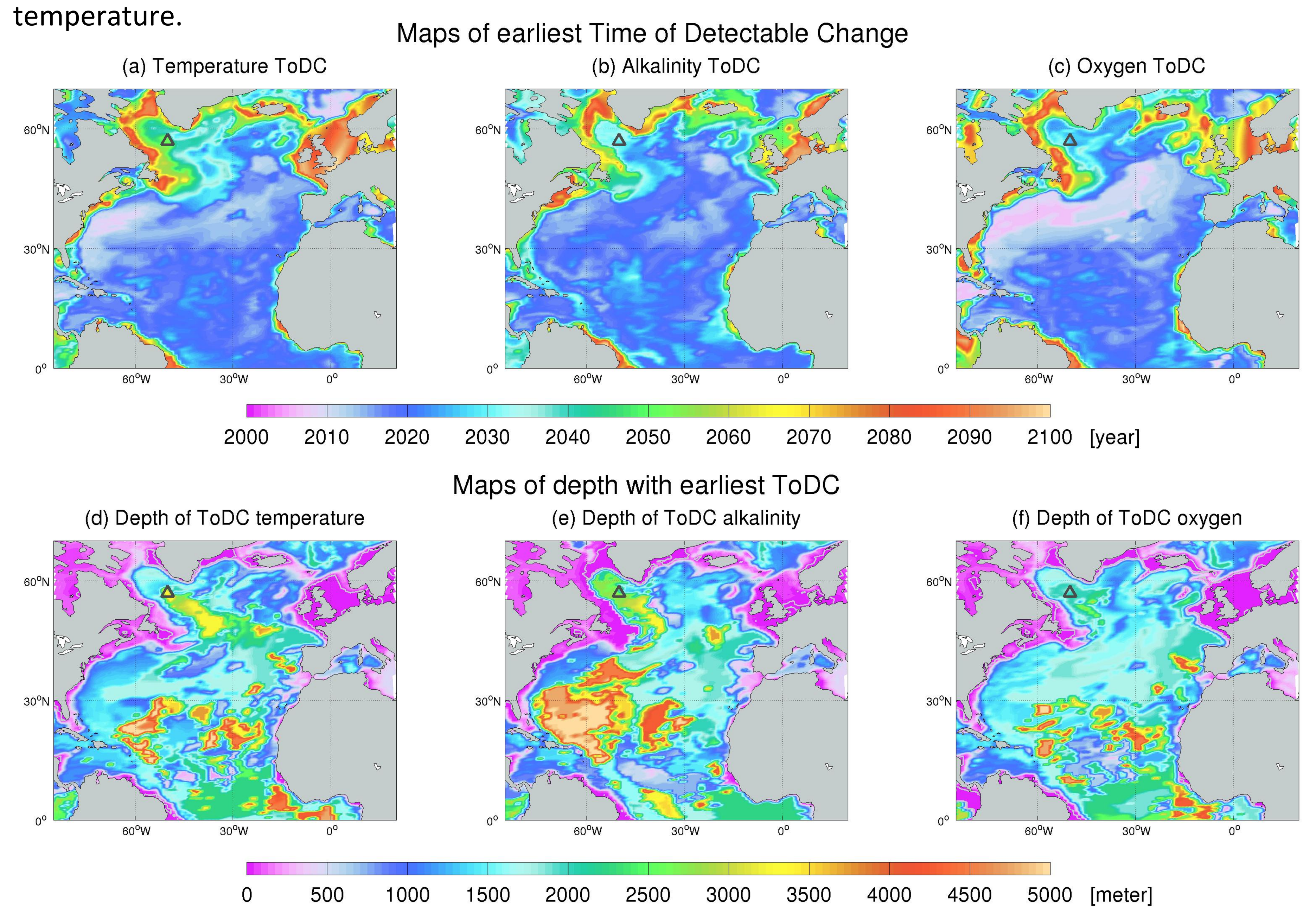


**Figure 7.** Maps of (top-row) ToDC in the North Atlantic for temperature, alkalinity, and oxygen. Maps of (bottom-row) depth where the ToDC signal is projected under the RCP8.5.

## V. Detecting climate change in the Labrador Sea

In the North Atlantic, large seasonal cycle is embedded in the surface temperature and oxygen signals, thus hinders the climate change signal. Surface Alkalinity increase in seasonal cycle (potentially due to changes in evaporation and precipitation) but still within the natural variability envelope. In the intermediate depth, the model simulates decadal variability in temperature and alkalinity, but climate change signal for temperature is projected to emerge in the 2nd half of the 21st century. The oxygen signal at 2000m depth emerges much earlier, and could be related to the combination of biological and physical changes.

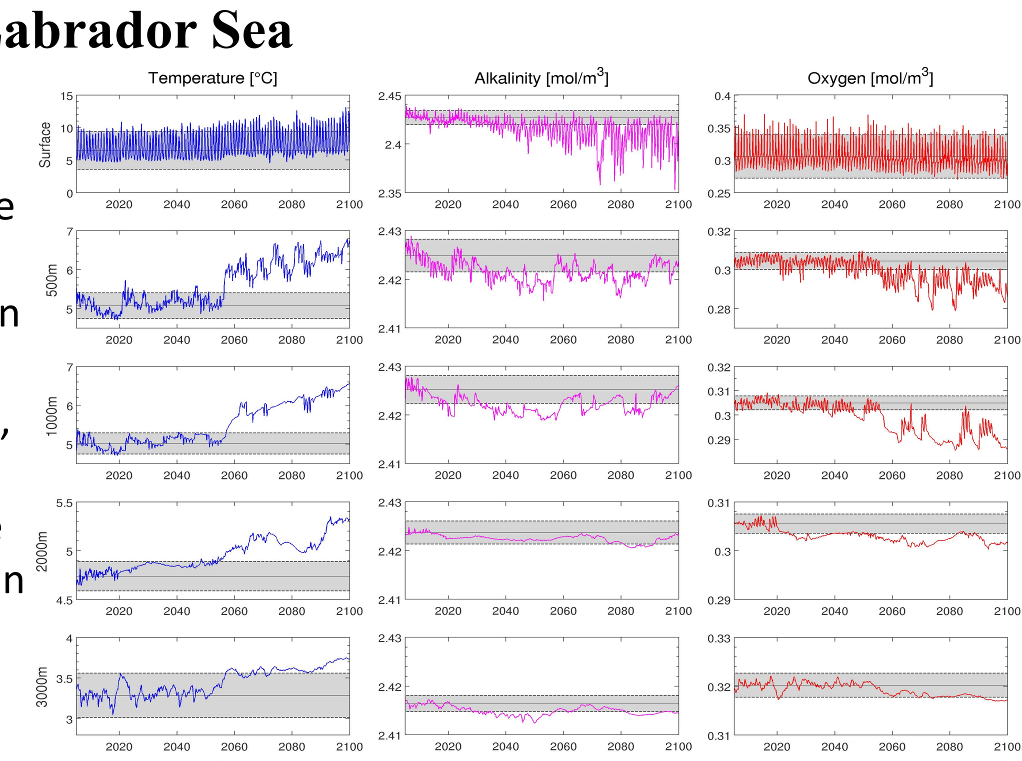


**Figure 8.** Time-series of monthly temperature, alkalinity, and oxygen in the Labrador Sea (triangle symbol in Fig. 7). Shown here are simulated values for the surface, 500m, 1000m, 2000m, and 3000m. Grey shadings represent 2x standard deviation from the preindustrial control.

## VI. Impact on benthic ecosystem

Anthropogenic carbon uptake reduces the saturation state of carbonate ion in the ocean, which could be detrimental for calcareous organisms. Future AMOC reduction ameliorate this negative impact on benthic ecosystem as less undersaturated watermass will be transported into depth.

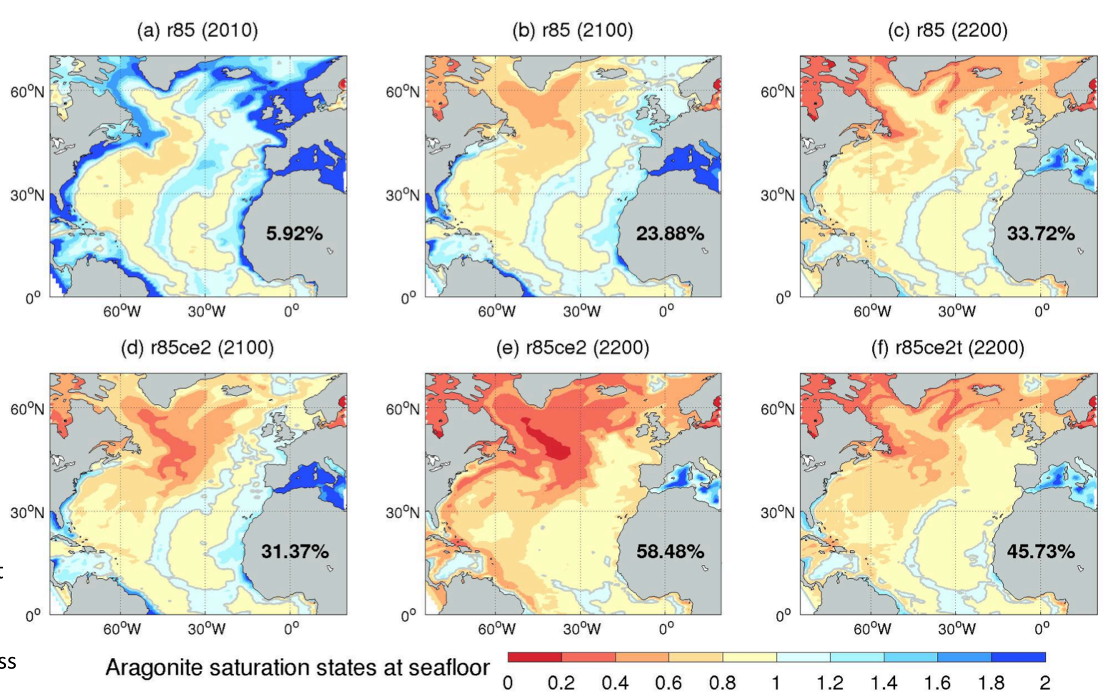


**Figure 9.** Maps of aragonite saturation states on the North Atlantic seafloor for the RCP8.5 projections in years (a) 2010, (b) 2100, and (c) 2200. The RCP8.5+CE projections in (d) 2100 and (e) 2200. (f) The projection at 2200 following CE termination in r85ce2t simulation. Grey contour lines represent saturation state at 1.0 values, where values less than 1 represent regions of undersaturation. The numbers inside each panel represents percentage of North Atlantic (north of 0◦ latitude) seafloor area with saturation state of less than 0.8.

## VII. Summary

- Interior biogeochemical tracer distribution in ESMs is sensitive to the simulated overturning circulation strength, and therefore will have impact on the projected biogeochemical change and its potential climate feedback.
- Projected weakening in AMOC reduces nutrient and oxygen concentration at depth.
- Biogeochemical tracers such as oxygen may provide an earlier indicator of AMOC changes at depth than temperature fields.
- Future AMOC-induced changes in deep ocean properties could have long-lasting negative impact on the deep ocean ecosystem.

**References**

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