Future Arctic Primary Productivity from CMIP5: Uncertain Outcome, but Consistent Mechanisms

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Bloom in the Barents Sea, Aug 31, 2010, earthobservatory.nasa.gov
Observations indicate a PP increase over 1998-2010
Simple projections suggest +300 Tg C y\(^{-1}\)

Perennial sea ice

\[6-7 \times 10^6 \text{ km}^2\]

\[\Delta \sim 20\%\]

1998-2009

! NO\(_3\) limitation

Arrigo & van Dijken (2011)
# CMIP5 Earth System Models

<table>
<thead>
<tr>
<th></th>
<th>Atmosphere</th>
<th>Ocean</th>
<th>Sea Ice</th>
<th>Marine biogeochemistry</th>
<th>Spinup (offline+online, yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CanESM2</td>
<td>35 lev., 2.8/2.8°</td>
<td>40 lev., 1.4/0.9°</td>
<td>CF, SM0L, 2lev</td>
<td>NPZD, 1 PG, N</td>
<td>6000 + 600</td>
</tr>
<tr>
<td>GFDL-ESM2G</td>
<td>24 lev., 2.0/2.5°</td>
<td>59 lev., 0.3-1°</td>
<td>EVP, W00, ITD</td>
<td>30tr., 3 PG, N, P, Si, Fe</td>
<td>1 + 1000</td>
</tr>
<tr>
<td>GFDL-ESM2M</td>
<td>24 lev., 2.0/2.5°</td>
<td>50 lev., 0.3-1°</td>
<td>EVP, W00, ITD</td>
<td>30tr., 3 PG, N, P, Si, Fe</td>
<td>1 + 1000</td>
</tr>
<tr>
<td>HadGEM2-CC</td>
<td>60 lev., 1.2/1.9°</td>
<td>40 lev., 0.3-1°</td>
<td>EVP, SM0L, ITD</td>
<td>NPZD, 2 PG, N, Si, Fe</td>
<td>CMIP3 + 500 + 100</td>
</tr>
<tr>
<td>HadGEM2-ES</td>
<td>38 lev., 1.2/1.9°</td>
<td>40 lev., 0.3-1°</td>
<td>EVP, SM0L, ITD</td>
<td>NPZD, 2 PG, N, Si, Fe</td>
<td>CMIP3 + 500 + 100</td>
</tr>
<tr>
<td>IPSL-CM5A-LR</td>
<td>39 lev., 1.9/3.8°</td>
<td>31 lev., 0.5-2°</td>
<td>VP, SM3L, 2lev</td>
<td>24tr., 2 PG, NO3, NH4, P, Si, Fe</td>
<td>3000 + 300</td>
</tr>
<tr>
<td>IPSL-CM5A-MR</td>
<td>39 lev., 1.2/2.5°</td>
<td>31 lev., 0.5-2°</td>
<td>VP, SM3L, 2lev</td>
<td>24tr., 2 PG, NO3, NH4, P, Si, Fe</td>
<td>3000 + 300</td>
</tr>
<tr>
<td>MIROC-ESM</td>
<td>80 lev., 2.8°</td>
<td>44 lev., 1.4/0.5-1.7°</td>
<td>EVP, SM0L, 2lev</td>
<td>NPZD, 1 PG, N</td>
<td>1245 + 480</td>
</tr>
<tr>
<td>MIROC-ESM-CHEM</td>
<td>80 lev., 2.8°</td>
<td>44 lev., 1.4/0.5-1.7°</td>
<td>EVP, SM0L, 2lev</td>
<td>NPZD, 1 PG, N</td>
<td>1245 + 480</td>
</tr>
<tr>
<td>MPI-ESM-LR</td>
<td>47 lev., 1.9°</td>
<td>40 lev., 1.5°</td>
<td>VP, SM0L, 2lev</td>
<td>NPZD, 1 PG, N, P, Si, Fe</td>
<td>x*1000 + 1900</td>
</tr>
<tr>
<td>MPI-ESM-MR</td>
<td>95 lev., 1.9°</td>
<td>40 lev., 0.4°</td>
<td>VP, SM0L, 2lev</td>
<td>NPZD, 1 PG, N, P, Si, Fe</td>
<td>x*1000 + 1500</td>
</tr>
</tbody>
</table>
What can we say about future primary production in a perennial ice-free Arctic from the IPCC Earth system models?
Models reasonably simulate present conditions

\[ PP \ [gC \ m^{-2} \ y^{-1}] \]

\[ \sigma = 40\% \times \mu \]

where models agree with each other
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PP [gC m\(^{-2}\) y\(^{-1}\)]

- Mean Model
  - σ = 40% × μ

Sea Ice

- σ = 17% × μ

NO\(_3\) [mmol m\(^{-3}\)]

- σ = 55% × μ

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where models agree with each other

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lundi 13 mai 13
PP is highly variable among models

spread, mean model vs obs, changes over time hard to guess
Can we tell anything about the change?

1980-1999
2080-2099

lundi 13 mai 13
Large increase: 2 models
Mild increase: 6 models
Decrease: 3 models
Large increase: 2 models
Mild increase: 6 models
Decrease: 3 models
Mean: +59 TgC/yr << 300 TgC/yr
Large increase: 2 models
Mild increase: 6 models (stable in 2, decreasing in 4)
Decrease: 3 models
Mean: +59TgC/yr $\ll 300$ TgC/yr
Models don’t agree on the sign of future PP change
Models don’t agree on the sign of future PP change. But change is mostly mild, and many models have decreasing PP by 2100.
# Models don’t agree on the sign of future PP change

Increase is due to the switch to seasonal ice zone and open ocean zones, that are more productive.
Nitrate and perennial sea ice explain PP time series

Perennial ice only ↔ Seasonal ice only

Annual mean, normalized, domain-integrated PP vs limitation factors. Each color represents a model and a year in the 1900-2100 time series.
Sea Ice and NO3 time series

Sep SIE [10^6 km^2]

Surface NO3 [mmol m^-3]

consistent mechanisms, spread NO3, timing of oloigotrophy
Why does NO3 decrease?

- Increased consumption and export
- Stratification increases
- Simultaneous NO3 decrease in the North Atlantic and North Pacific => reduced advective sources

Normalized measure of maximum mixed layer depth anomalies
2 extreme models

Each point is an annual value in the time series.
September ice extent [$10^6$ km$^2$]

**GFDL-ESM2G**
- Normalized PP
- Normalized NO3
- NO3 suitability
- light suitability
- light x NO3 suitability

**IPSL-CM5A-MR**

**Integrated PP [Tg C yr$^{-1}$]**

**NO3 [mmol m$^{-3}$]**

**Time**
#2 Sea ice and NO3 decrease
NO3 spread is very large; onset of oligotrophy (if any) is quite variable
Why a large initial NO₃ scatter?

- Models are initialized using equilibrium model states
- Reached after long spin-ups (>1000 yrs), necessary to avoid spurious model drift
- Equilibrium nitrate depends on model processes (ocean circulation / biogeochemistry) and is hard to calibrate.
- Very few observations
Summary
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3. NO3 decrease?
   a) More consumption & more stratification
   b) Reduced NO3 content of Atlantic and Pacific waters
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   Models have very different initial levels (spin-up)
   The timing of effective oligotrophy onset is highly variable among models
   (1921 - >2100)

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5. Mechanisms are similar
   => Improved nitrate observations; improved model equilibrium response would give more consistent projections
The diagram shows a time series of changes in a variable $I^{PP}$ over decades, with a notable increase from 1980 to 2000. The graph compares multiple models (GFDL-ESM-2M, MPI-ESM-MR, IPSL-CM5A-LR) projecting emissions to 2080-2100, where the model GFDL-ESM-2M shows a significant increase in emissions to 253 TgC/yr. The onset of a seasonal ice cover is marked around 2000, with a notable decrease in $I^{PP}$ following the ice cover onset. The oligotrophy onset is indicated by the horizontal line at -110 TgC/yr.
Specialist opinion about the sign of the Arctic PP change by 2100

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Arctic (&gt;66°N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>58 %</td>
</tr>
<tr>
<td>-</td>
<td>42 %</td>
</tr>
<tr>
<td>no change</td>
<td>0 %</td>
</tr>
<tr>
<td>no answer</td>
<td>0 %</td>
</tr>
<tr>
<td>net</td>
<td>+</td>
</tr>
</tbody>
</table>

% individuals favouring each hypothesis

Reasons invoked: light, nutrients, stratification, rivers, multi-stresses, episodic upwellings