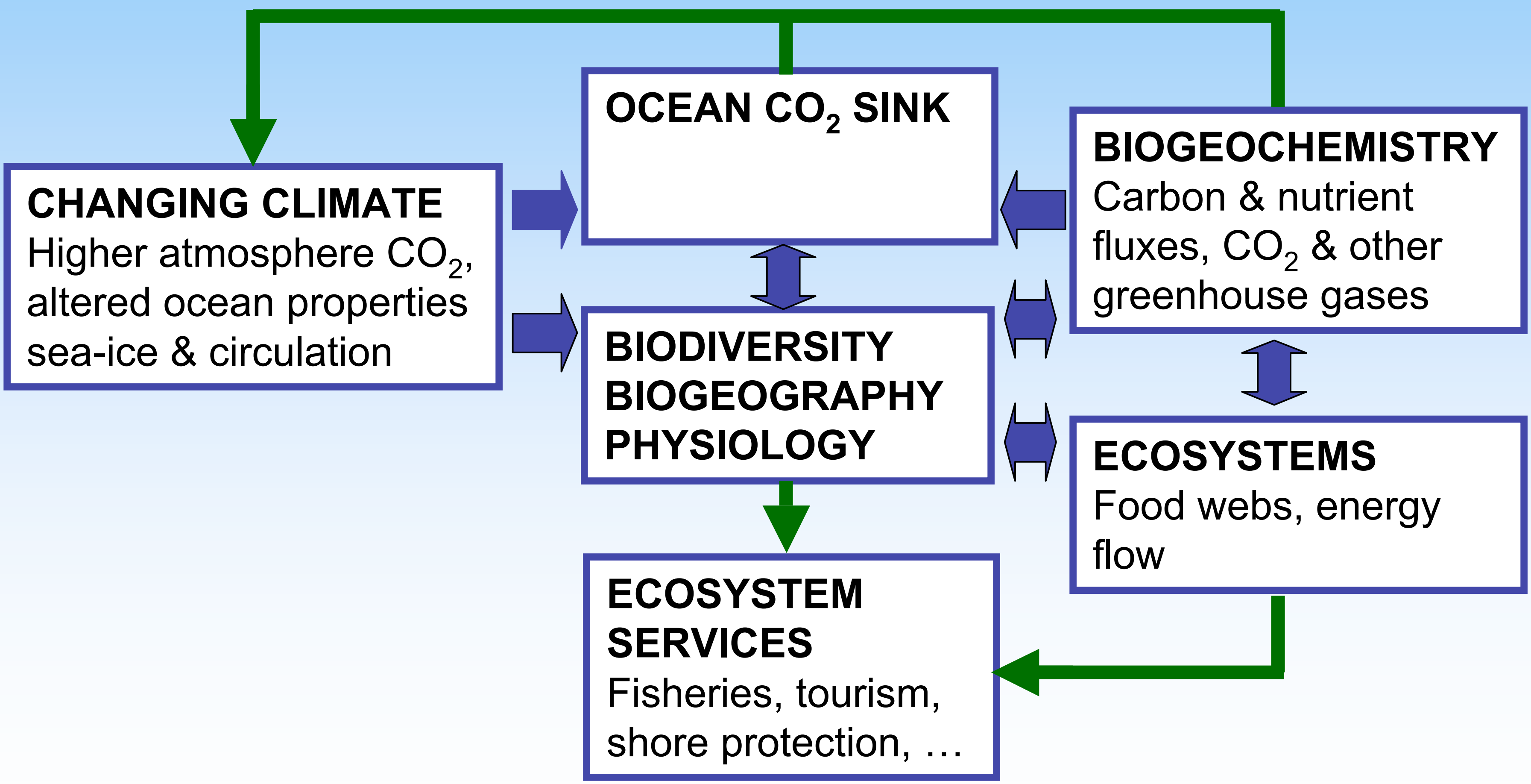
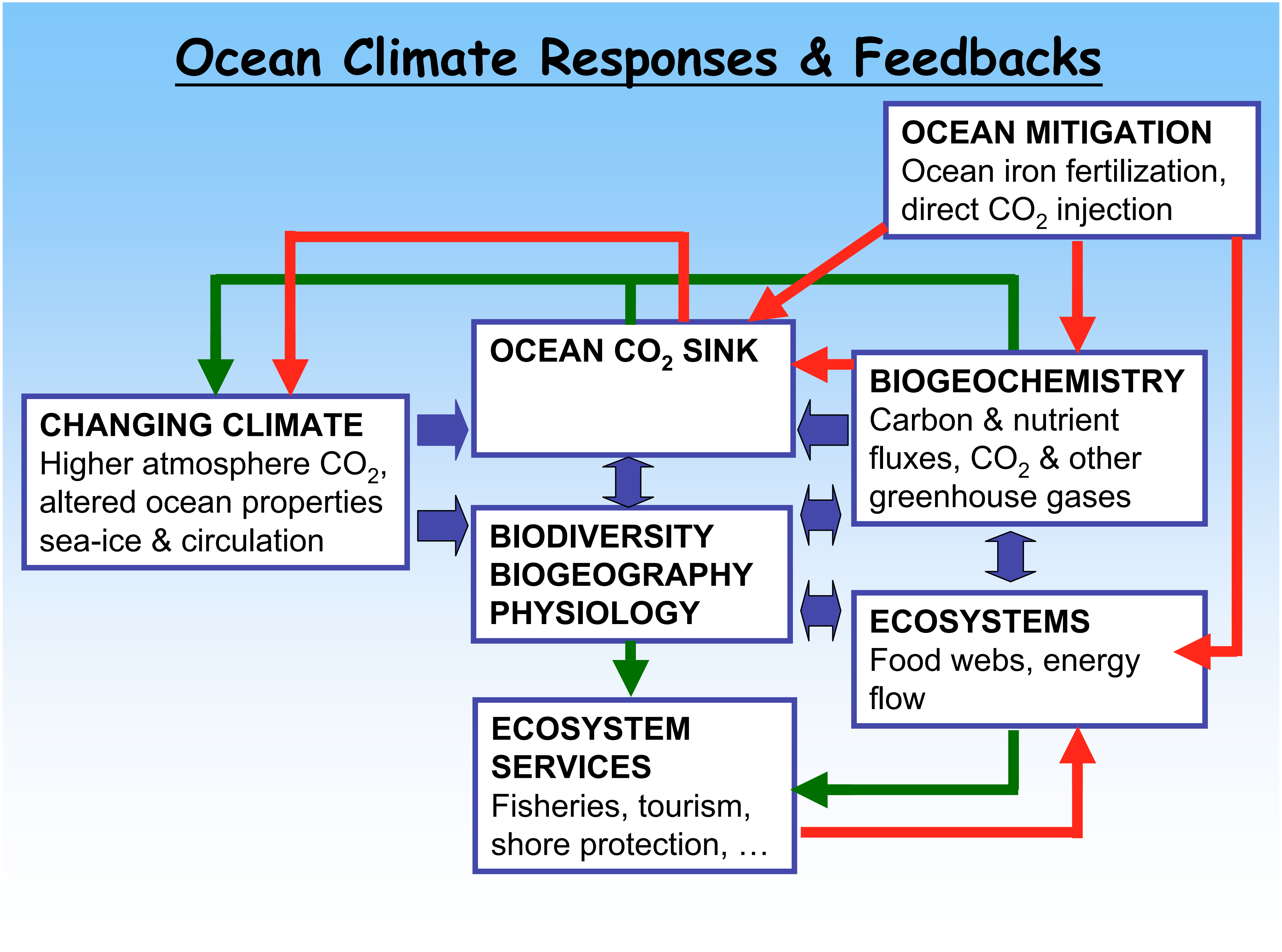
The Future Ocean Under High CO_2

Scott Doney
Woods Hole Oceanographic Institution

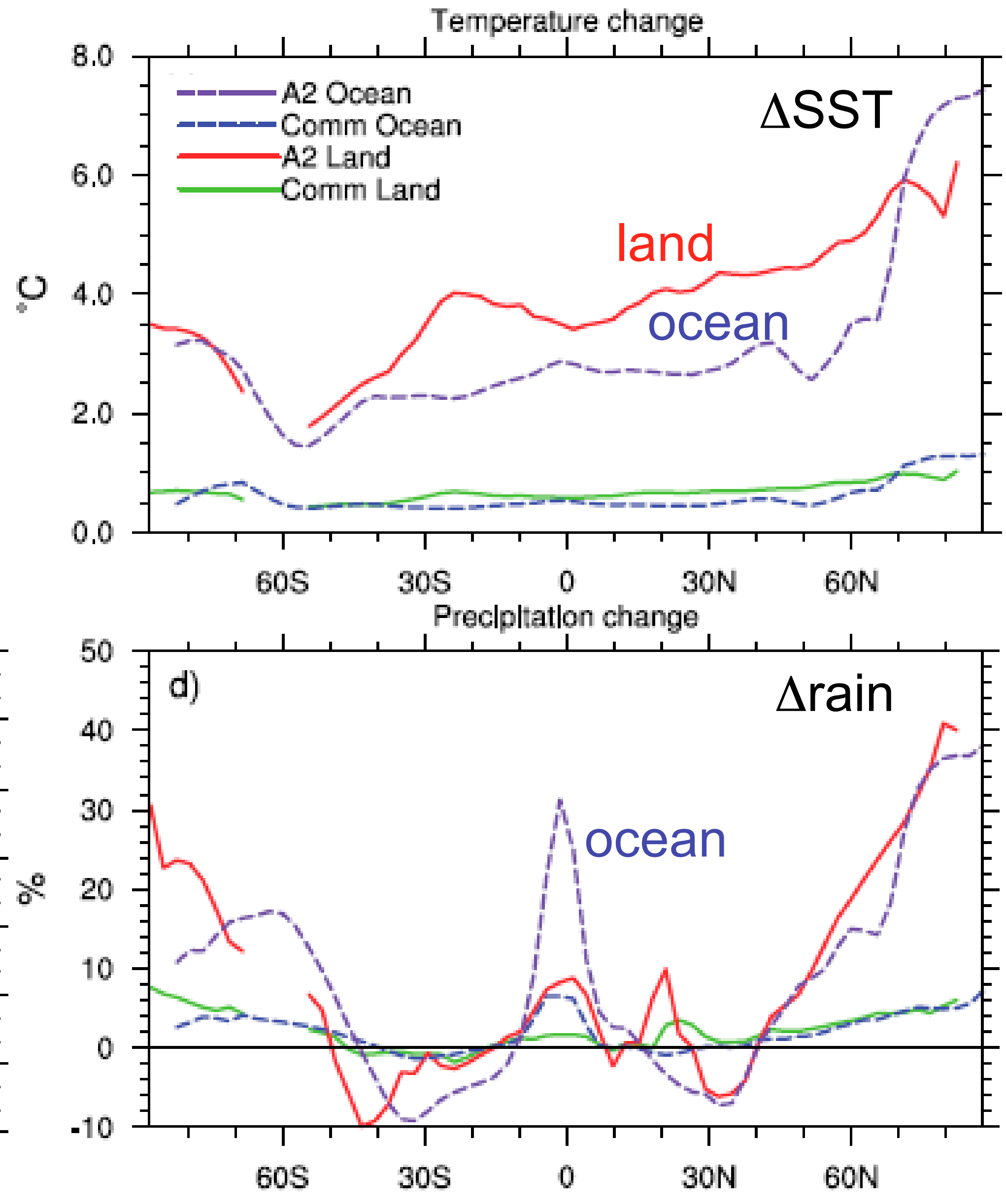
Ocean Climate Responses & Feedbacks




Ocean Climate Responses & Feedbacks
OCEAN MITIGATION
Ocean iron fertilization, direct CO_2 injection
OCEAN CO_2 SINK
CHANGING CLIMATE
Higher atmosphere CO_2, altered ocean properties sea-ice & circulation
BIOGEOCHEMISTRY
Carbon & nutrient fluxes, CO_2 & other greenhouse gases
BIODIVERSITY
BIOGEOGRAPHY
PHYSIOLOGY
ECOSYSTEMS
Food webs, energy flow
ECOSYSTEM SERVICES
Fisheries, tourism, shore protection, …

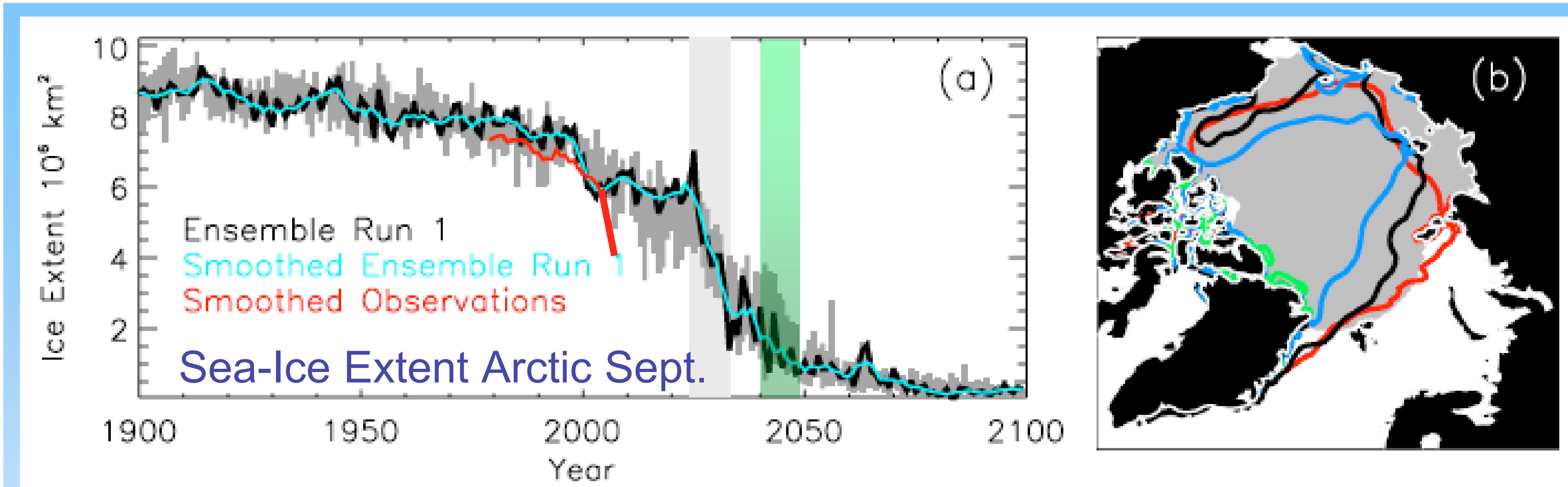
Spatial Patterns of Climate Change

zonal means; 2080-2099 minus 1980-1999



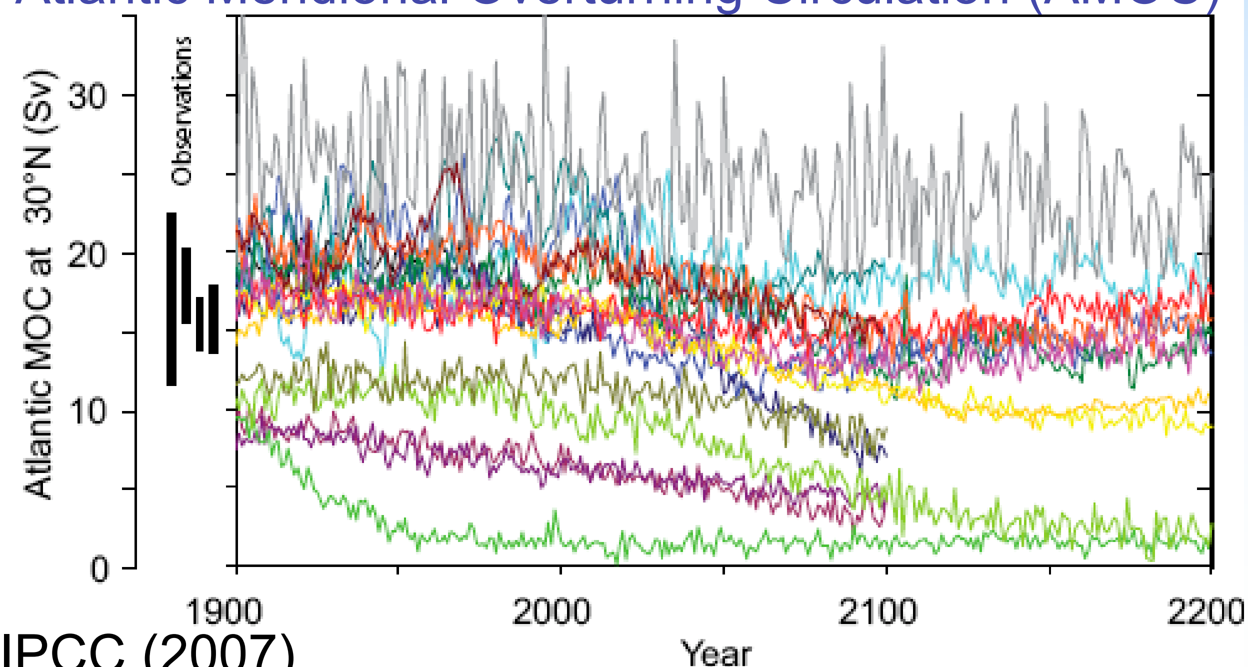
- poles warm faster than tropics
- freshening in tropics & poles from more rain and sea-ice melt
- increased surface stratification
- sea-level rise

IPCC (2007)



Holland et al., Geophysical Res. Lett. (2006)

Atlantic Meridional Overturning Circulation (AMOC)



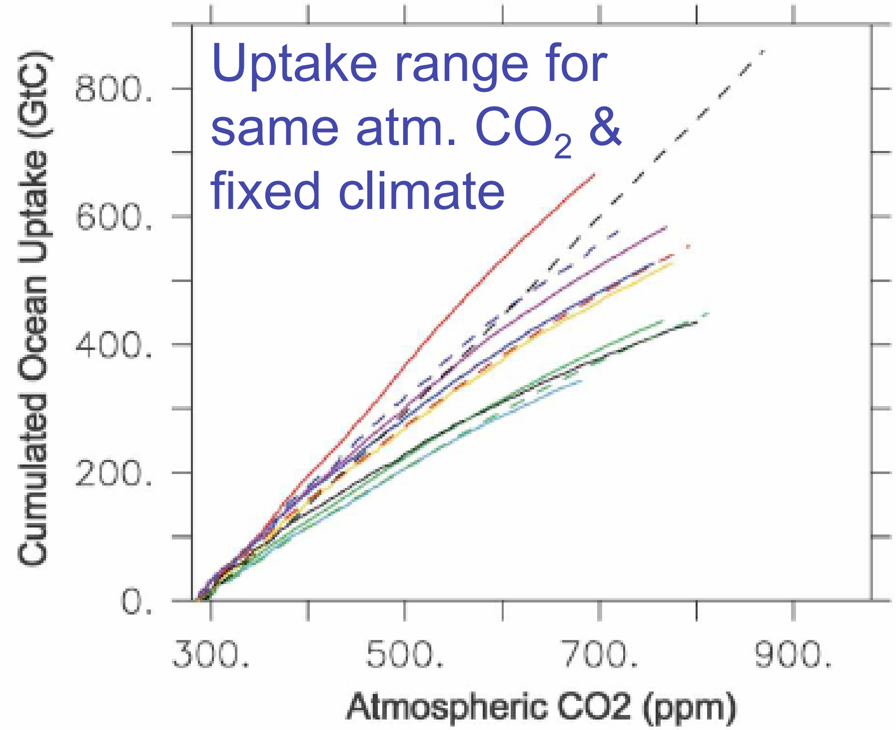
IPCC (2007)

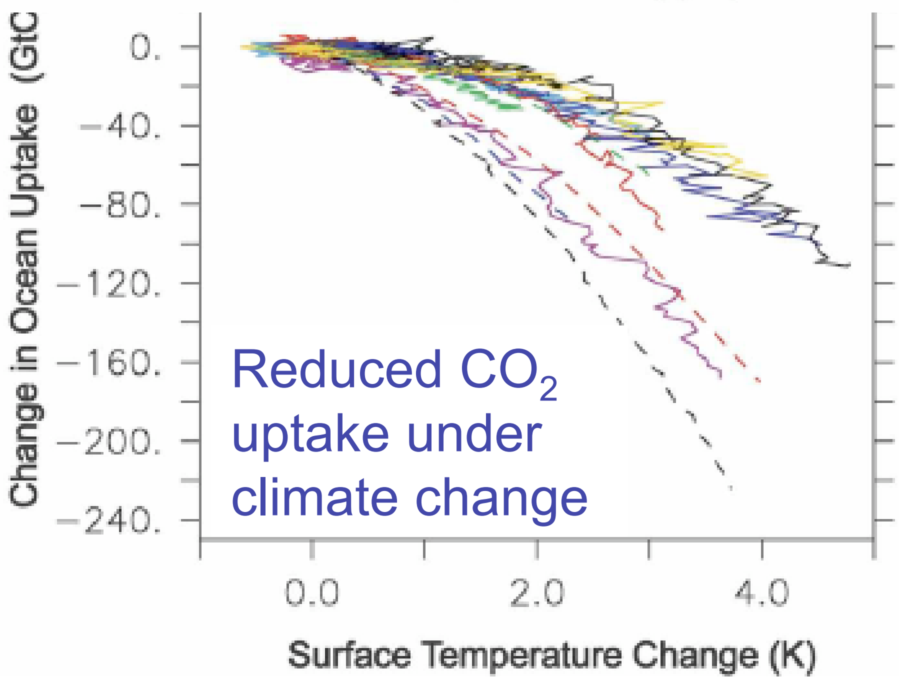
-Ice-free summer Arctic by ~2050

-Lower formation of North Atlantic deep-water but abrupt shutdown of AMOC unlikely

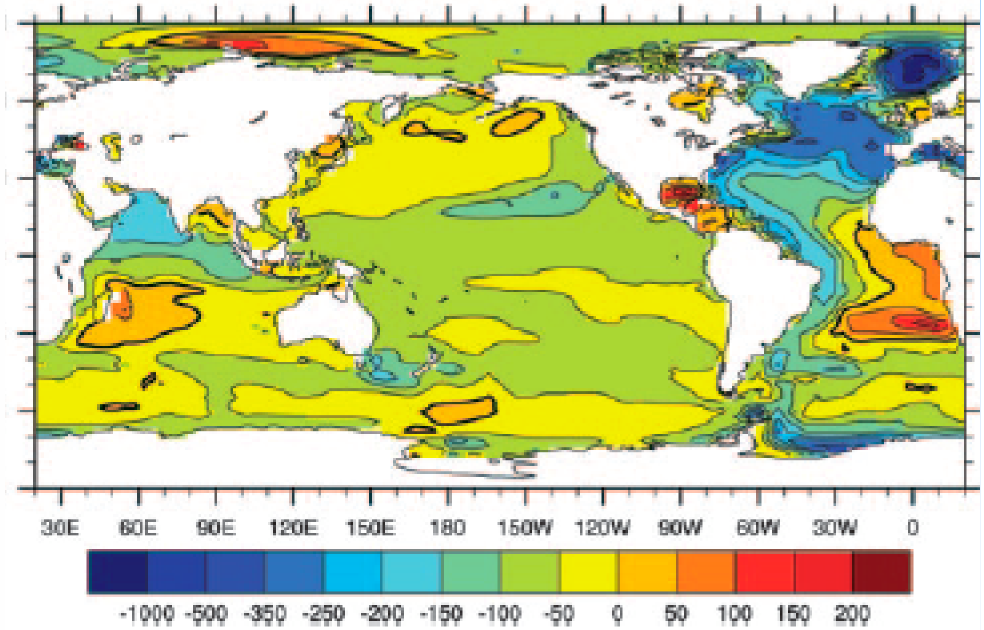
-Slower ocean CO_2 uptake & warming

Ocean CO_2 Sink & Climate Feedbacks





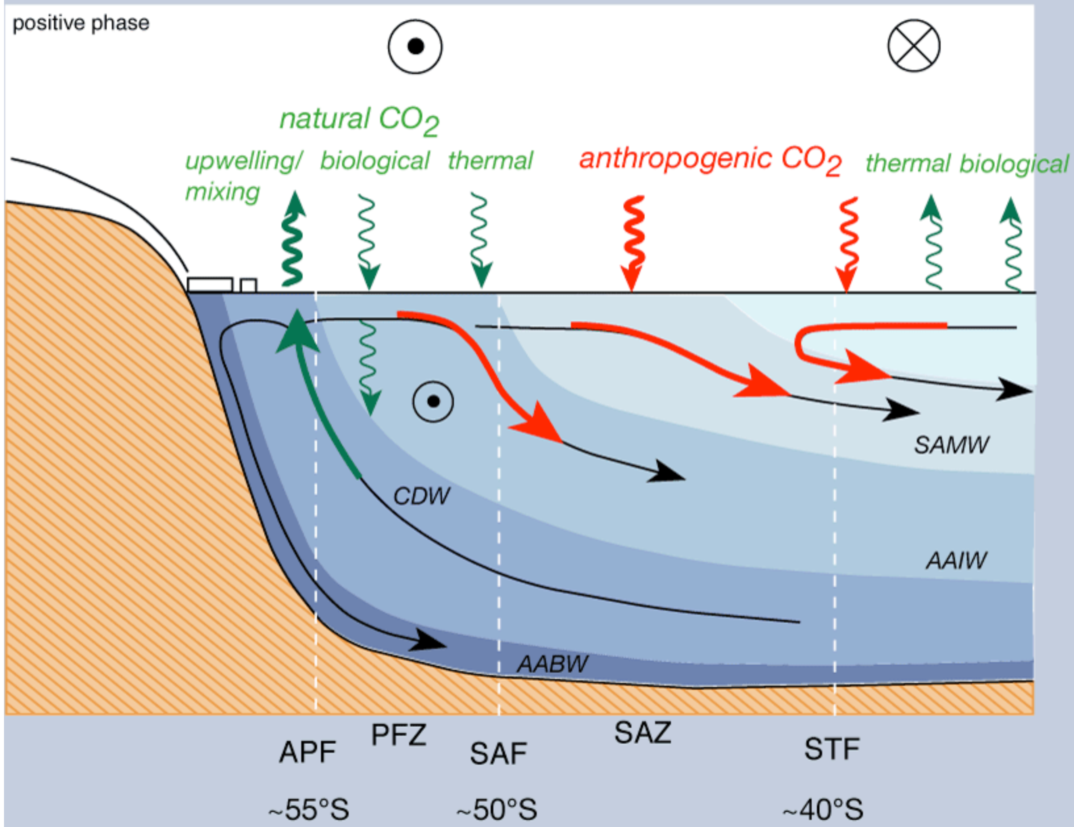
Lower uptake due to warming, stratification & weaker deep-water formation in N. Atlantic and Antarctic

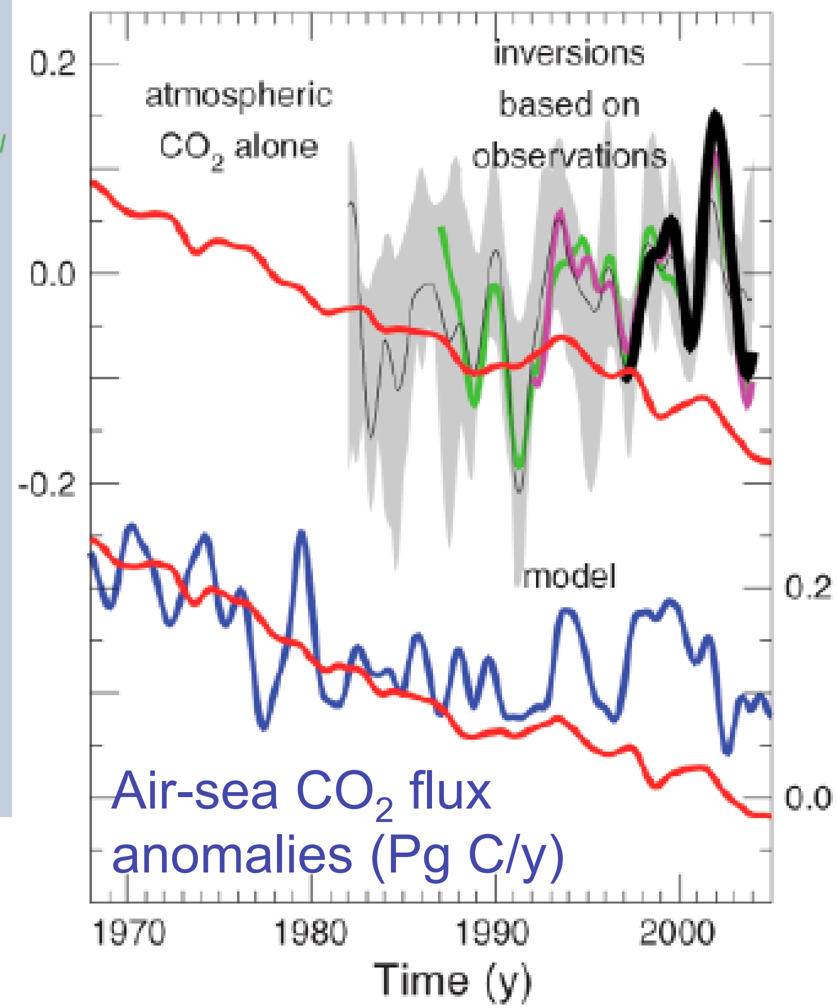


Fung et al., Proc. Nat. Acad. Sci. (2005); Friedlingstein et al., J. Climate (2006)

WOODS HOLE OCEANOGRAPHIC INSTITUTION 1930

Stengthening of Southern Annular Mode (SAM)



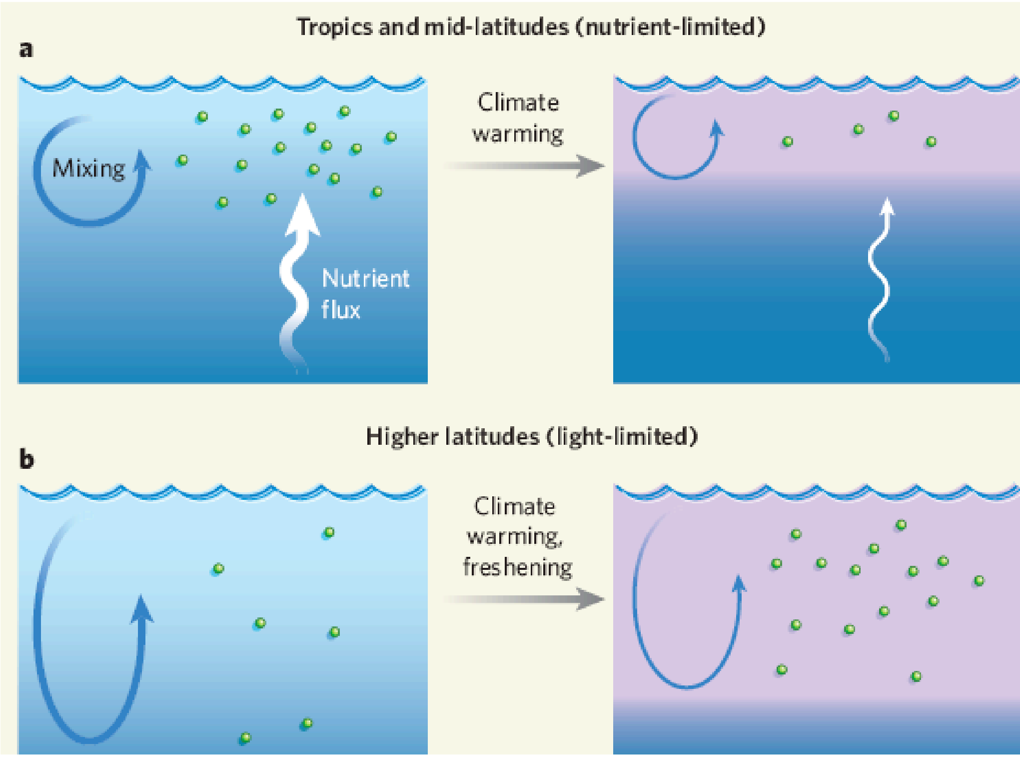


-positive SAM from atm. ozone and CO_2 trends

-natural CO_2 efflux > anthro. CO_2 uptake

-net decrease in effectiveness

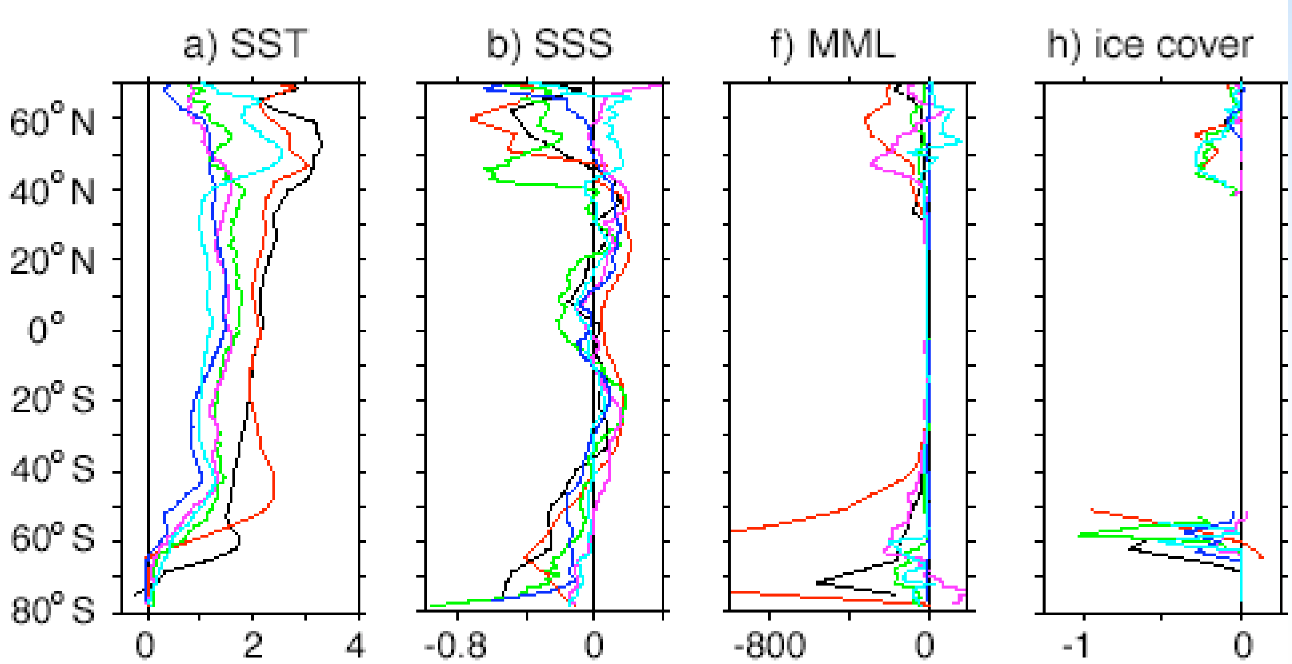
Le Quere et al., Science (2007)
Lovenduski et al., Global Biogeochem. Cycles (2007; submitted)

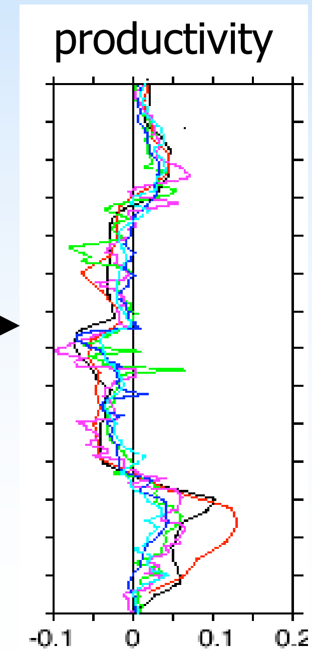


-stratification alters mixed layer depth (light) and nutrient supply

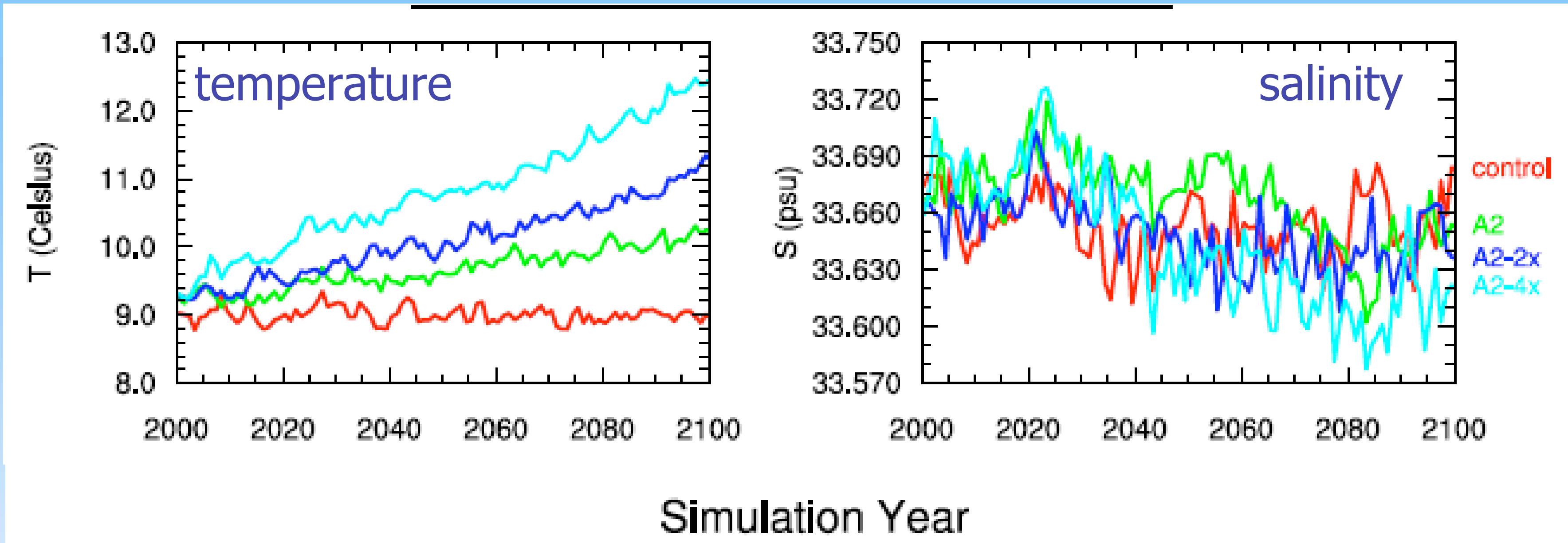
-primary productivity lower in subtropics, higher in subpolar gyres

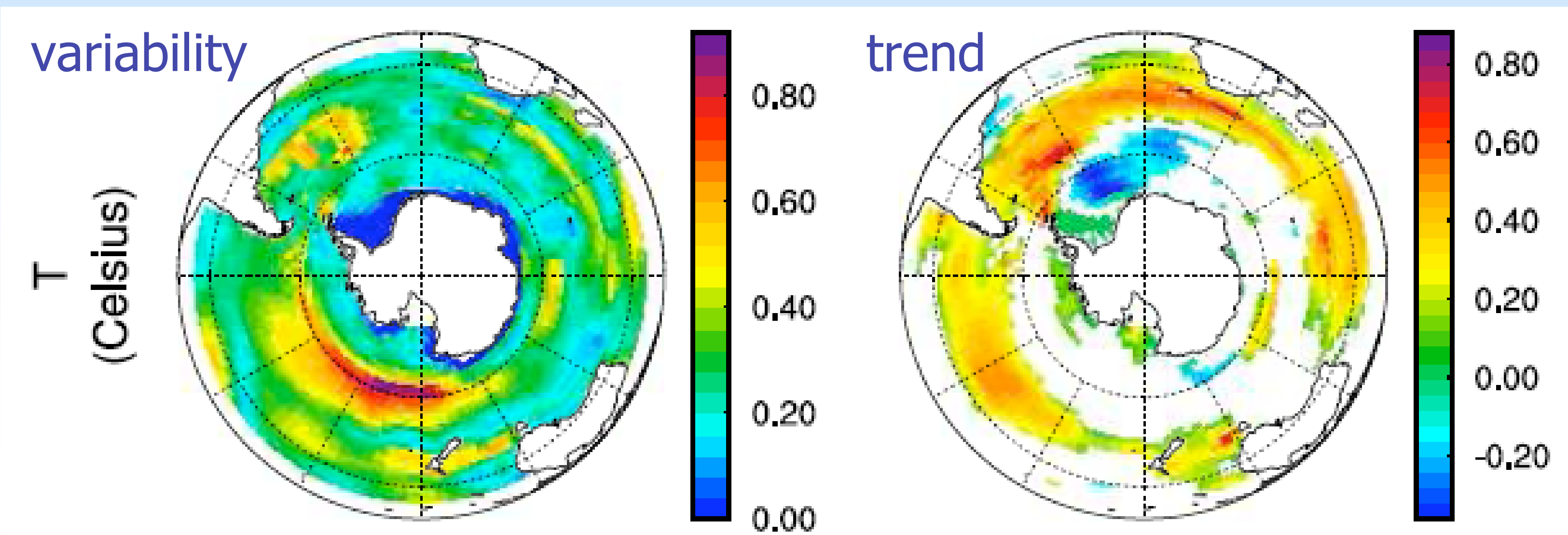
Doney, Nature (2006); Sarmiento et al., Global Biogeo. Chem. (2004)





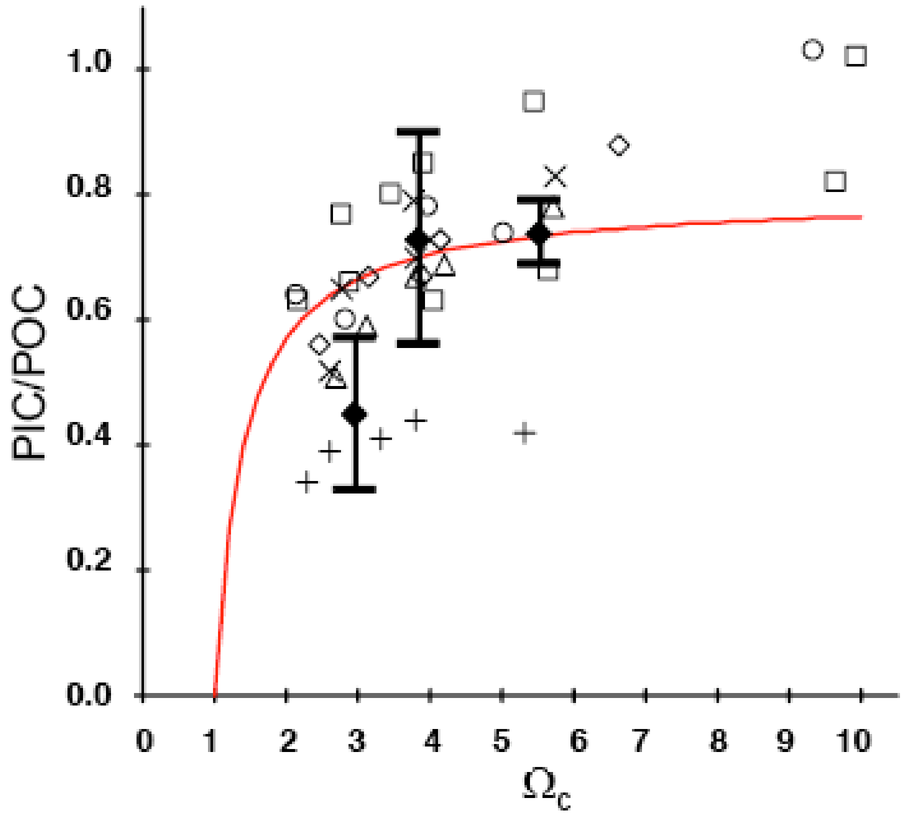
Detection & Attribution

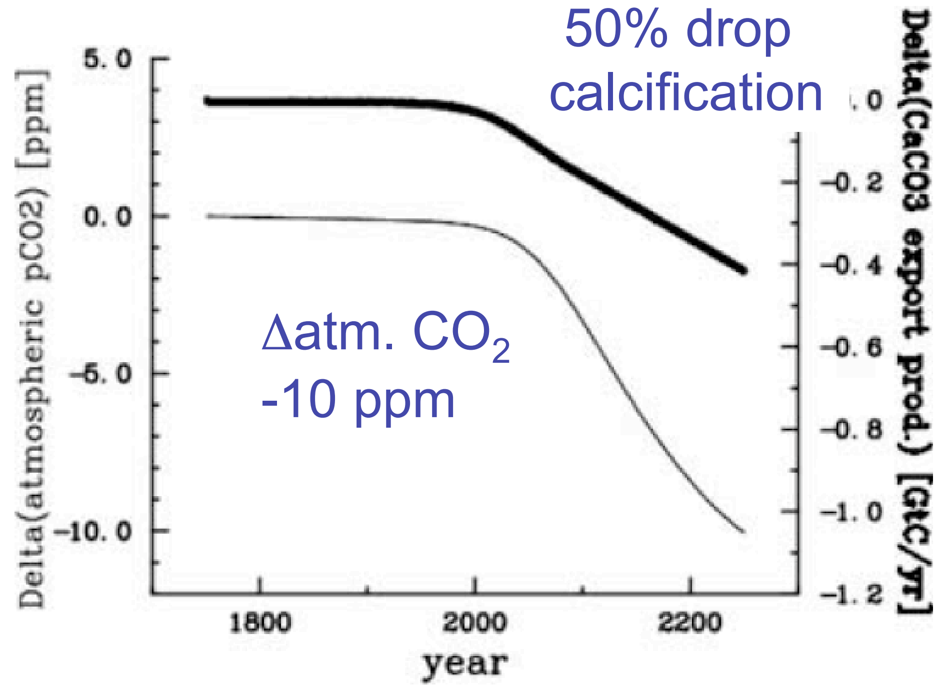




Boyd et al., Biogeosciences (submitted)

CO_2 & Calcification





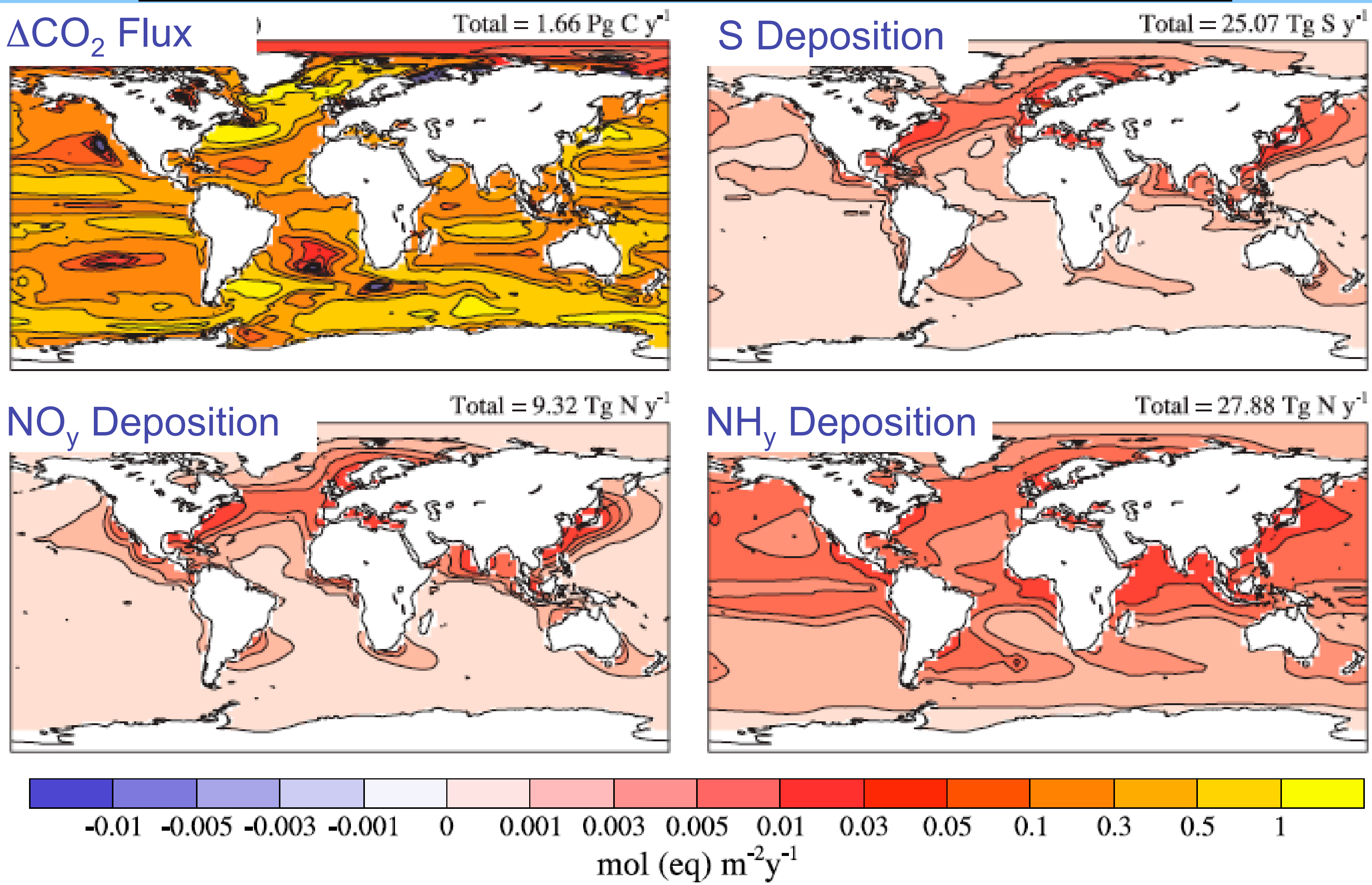
Gehlen et al. Biogeosciences (2007)

Heinze, Geophys. Res. Lett. (2004)

- Reduced formation of biogenic $CaCO_3$
- Decrease organic remineralization lengthscale (ballasting)
- Increase subsurface $CaCO_3$ dissolution surface
- Negative (damping) climate feedback

(Δ atm. $CO_2 < 0$; $\Delta DIC_{surf} < 0$, $\Delta Alk_{surf} > 0$)

Acid Rain & Coastal Ocean Acidification

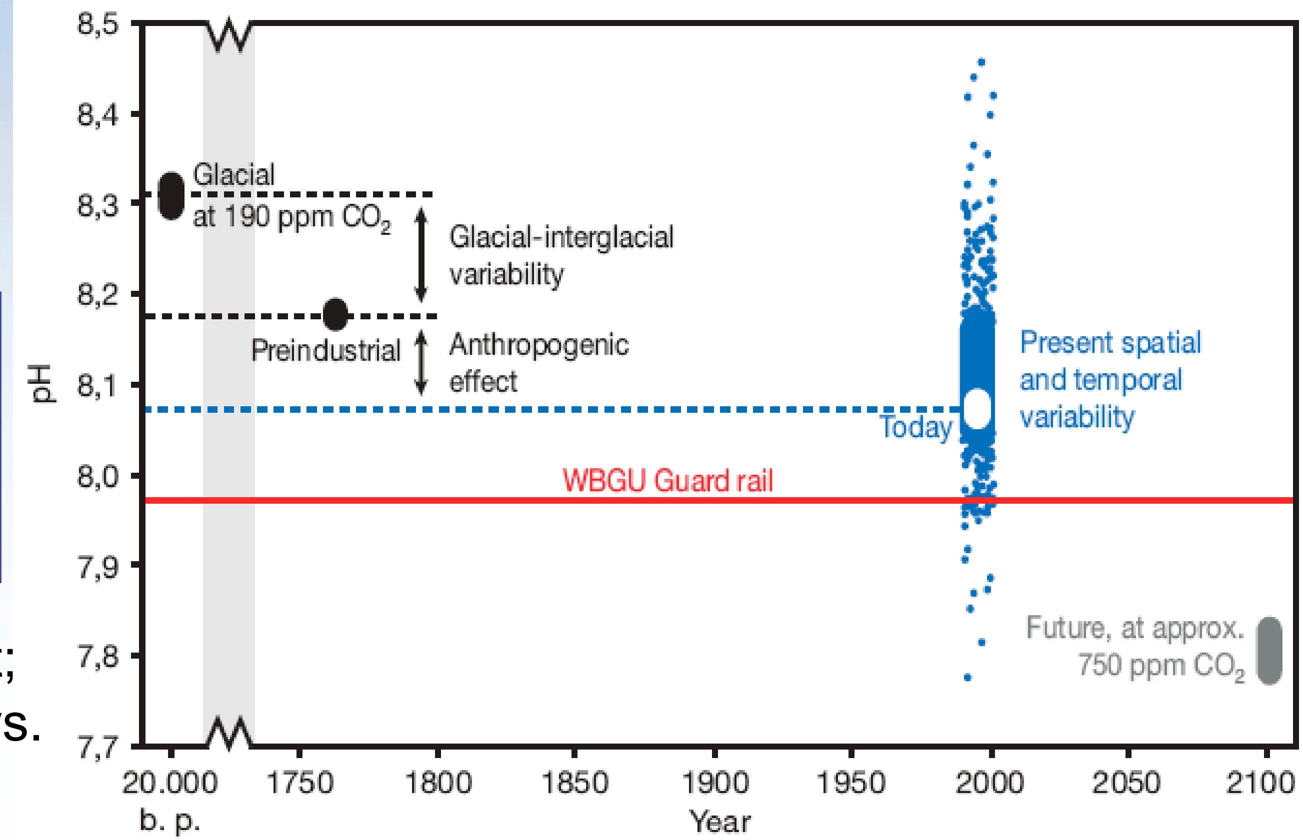


Doney et al., Proc. Nat. Acad. Sci. (2007)

4.4.1
Proposed guard rail

To prevent undesirable or high-risk changes to the marine food web due to aragonite undersaturation (Section 4.3), the pH value of near surface waters should not drop more than 0.2 units below the pre-industrial average value of 8.18 in any larger ocean region (nor in the global mean). A pH drop of 0.2

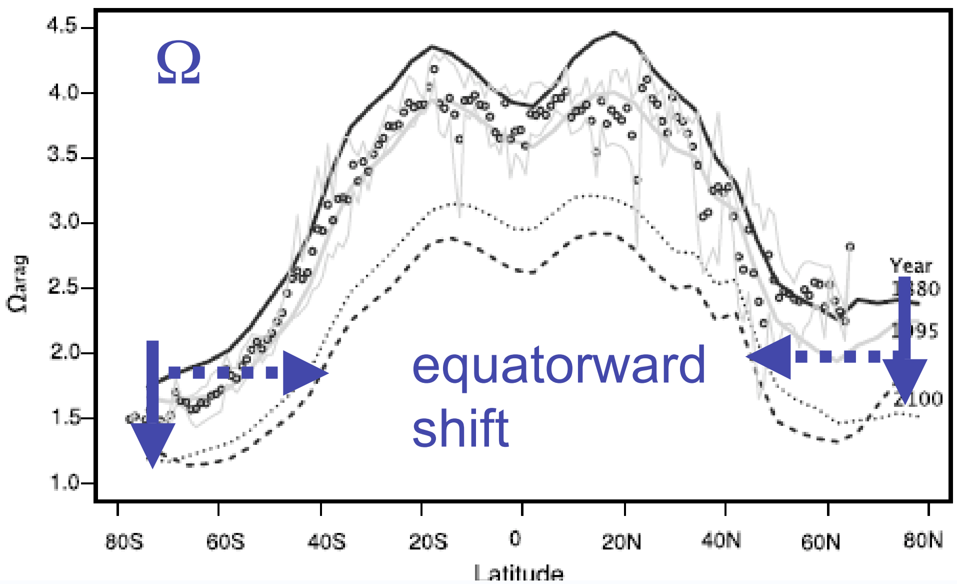
U.S. EPA Quality Criteria for Water
<0.2 pH change
<500 ppm atm. CO_2

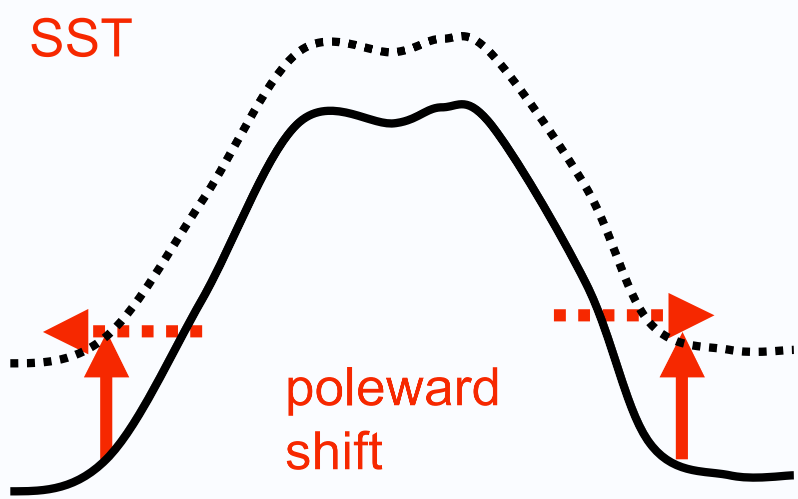


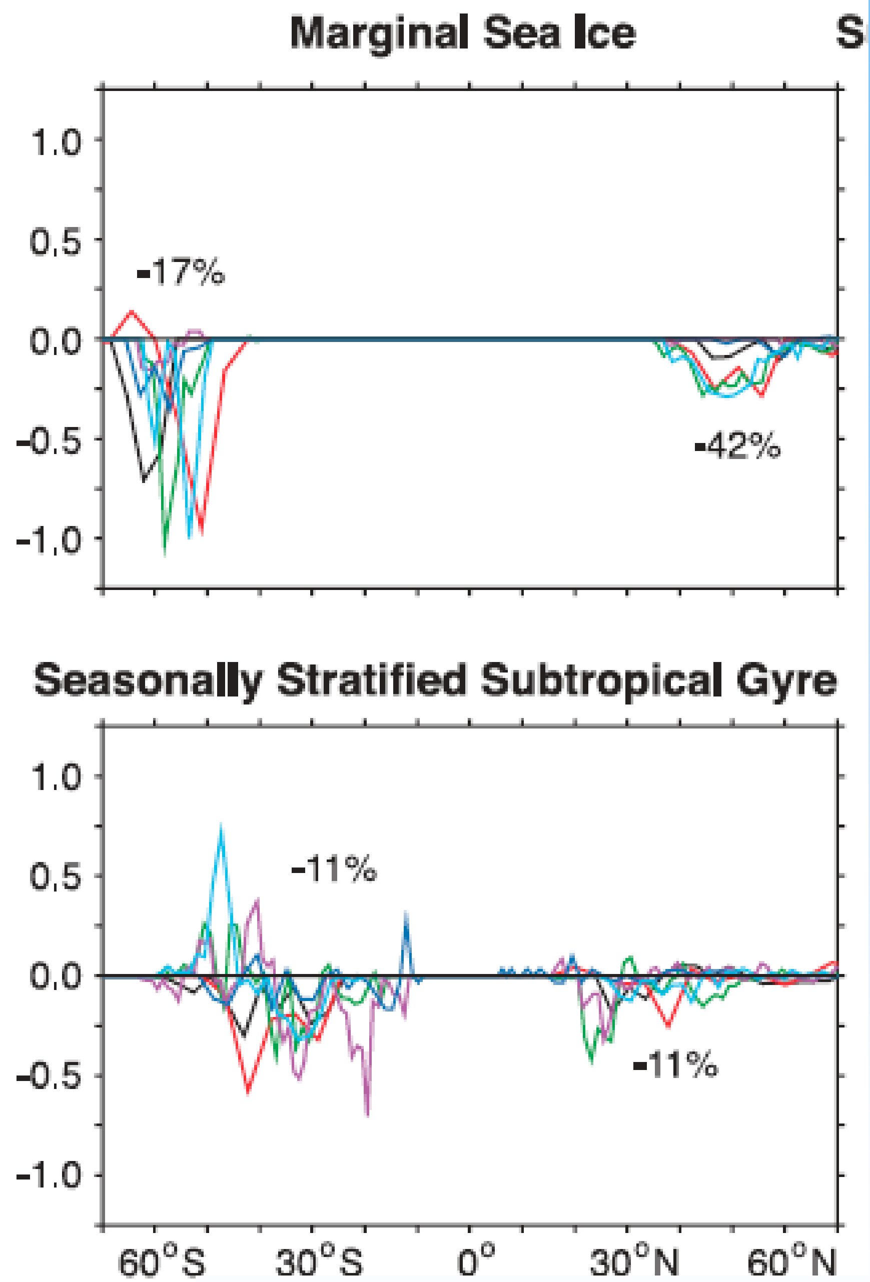
WBGU Special Report; Caldeira et al. Geophys. Res. Lett. (2007).

Ecological Niches

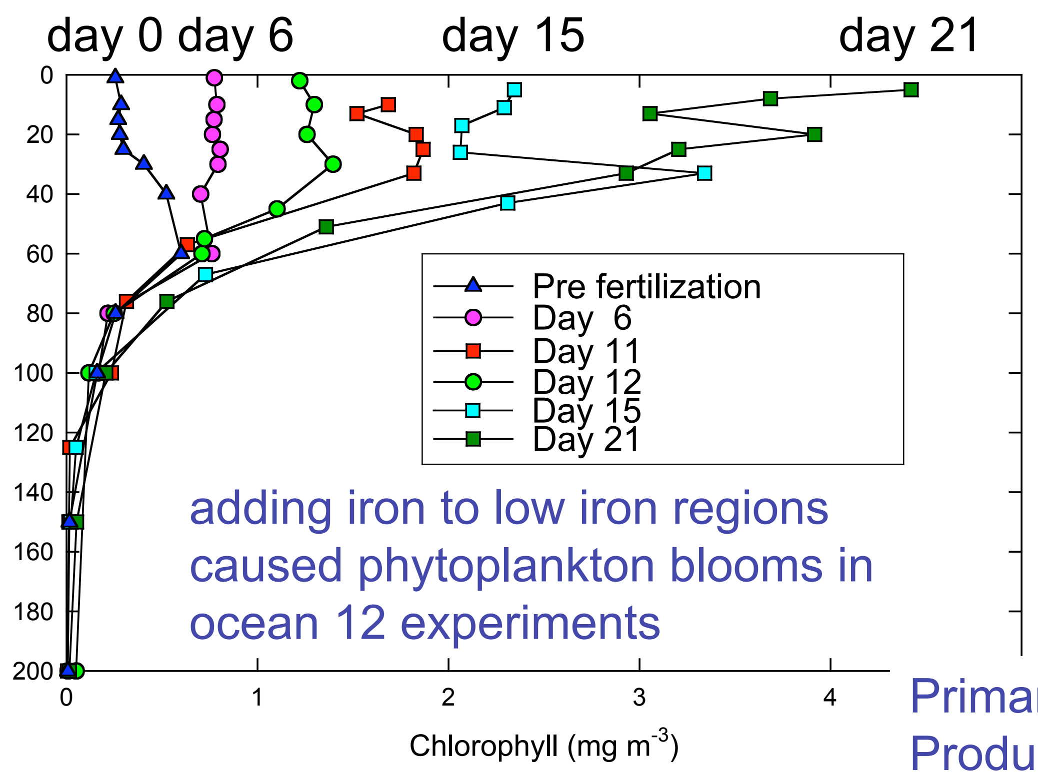
No current analogues to some future climate conditions??



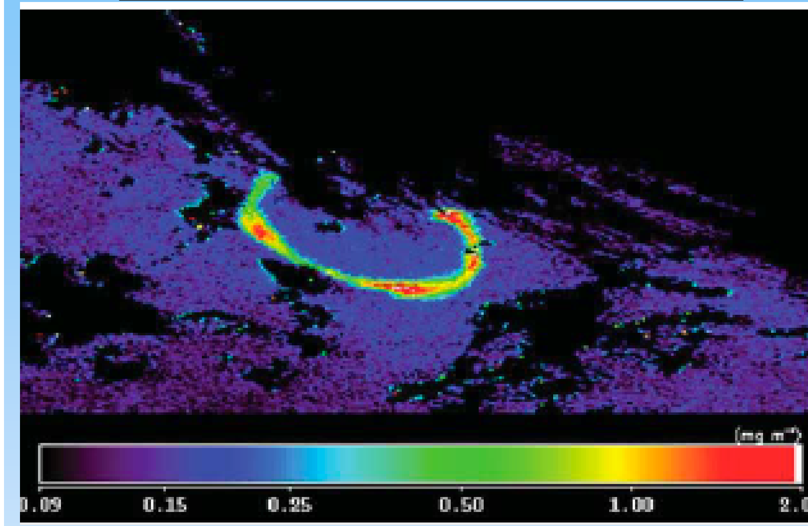




Sarmiento et al. Global Biogeochem. Cycles (2004)



Iron Fertilization



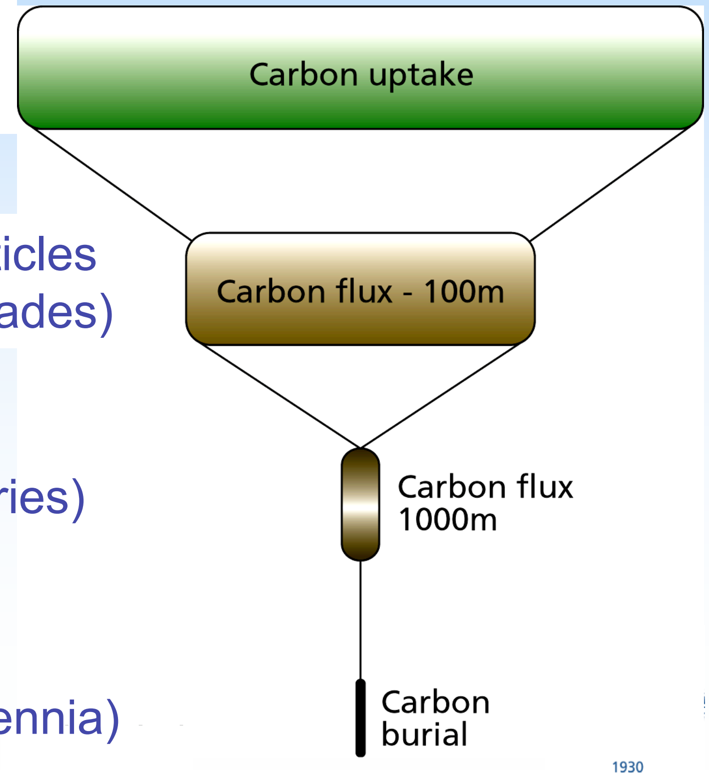
- Efficacy & C storage time
- Verification & additionality
- Other greenhouse gases
- Ecological consequences, low oxygen zones, ...
- Legal, economic & political framework

Primary Production

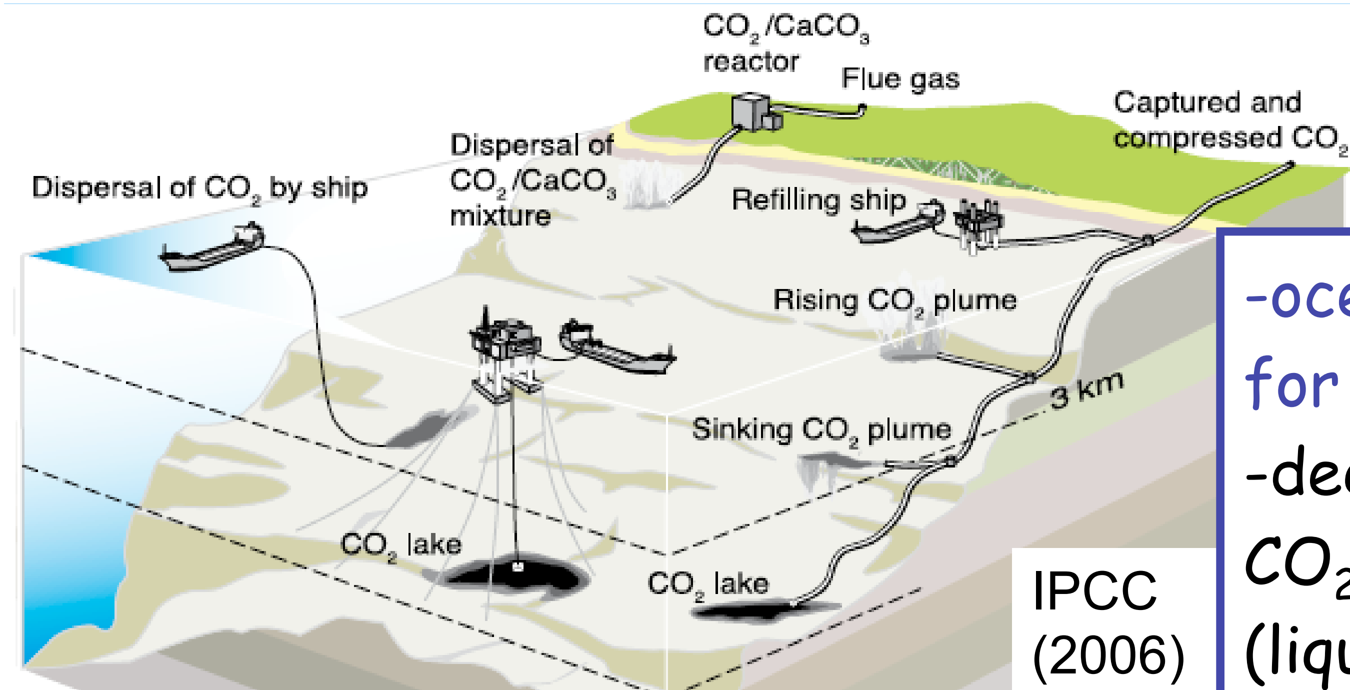
Sinking particles
5-20% (decades)

~1% (centuries)

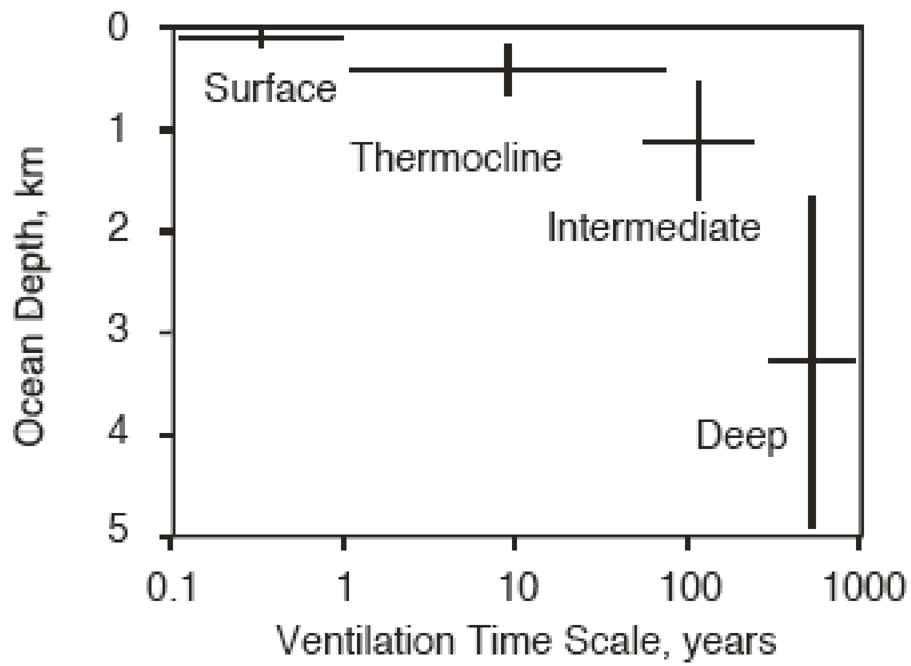
~0.1% (millennia)



Direct CO_2 Injection

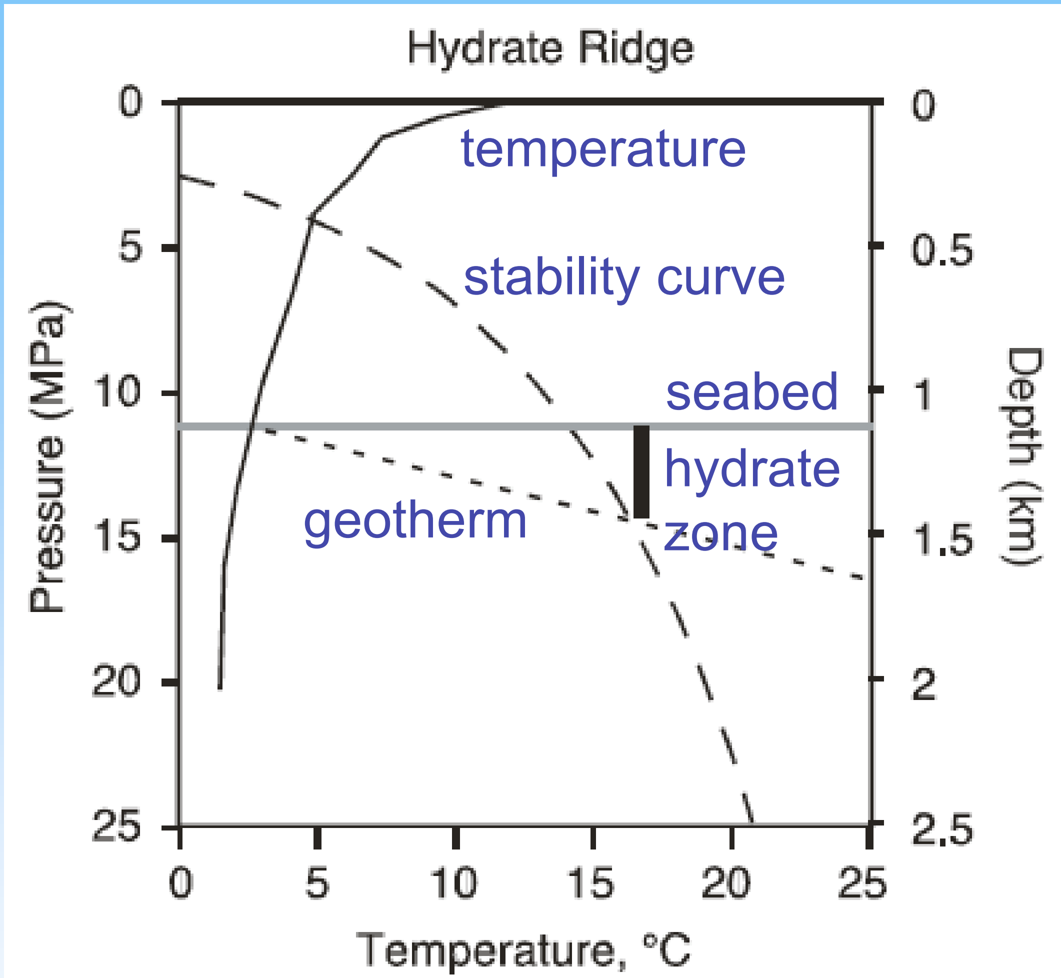


IPCC (2006)



Archer, Biogeosciences (2007)

- ocean ultimate sink for excess CO2
- deep injection as CO_2 gas or liquid CO_2 (liquid may form CO_2 hydrates)
- CO_2 storage time-scale of centuries
- acute acidification at injection site
- chronic biological effects on larger-scale (diffusion &

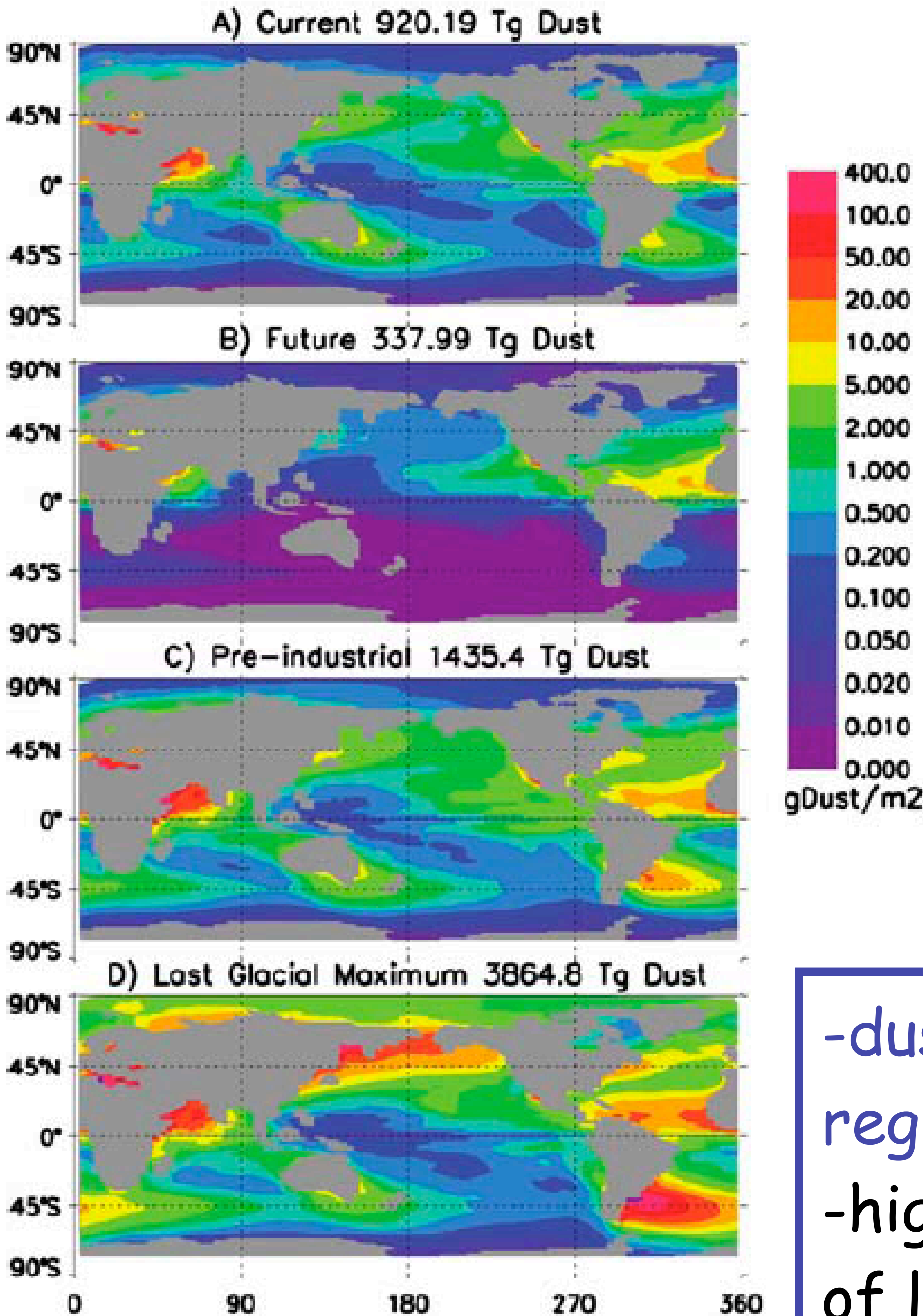


Archer, Biogeosciences (2007)

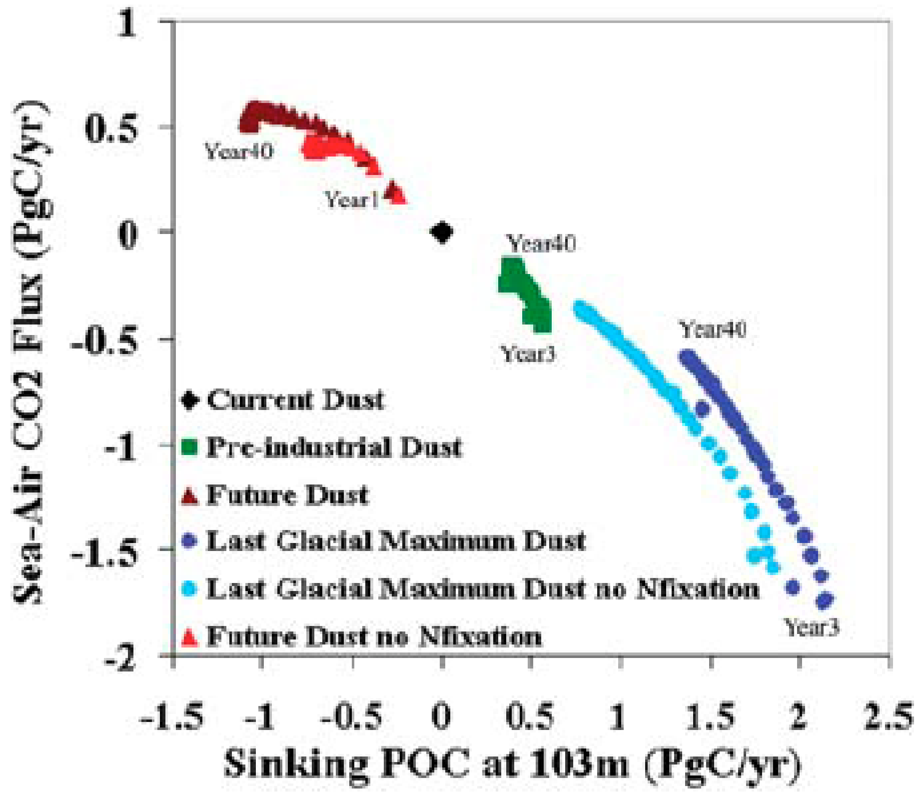
Methane Hydrates

- ΔCH_4 has ~20x radiative impact ΔCO_2
- potentially large CH_4 hydrate pool in ocean sediments, permafrost (10^3-10^4 Pg C)
- warming destabilizes hydrates
- question is time-scale catastrophic versus gradual release

Dust, Iron, Ocean CO_2



Moore et al., Tellus (2006)



-dust fertilizes low ocean iron regions (e.g. Southern Ocean)

-higher iron may explain ~30 ppm of lower glacial atm. CO_2

-sign of future dust uncertain

Projected Oceanic Responses & Feedbacks

-Ocean Physical Climate Change

- temperature, rainfall, sea-ice & circulation

-Ocean Carbon Sink

- efficiency, climate feedbacks & acidification

-Biogeochemical & Ecological Responses

- productivity, regime shifts & calcification

-Ocean Carbon Mitigation

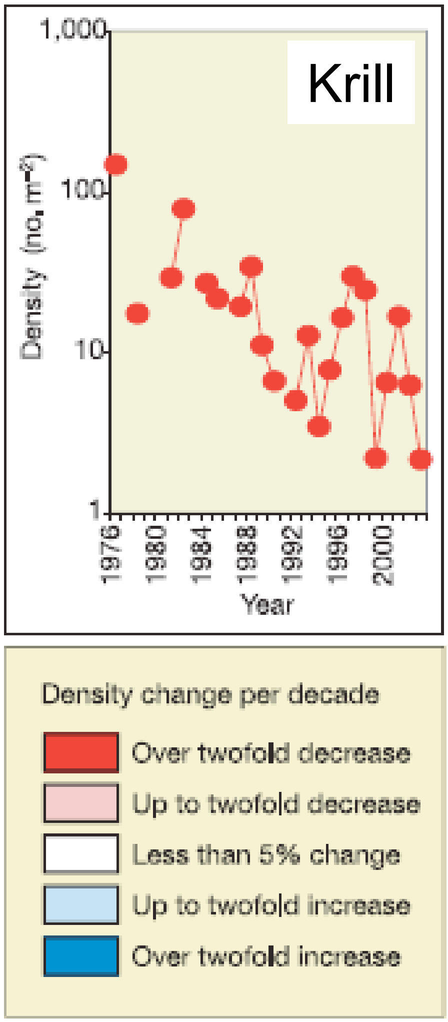
- ocean iron fertilization, direct CO_2 injection

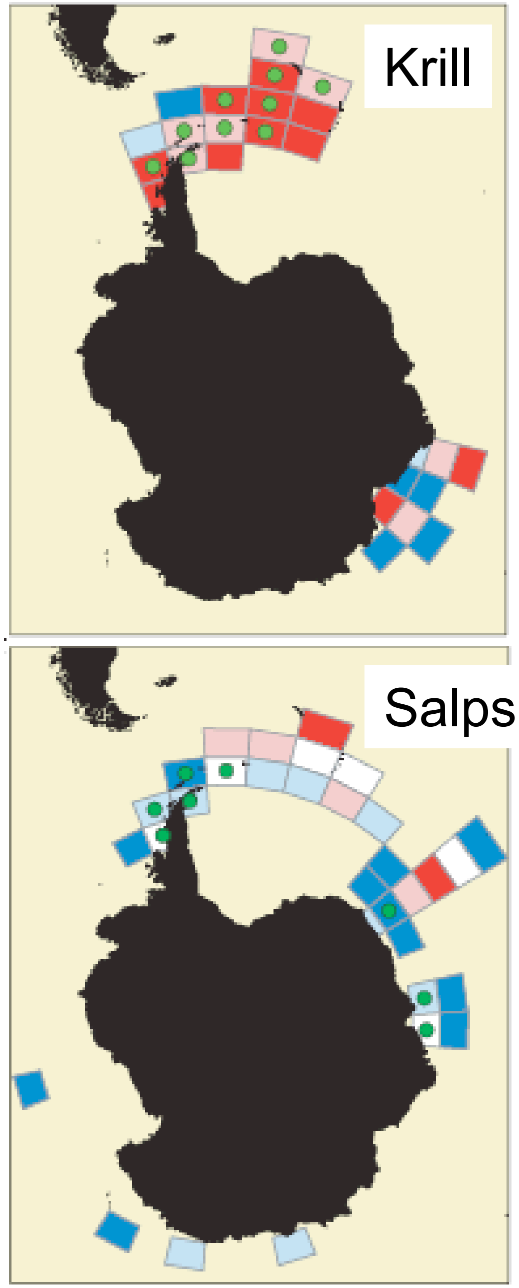
-Potential Surprises & Other Factors

- atmospheric dust, methane hydrates

IPCC 4th Assessment; C[4]MIP and OCMIP (international model intercomparison projects); Community Climate System Model

Possible Ecological Regime Shifts





Atkinson et al., Nature (2004);

- Krill distributions:
  - •spatial correlation with chlorophyll;
  - •temporal correlation with winter sea-ice extent
- May see future shift from krill dominated to salp dominated system
- Poleward shifts in other species (e.g., Adelie Penguins

Ducklow et al., Phil. Trans. Roy. Soc. B (2007)