Impacts of shifting seasonality on Arctic Ocean carbon and nutrient cycles

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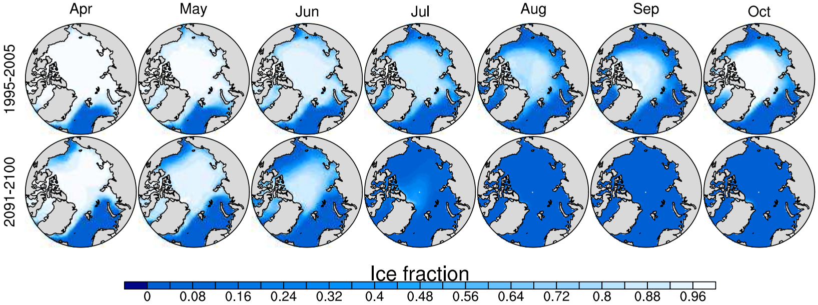
The Arctic Ocean

Seasonally ice-free Arctic under RCP8.5 (prognostic CO_2^{atm})

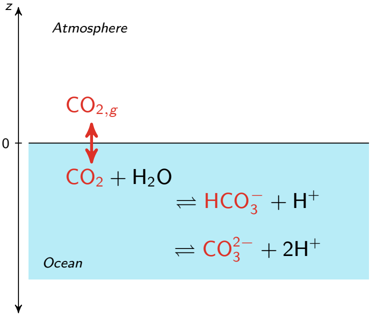


- How will changes in the physical climate system manifest in altered carbon and nutrient cycling in the Arctic?

Primary productivity enhances ocean carbon uptake

Organic matter formation

$$106\,CO_2 + 16\,HNO_3 + H_3PO_4 + 78\,H_2O \rightleftharpoons C_{106}H_{175}O_{42}N_{16}P + 150\,O_2$$



Dissolved inorganic carbon:

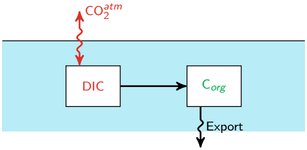
$$DIC \equiv [CO_2] + [HCO_3^-] + [CO_3^{2-}]$$

where [ ] denote concentrations in solution.

Solubility pump

$$[CO_2]_{sat} = f(T, S)$$

Biological pump

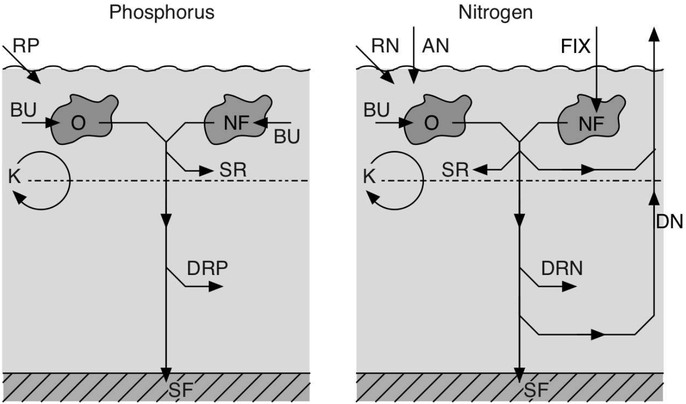


Nutrient availability regulates primary production

Organic matter formation (net primary production)

$$106\,CO_2 + 16\,HNO_3 + H_3PO_4 + 78\,H_2O \rightleftharpoons C_{106}H_{175}O_{42}N_{16}P + 150\,O_2$$

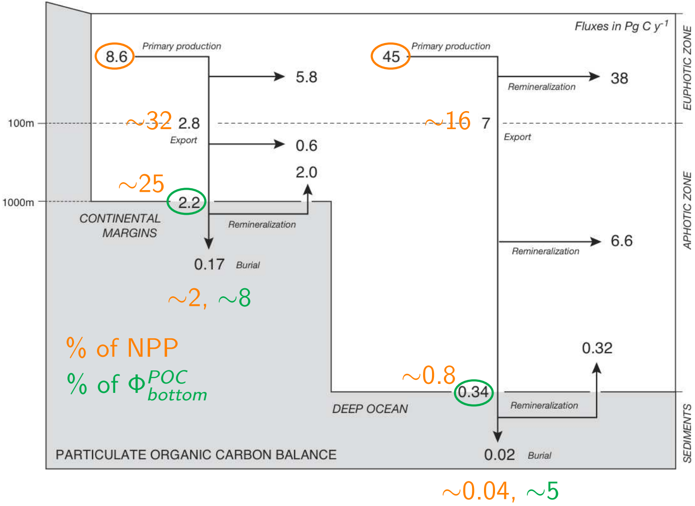
Regulation of oceanic N and P inventories



Tyrrell 1999

Export and burial are most efficient on continental margins

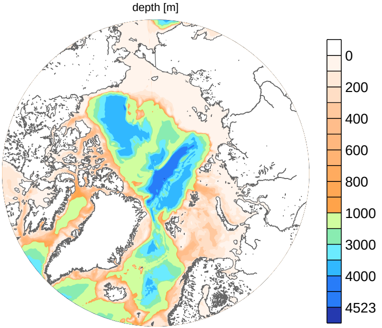
Global ocean particulate organic carbon budget

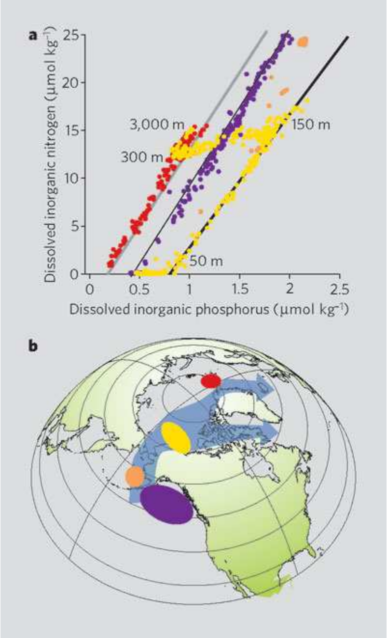


Sarmiento & Gruber 2006

Strong benthic-pelagic coupling

25% of ocean sediments above 200 m



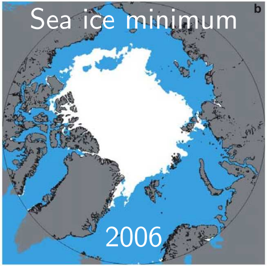


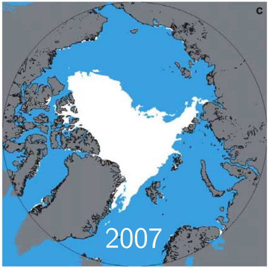
Yamamoto-Kawai 2006

Sedimentary denitrification

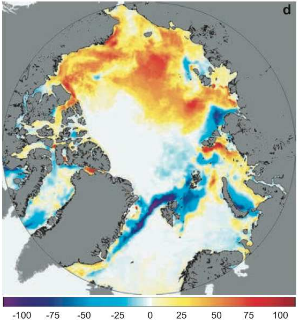
N deficiency develops as waters flow from the Pacific to Atlantic. } →

Hypotheses: Longer growing season → increased NPP

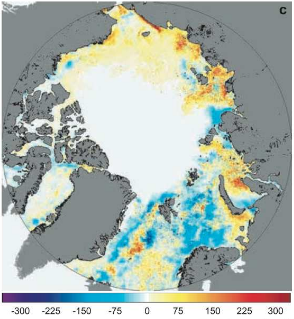




Arrigo et al. 2008



Δ(Growing season) [days]

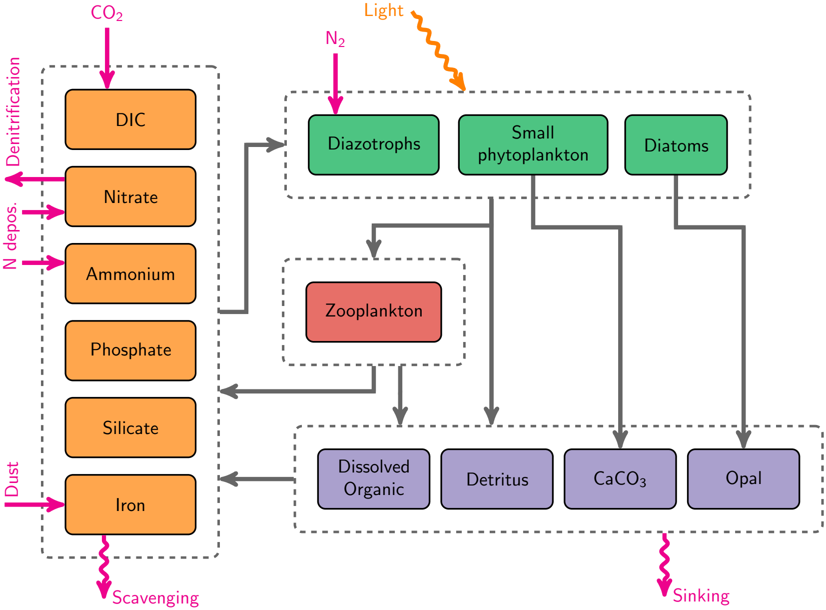


Δ(NPP) [g C m^{-2} yr^{-1}]

Less ice, longer season → more NPP

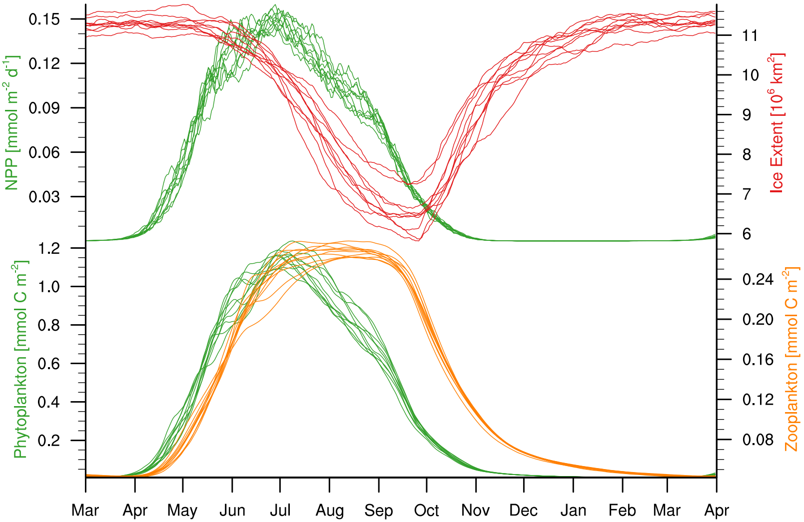
In the future will:
→ Δ(NPP) $\propto$ Δ(Ice)?
→ greater NPP = more export?

CESM1 biogeochemistry



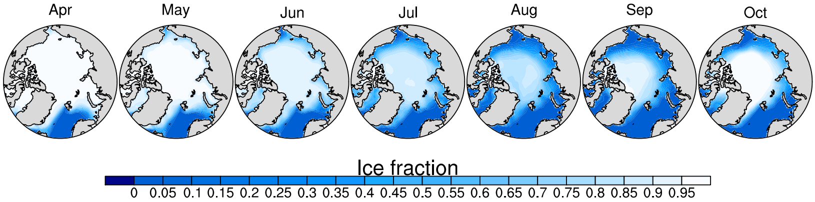
Arctic biogeochemical system: CESM1 1995–2005

Annual cycle

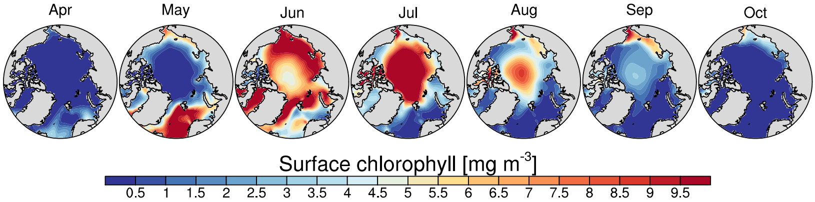


Bloom begins over continental shelves, follows ice retreat into central basin

Sea-ice climatology

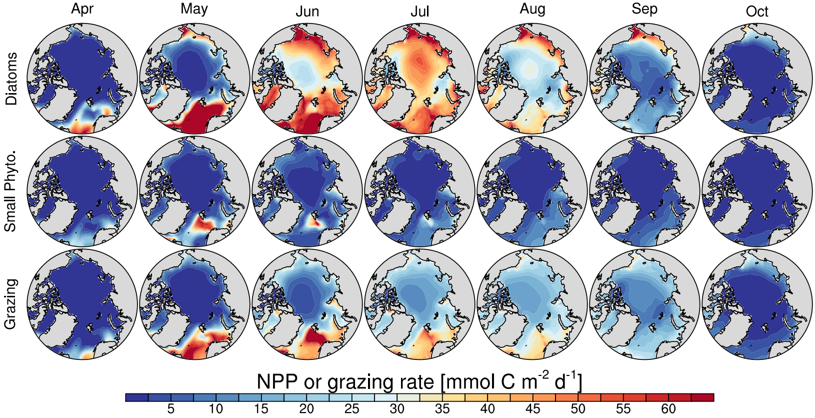


Surface chlorophyll



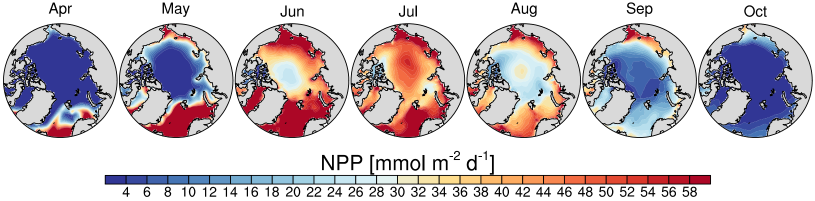
Diatoms dominate, grazing rates are relatively low

Community composition

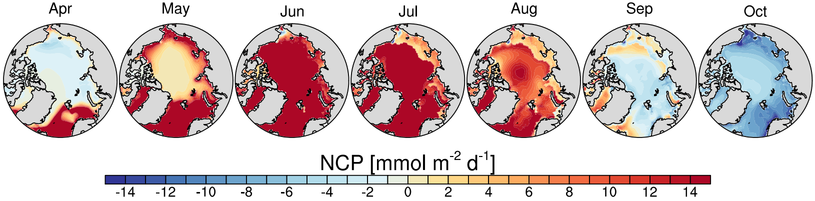


Autotrophic summer, heterotrophic winter

Net primary productivity (above 100 m)



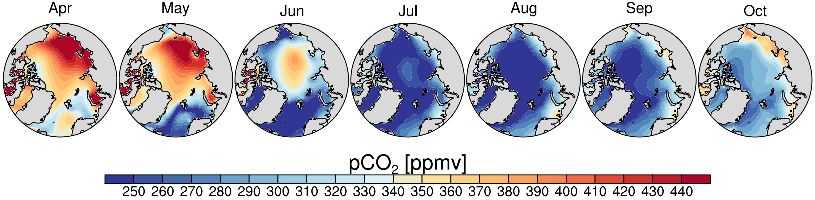
Net community production (above 100 m)



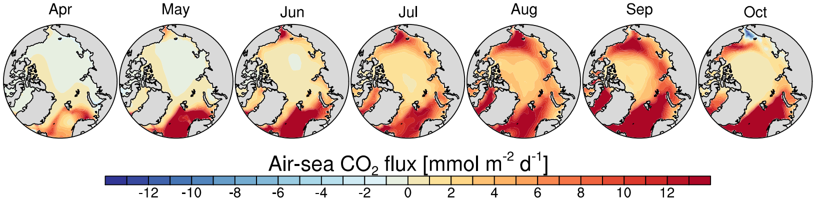
NCP = NPP − Respiration

NPP drives summer influx, sea ice impedes winter exchange

Surface ocean pCO_2

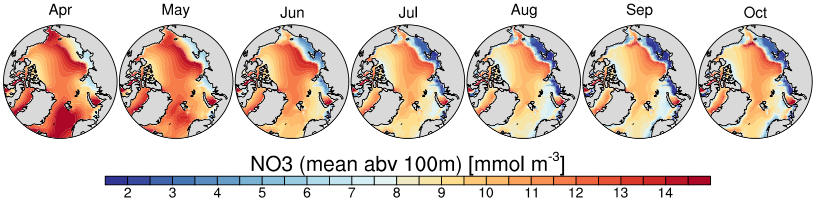


Air-sea CO_2 flux (positive downward)

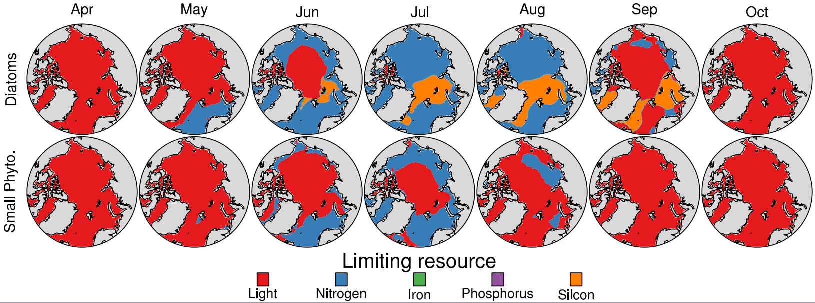


Surface nutrient depletion and light limitation

Nitrate above 100 m

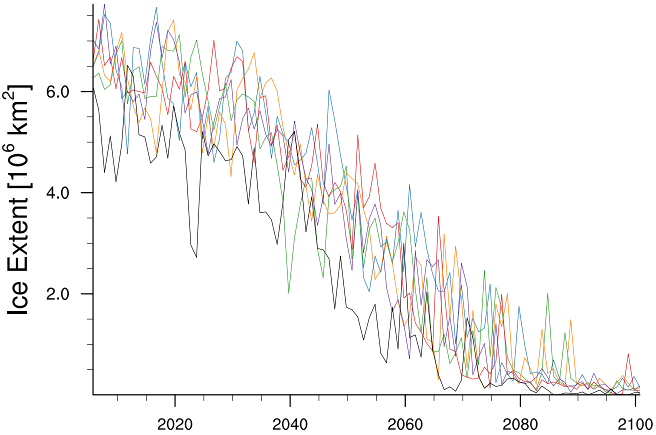


Most limiting resource



Arctic biogeochemical system: RCP 8.5 2091–2100

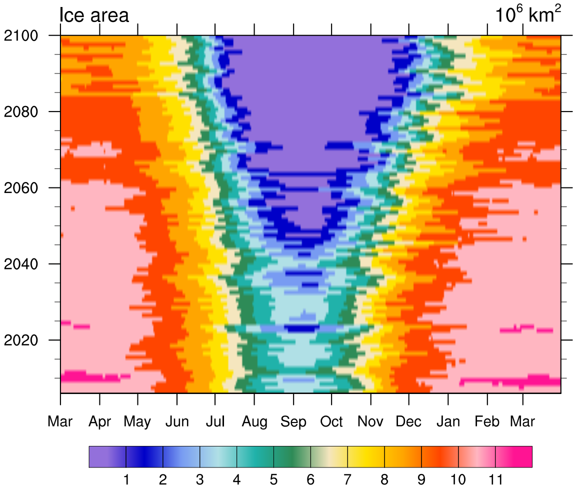
September sea ice extent under RCP 8.5



black line: RCP 8.5 (prognostic CO_2^{atm})

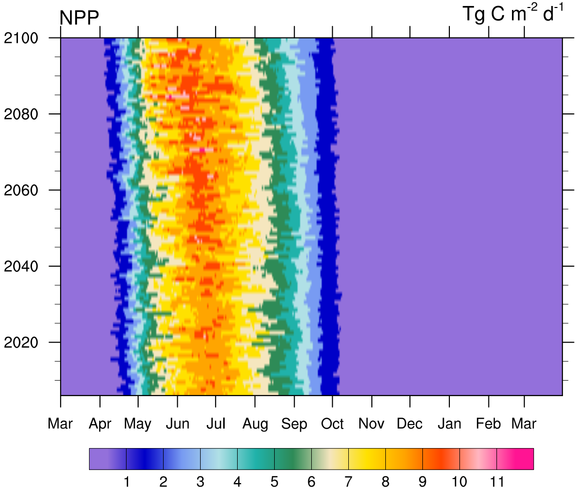
colored lines: CCSM4 ensemble members

Arctic biogeochemical system: RCP 8.5 2091–2100



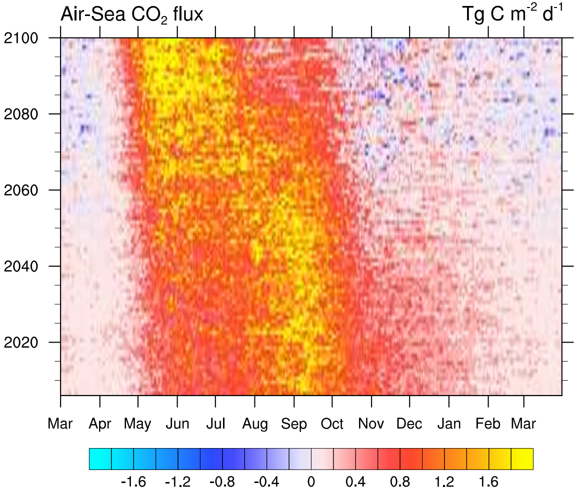
Seasonally ice free by mid-century

Arctic biogeochemical system: RCP 8.5 2091–2100



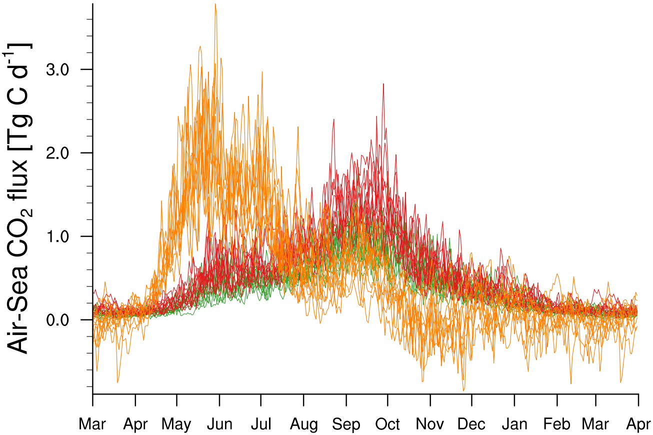
Bloom intensity increases, shifts to earlier in Spring.

Arctic biogeochemical system: RCP 8.5 2091–2100



Peak in CO_2 uptake occurs earlier; Arctic Ocean becomes a weak sources during Winter.

Arctic biogeochemical system: RCP 8.5 2091–2100



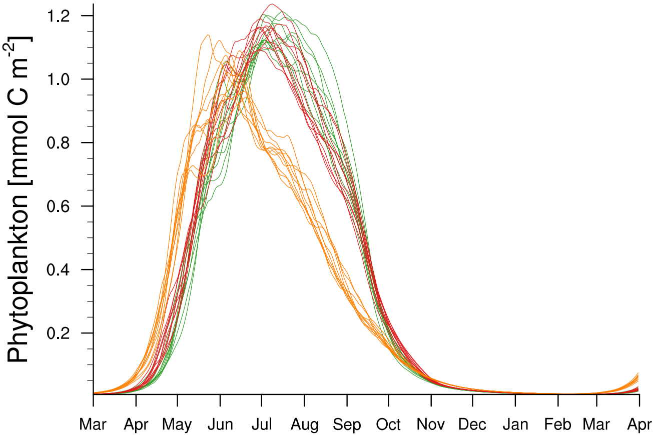
Still a net annual sink; variance increases.

orange: RCP8.5

red: 20th

green: 1850

Arctic biogeochemical system: RCP 8.5 2091–2100



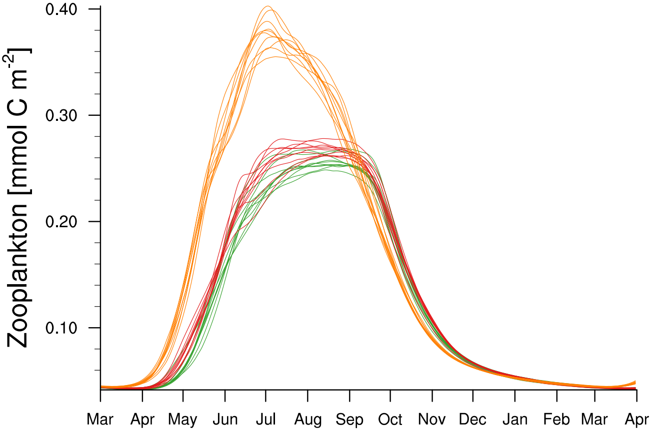
Rates of NPP increase, yet there is phytoplankton biomass.

orange: RCP8.5

red: 20th

green: 1850

Arctic biogeochemical system: RCP 8.5 2091–2100



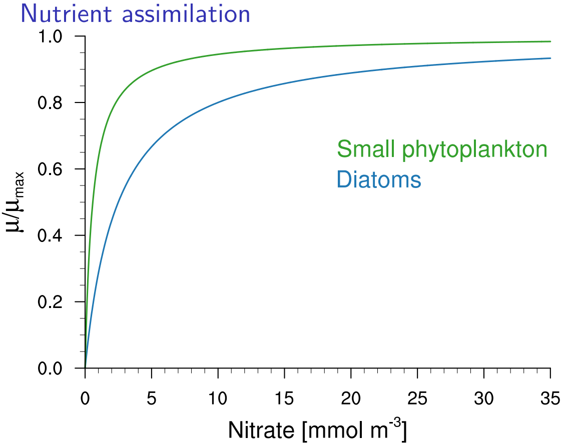
Grazing pressure increases.

orange: RCP8.5

red: 20th

green: 1850

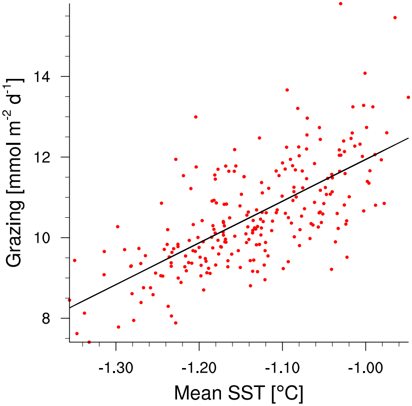
Variable physiology, local selection



Since small phytoplankton are more efficient at low $[NO_3^-]$, they are likely to benefit as light limitation is alleviated.

Temperature sensitivity of trophic coupling

Grazing in 1850-control (May):

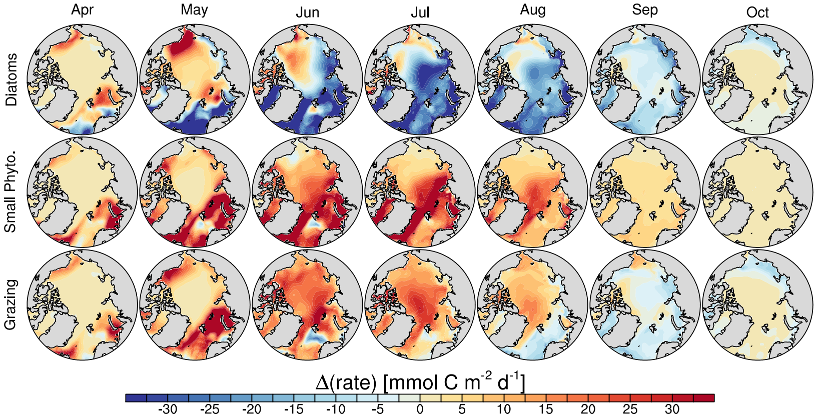


slope = 0.012 mmol m^{-2} d^{-1} $^\circ C^{-1}$, $r^2 = 0.458$

Tighter trophic coupling in upper water column leads to less carbon available for export.

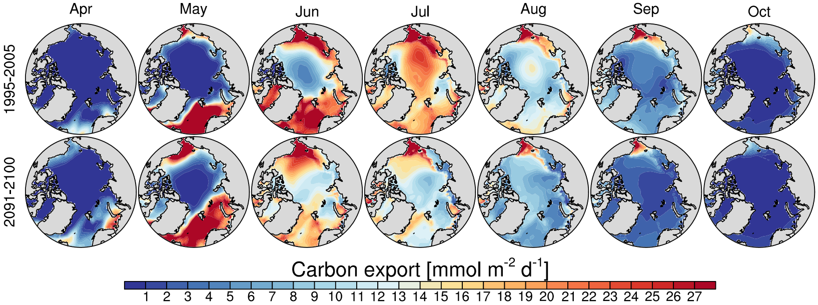
Small phytoplankton ascendency; more grazing

(2091-2100) – (1995-2005)



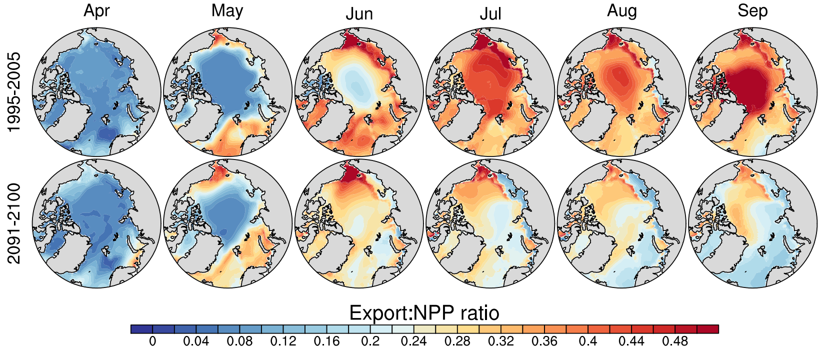
Reductions in export

Fate of fixed carbon

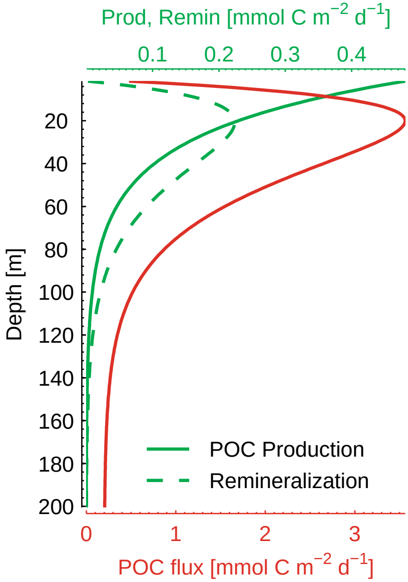


Reductions in export

Export ratio declines



CESM's export production

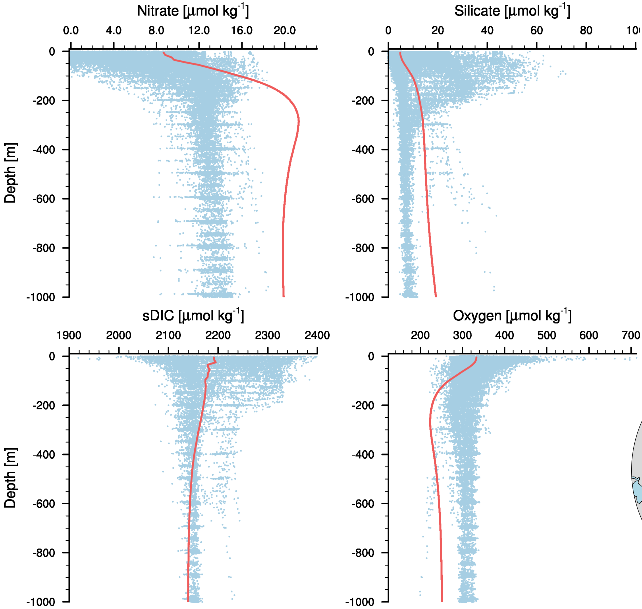


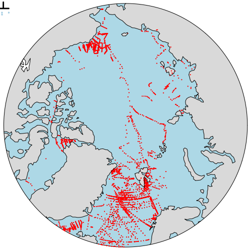
Export is an empirical function of production [*Armstrong et al. 2002*]:

$$\Phi(z) = C_\infty + (C_0 - C_\infty)\exp\left(\frac{z_0 - z}{z^*}\right)$$

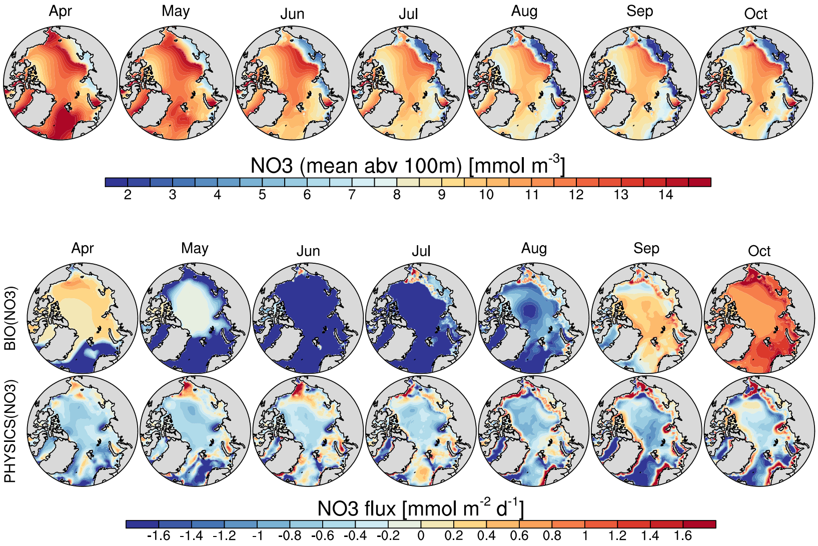
No burial or sediment denitrification: material reaching the bottom layer is remineralized in a single timestep.

Nutrient biases: CARINA data



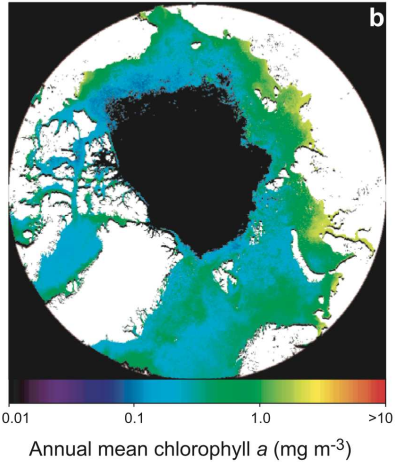


Arctic nutrient budgets: NCP and resupply



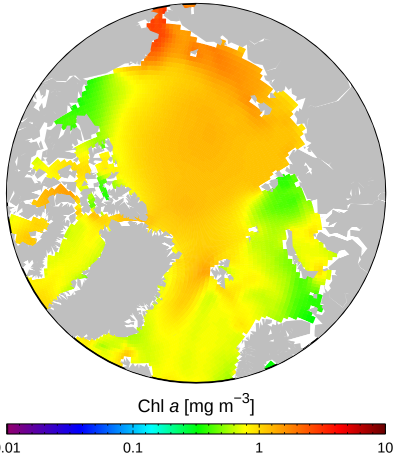
Indications of too much chlorophyll

SeaWiFS climatology (1998–2006)



Pabi et al. 2008

CESM climatology



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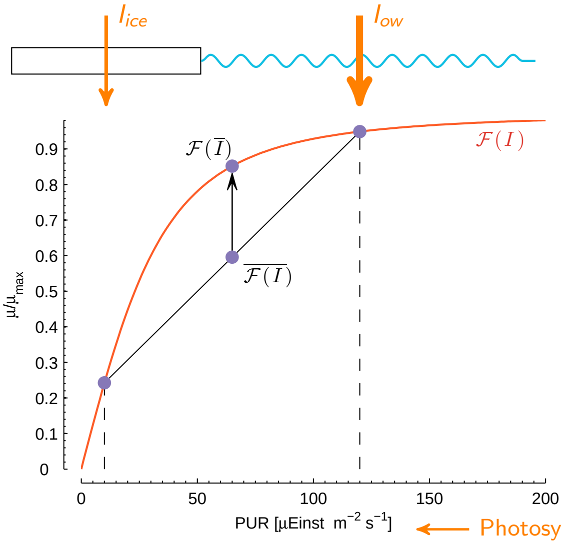
Photosynthesis-irradiance relationship: $f(x+y) \neq f(x) + f(y)$

Subgrid scale heterogeneity



← Photosynthetically usable radiation

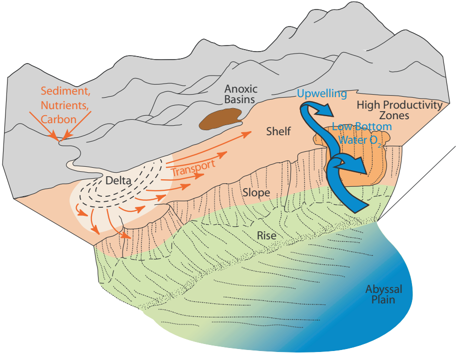
Photosynthetic rates computed from spatially averaged irradiance over predict true rates.

μ = growth rate

μ_{max} = temperature/ nutrient limited growth

Summary

- Reduced sea ice leads to increased pan-Arctic NPP; export, however, is less efficient.
- CESM1 cannot currently assess the impact of altered export rates on nutrient cycles.



- Biases in nutrient fields are substantial; adding burial and denitrification may help.
- Improved handling of light limitation in heterogenous ice cover will reduce chlorophyll (and hence NPP) biases.
- Careful examination of the temperature dependence of metabolic rates is required.