Multicentury Climate Warming Impacts on Ocean Biogeochemistry

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Climate Impacts to 2100

Surface ocean warms increasing stratification, and decreasing nutrient flux to surface waters.

NPP declines under RCP4.5 & RCP8.5 scenarios.
Larger decreases in RCP 8.5, but similar spatial pattern.

NPP down 6% globally, decreasing > 50% in NA.

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)
Prescribed atmospheric CO₂ trajectory. The historical record to 2005, then RCP 8.5 to 2100, then ECP 8.5 to 2300

Atmospheric CO₂ reaches 1960 ppm

Mean surface air temperature warms 9.6 °C

Arctic air temperatures rise by >25 °C

Ocean CO₂ uptake peaks ~2100, 4.5 PgC/yr, then declines as surface waters saturate, in spite of the ongoing CO₂ rise.

Fully Coupled Simulation
No CO₂ Warming, Other GHGs Active
No GHG Warming, but CO₂ Affects Biota

(Randerson et al., 2015)
North Atlantic Deep Water (NADW) formation is greatly reduced (30 to 5 Sv), as deep winter mixing collapses.

Stratification increases steadily to 2200.

85% of ocean warming occurs after 2100!

Most of the warming at 2100 is still near the surface, it takes centuries for the heat to move downwards modifying circulation.

(Randerson et al., 2015)
Sea Surface Temperature (°C)

Increases of 1-5 °C by 2100
Increases of 4-11 °C by 2300

(Moore et al., 2018)
At depth, the oceans are still warming and stratification between mid-depths and the deep ocean is still increasing at 2300.

(Moore et al., 2018)
Global warming removes nearly all sea ice from polar regions by 2300.

Sea Ice Cover Decline 2300
Southern Hemisphere - 97%
Northern Hemisphere - 99%

(Moore et al., 2018)
The midlatitude westerly winds intensify and shift southwards with strong climate warming.

Common pattern across the CMIP5 models under RCP 8.5.

The Antarctic Divergence upwelling zone also intensifies and shifts south, leading to coastal upwelling around Antarctica.

(Moore et al., 2018)
As the Westerlies intensify and shift poleward, upwelling at the Antarctic Divergence shifts south and intensifies. Eventually coastal upwelling is initiated along Antarctica.

Mean upwelling velocity (below 60°S) up 25% by 2150.

Southern Ocean NPP and POC export increase due to:
1) sea ice removal reduces light limitation
2) warming oceans increase phytoplankton growth rates
3) shifting winds increase upwelling rate and location

(Moore et al., 2018)
Sinking particulate organic carbon (POC) flux increases in the Southern Ocean and equatorial Pacific, and declines everywhere else.

Above 30°S, the POC flux declines 41% by 2300, NPP declines by 24%.

Increasing Southern Ocean NPP and POC flux drives "nutrient trapping" with increasing subsurface (200-1000m) phosphate concentrations.

The trapped nutrients help drive increasing SO productivity, which further strengthens the nutrient trapping, in a positive feedback.

Trapping nutrients in the Southern Ocean reduces the northward nutrient transport that fuels low latitude biological productivity.
Nutrient Transfer to Deep Ocean Via the Southern Ocean

Current Era
- low NPP near Antarctica from:
  - heavy sea ice / low light / cold ocean / slower growth / iron-limitation

Hothouse Earth
- higher NPP near Antarctica from:
  - less sea ice / more light / warmer ocean / faster growth / more upwelling / more nutrients
Southern Ocean nutrient trapping decreases northwards nutrient flux, within AAIW and SAMW, into the low-latitude thermocline.

Some trapped nutrients are moved back into the deep ocean by circulation and vertical mixing, driving a net transfer to the deep ocean.

Phosphate concentrations decline in the upper ocean (down to 1500m!), initially due to increasing stratification (B), then due to upper ocean nutrient declines (C).

The collapse of deep winter mixing in the high latitude North Atlantic, also acts to deplete upper ocean nutrients and increase deep ocean nutrient concentrations (above 60°N).

Nutrient concentrations in the Southern Ocean (all depths) and global deep ocean are still increasing linearly at 2300. Transfer to the deep ocean is ongoing at 2300. (Moore et al., 2018)
Similar Transfer of Nitrate and Silicic Acid to the Deep Ocean

A) 1990s Nitrate (µM)

B) 2090s - 1990s

C) 2290s - 1990s

A) 1990s Silicic Acid (µM)

B) 2090s - 1990s

C) 2290s - 1990s
The Southern Ocean increasingly dominates CO₂ uptake with climate warming.

CO₂ uptake begins saturating elsewhere as anthropogenic CO₂ accumulates.

Oceanic uptake of heat and anthropogenic CO₂ will eventually cool the climate.

Southern Ocean dynamics will drive the climate cooling timescale.

(Moore et al., 2018)
Summary and Conclusions

1) **ESM simulations** need to extend well beyond 2100 to fully account for the impacts of global warming.

2) If warming removes the Southern Ocean sea ice, nutrient trapping and net transfer to the deep ocean seem likely, marking a new, critical **tipping point** in the Earth System.

3) Nutrient transfer to the deep ocean will continue until the climate cools and sea ice returns to the Southern Ocean, depressing NPP, and increasing northward nutrient flux in surface waters.

4) The long timescales for ocean CO$_2$ uptake, and then for circulation to return depleted nutrients to the upper ocean, ensures that global-scale marine biological productivity will be depressed for at least a millenium.
Multicentury Climate Warming

- Westerly winds strengthen and shift southwards
- Polar oceans warm
- Sea ice disappears
- Collapse of deep winter mixing and NADW formation

Increasing Southern Ocean Net Primary Production (NPP) and Biological Export

- Nutrients "trapped" locally, increasing concentrations near Antarctica, and later throughout the deep ocean

Northward nutrient flux weakens, Upper ocean nutrient concentrations decline everywhere to the north

Declining productivity reduces the maximum potential fishery catch, down 20% globally, and by nearly 60% in the North Atlantic by 2300

NPP steadily declines as upper ocean nutrients are increasingly depleted, north of 30°S export production is down 30% by 2300
Long-term Fate of Anthropogenic CO$_2$

**Over ~1000 Years**
Most of the anthropogenic CO$_2$ added to the atmosphere will be absorbed by the oceans due to the solubility pump (~70-80%). The anthropogenic CO$_2$ will be carried throughout the deep ocean by the circulation, beginning to interact with the sediments.

**Over ~10,000 Years**
As the anthropogenic CO$_2$ is circulated throughout the deep ocean the decrease in pH will lead to dissolution of CaCO$_3$ in the sediments. This dissolution will increase the alkalinity (and raise pH) allowing the water to absorb additional CO$_2$ from the atmosphere when it is brought back to the surface (~10-15%).

**Over ~100,000+ Years**
The remaining anthropogenic CO$_2$ in the atmosphere (~10%) will be removed slowly due to rock weathering on the continents.
We find very similar nutrient transfer to the deep ocean in two other ESMS that followed RCP8.5-ECP8.5 to 2300
Under strong warming scenarios, most of the warming occurs after 2100. By 2300 mean surface temperature has increased by 9.6 °C, nearly ten time the warming we have seen up to this point! Arctic air temperatures increase by > 25 °C.
Factors Boosting Southern Ocean Productivity

1) **Reductions in sea ice cover**, increases light reaching the ocean.

2) **Warming surface waters**, increases phytoplankton growth rates, and shoals mixed layer depths, improving the light regime.

3) **Shifting Westerlies** increases upwelling rate, and incorporates more margin-influenced, high-iron waters along Antarctica.

Mean light levels experienced by phytoplankton in the Southern Ocean surface mixed layer **increase by 245%** at 2300 relative to the 1850s.

The **six degree warming** of polar surface waters (below 60 °S), increases maximum phytoplankton growth rates by **52%**.

Mean upwelling rate increases by **25%** at 2150, then levels off to 2300.
Upper ocean iron concentrations increase in the upper ocean around Antarctica due to nutrient trapping.

However, due to the short residence time of iron in the oceans, there is no global redistribution of iron.

Particle scavenging removes the iron before it can be transported long distances.

Over much of the oceans, iron increases modestly throughout the water column. This is due to the weakening biological pump, which reduces sinking particle flux, and thus lowers the scavenging loss for iron.
The magnitude of the global-scale productivity declines is much larger than regional Southern Ocean increases, leading to large global declines in NPP and POC export by 2300.

Note increasing Southern Ocean POC export over time (below 50S) and the decline in POC export everywhere outside the Southern Ocean (above 50S).

Note changes in mean zonal POC flux after year 2100 are larger than changes before 2100.

Big impact in the high latitude North Atlantic do to the greatly reduced deep winter mixing, decreases nutrient inputs to the Arctic basin as well.
Increasing Southern Ocean NPP and POC flux leads to "nutrient trapping" in the Southern Ocean, with increasing subsurface (200-1000m) phosphate concentrations around Antarctica.

(Moore et al., 2018)
We use an empirical model to estimate potential fishery yield from the phytoplankton and zooplankton simulated by CESM.

This model by Stock et al. (2016) used ESM simulated zooplankton productivity, combined with observed fisheries catch to optimize a simple model of trophic transfer efficiency.

Bottom Up Constraints on Fishery Catch

Changes in productivity at trophic levels 3 and 4 (would include most commercial fish catch)

Globally down 20% at 2300
Down more than 50%
North Atlantic, western Pacific, and Indian basins.
Decreasing export production, sinking Particulate Organic Carbon (POC at 100m) under both future scenarios.

Larger decreases under RCP 8.5, but with similar spatial patterns. Export down 13% globally, with decreases > 50% in some regions.

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.