Climate Change Impacts on Marine Productivity in the Community Earth System Model

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Climate Change Impacts on Productivity

Net Primary Production (NPP) = total photosynthesis

Export Production (EP) = fraction of organic matter that sinks out of surface waters to ocean interior

Stratification = strength of vertical density gradient (defined here as the difference in density between the surface and 200 m depth)

Diatoms = large phytoplankton, export organic matter more efficiently than small phytoplankton
Biogeochemical Elemental Cycling (BEC) Model

- **Small Phytoplankton**: C, Chl, Fe, CaCO₃
- **Diatoms**: C, Chl, Fe, Si
- **Diazotrophs**: C, Chl, Fe
- **Zooplankton**: C
- **Sinking Particulates**: C, Fe, Si, CaCO₃, Dust
- **Dissolved Organic Matter**: C, N, P, Fe
Surface Nutrient Concentrations

CESM1.0
- Nitrate: $r = 0.79, 0.79$
- Phosphate: $r = 0.79, 0.79$

CESM1.2
- Nitrate: $r = 0.73, 0.88$
- Phosphate: $r = 0.73, 0.88$

WOA2009
- Observations
Representative Concentration Pathways (RCPs)

To simulate future climate, we have to make assumptions about how human populations and the emissions of greenhouse gas pollutants will change over time.

**RCP 8.5** is the strong warming, “business as usual” scenario, where fossil fuel use continues to increase.

**RCP 4.5** is a more optimistic scenario, fossil fuels decline sharply by 2050, Atmospheric CO$_2$ stabilizes by 2100.
RCP 8.5 – Continued increasing fossil fuel use, rapid warming 2100. RCP 4.5 – Dramatic shift off fossil fuels, stabilizing climate by 2100.

Figure 1: Temporal evolution of (a) atmospheric CO₂ and (b) sea surface temperature (SST) under RCP4.5 (dotted) and RCP8.5 with prescribed (solid) and prognostic (dashed) atmospheric CO₂. Gray lines in (b) show constant climate integrations (4.5rCO₂ and 8.5rCO₂). The character of SST variability in the 1850 controls was comparable to the two constant climate integrations.
Surface warming and freshening increases ocean stratification

As stratification increases, upward nutrient flux decreases.

Fu et al., (submitted)

Fig. 1: Time series of global mean stratification, SST and SSS for historical run and RCP8.5 over 1850-2100. Stratification is defined as the density difference between 200 m and the surface. Red square indicates observations from the WOA2009 data.
Change in stratification between the 1990s and 2090s under RCP8.5.

Global increases with strongest changes in the western tropical Pacific, the Arctic Ocean, and the high-latitude North Atlantic.

Fu et al., (submitted)
Winter mixing is greatly reduced in the high latitude North Atlantic

Moore et al. (2013)

Figure 10. Monthly mean maximum and minimum mixed layer depths from the CESM during the 1990s are compared with simulated mixed layer depths from the 2090s under the RCP 4.5 and RCP 8.5 scenarios. Mixed layer depths were calculated as the depth with a density difference from surface waters > 0.125 g/L.
As stratification increases, surface nutrient concentrations decline.

Fig. 5: Time series of mean nitrate (NO₃), phosphate (PO₄), silicate (SiO₄) and dissolved iron (dFe) concentrations (0-100 m) are shown for 1850-2100. Red square indicates WOA2009 global mean values. **Note wide spread in surface nutrients (Fu et al., submitted).**
Similar spatial patterns, but larger reductions in the stronger warming scenario (RCP 8.5).

Figure 11. CESM simulated annual mean surface nitrate concentrations from the 1990s are compared with simulated values for the 2090s under the RCP 4.5 and RCP 8.5 scenarios.
As nutrients decline, biological production decreases

Net Primary Production

Export Production

Note large model spread in simulated NPP.

Fu et al., (submitted)
As nutrients decline, biological production decreases

The group of models that show smaller declines in NPP than in EP (CESM, GFDL, IPSL) are those that can capture a shift in phytoplankton community with increasing nutrient stress (less diatoms, more small phytoplankton).
Net primary production decreases with climate warming

A) NPP 1990s  56.0 PgC/yr

B) RCP 4.5  2090s – 1990s  54.9 PgC/yr

C) RCP 8.5  2090s – 1990s  52.8 PgC/yr

Figure 16. Annual mean net primary production for the 1990s is compared with the 2090s under the RCP 4.5 and RCP 8.5 scenarios.

(Moore et al., 2013)
Export production decreases with climate change

Export production in the 1990s

Decreases by 5% under RCP 4.5

Decreases by 13% under RCP 8.5

Figure 17. The annual mean sinking particulate organic carbon flux at 100 m depth for the 1990s is compared with the 2090s under the RCP 4.5 and RCP 8.5 scenarios.

(Moore et al., 2013)
As surface nutrients drop, diatom production decreases.
Quantifying the relations between stratification, nutrients, and NPP

The change in stratification Vs. change in nutrients and NPP (relative to 1990s).
All annual output from nine ESMs over the period 1850-2100.

Fu et al., (submitted)
Relations between stratification, NPP, EP, and Diatom Production

(e) $\Delta S_I$ vs $\Delta EP$

(f) $\Delta S_I$ vs $\Delta NPP$ by diatom

(g) $\Delta NPP$ by diatom vs $\Delta EP$

(h) $\Delta NPP$ vs $\Delta EP$
% change in Stratification versus % change in NPP and EP (mean 1990s and mean 2090s)

The declines in NPP and EP are proportional to stratification increases.

The models which show the largest increases in stratification in the 2090s also have strong positive biases in stratification during the 1990s.

These models show the strongest declines in NPP and EP.

This suggests the more biased models in the 1990s may be overestimating the reductions in productivity due to climate change.

Fu et al., (submitted)
BGC WG recently extended the RCP8.5 out to year 2300.

Red line is from the fully coupled model (Randerson et al., 2015).
Climate Change Impacts on NPP & Export Production

1) The CESM and other ESMs predict decreasing ocean productivity with climate change (particularly under RCP 8.5).

2) These reductions in production will work their way up the food chain, resulting in lower biomass at higher trophic levels (including wild fish for commercial harvest).

3) Reductions are larger, and still rapidly increasing under RCP 8.5 by 2100, perturbations stabilize under RCP 4.5.

4) Thus, beyond year 2100 the climate change consequences for marine biology are drastically different, depending on which developmental pathway we choose (RCP 8.5 vs. RCP 4.5).

5) To better predict shifting patterns in NPP and EP, changes in phytoplankton community (decreasing role for diatoms) must be considered, and ESMs will need to better represent biological communities and ecology in the future.