Lecture 1:
Use and importance of ocean color remote sensing in global coupled biogeochemistry models

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Impact of climate change on ocean physical and biological processes and fisheries

Jorge L. Sarmiento
Also T. Frölicher, W. Cheung, J. Dunne, D. Pauly, and C. Stock

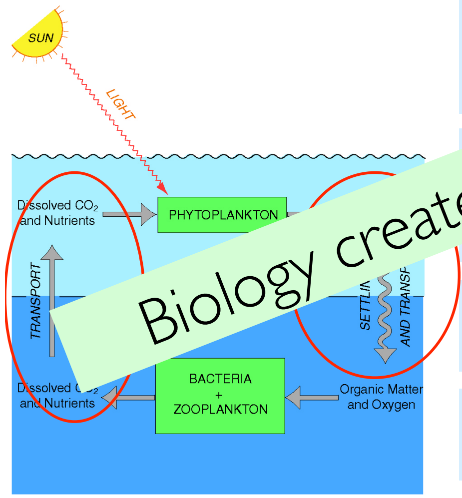
Outline

I. A brief tutorial:
Control of biological production by physical processes
II. Biome shifts:
Climate change impact on physical processes
III. Lower trophic level response:
Model projections of the response of ocean biology to global warming
IV. Fisheries response

I. A brief tutorial

Sarmiento & Gruber, 2006. Ocean Biogeochemical Dynamics, Princeton University Press

The Great Biogeochemical Loop



-- Organic matter is exported from th... ace to the d...

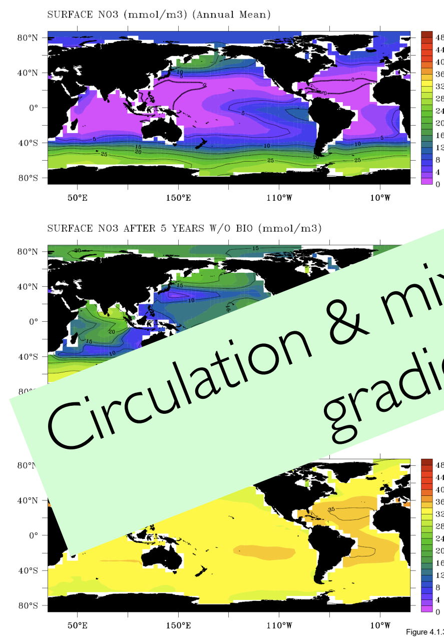
... nutrients ... the surface and adds them to the deep ocean

--Nutrients return to the surface by transport

(--Iron input by dust is also an important factor)

Sarmiento & Gruber (2006)

Biology creates gradients



Modeled surface nitr...

Circulation & mixing remove gradients

(Note: Global mean nitrate is 31.0 mmol m^{-3})

Sarmiento & Gruber (2006)

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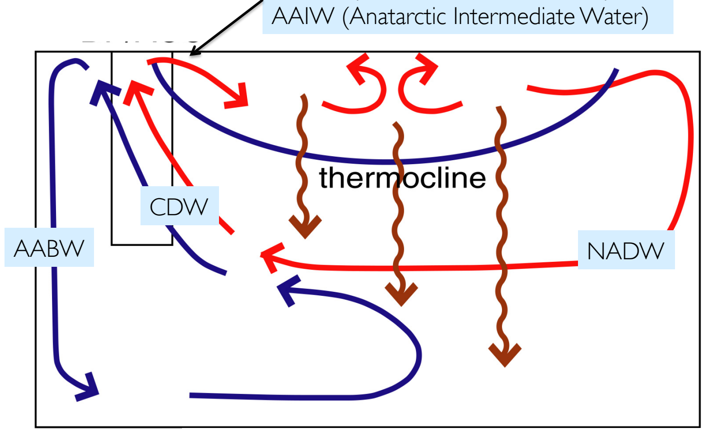
Nutrients return from the abyss in the Southern Ocean (also in the North Pacific)

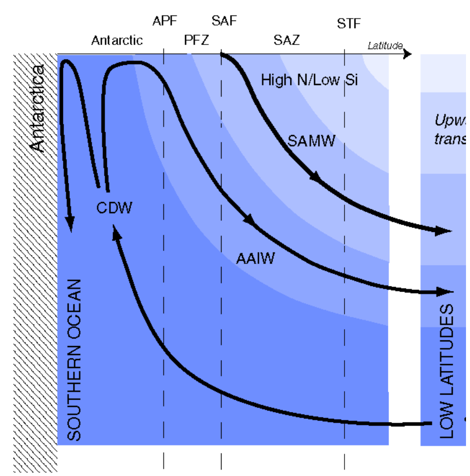
SAMW (Subantarctic Mode Water)
AAIW (Anatarctic Intermediate Water)



Sarmiento et al. (2004). Figure from Marinov et al. (2006)

Large scale vertical overturning circulation in the Southern Ocean

High surface nutrients



The main return pathway for nutrients lost to the deep ocean by the biological pump is upwelling in the Southern Ocean and northward transport in Subantarctic Mode Water and Antarctic Intermediate Water

(Sarmiento et al., 2004)

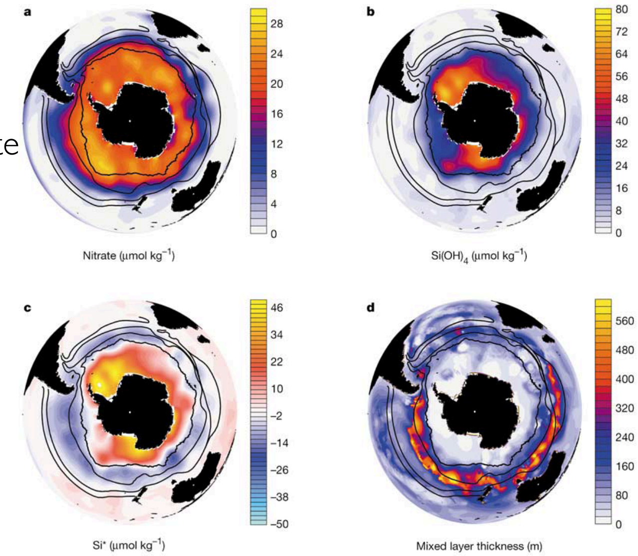
$Si^* = Si(OH)_4 - NO_3^-$ as a tracer of SAMW

Nitrate

Silicic acid

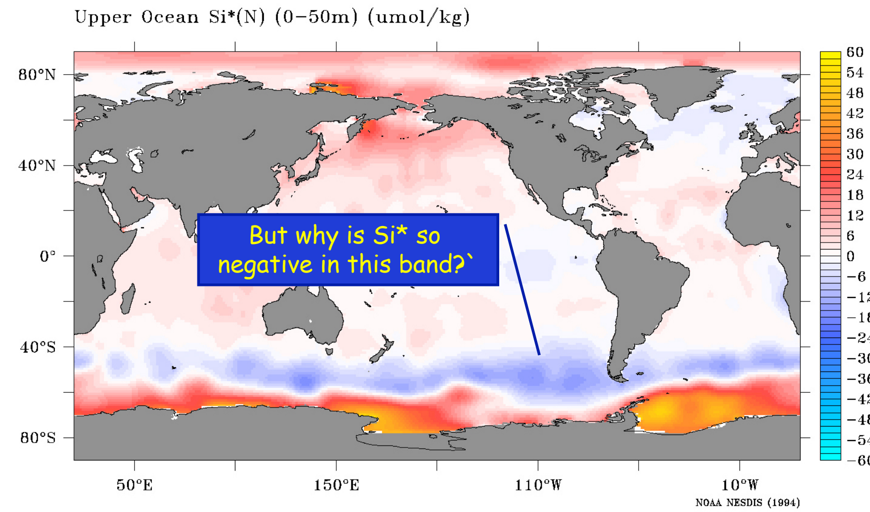
Si*

Winter ML depth



Sarmiento et al. (2004)

There is nowhere else at the surface of the ocean where Si* is negative

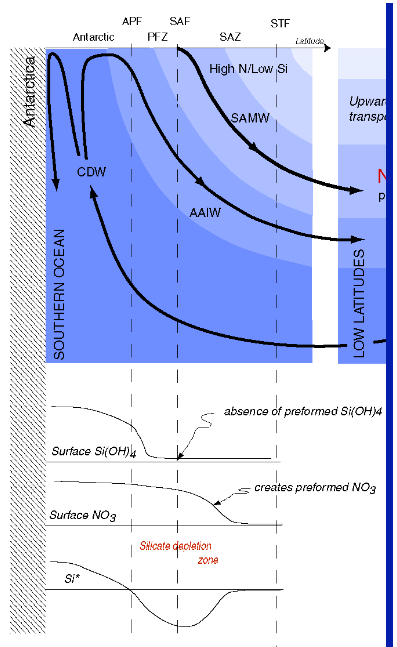


Schematic of nutrient cycle in Southern Ocean

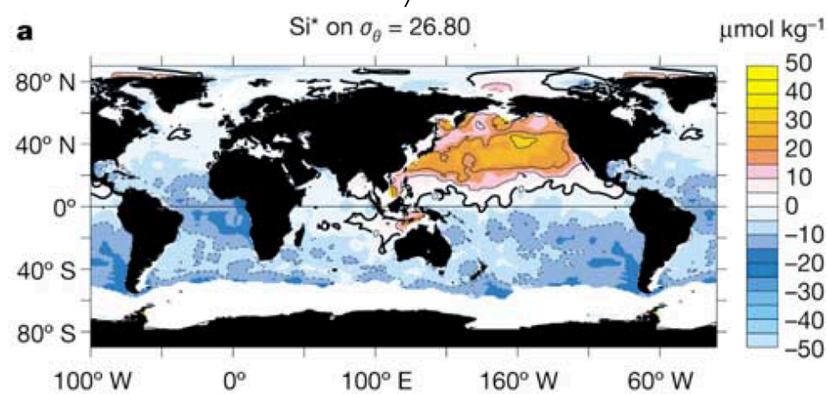
-When diatoms have adequate light and nutrients, they tend to take up Si and nitrate in a ratio close to 1:1

-When stressed (e.g., by iron or light limitation), diatoms tend to build more silicified shells, leading to a Si to NO_3 uptake ratio of 2:1 and higher [Hutchins and Bruland, 1998; Takeda, 1998.]

-Hypothesis: iron or light stress in Southern Ocean leads to high Si to NO_3 uptake ratio, which generates negative Si*

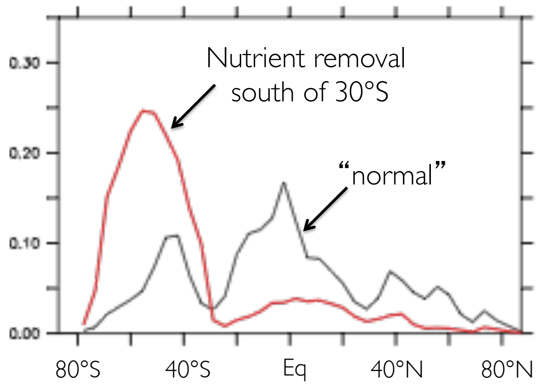


$Si^* = Si(OH)_4 - NO_3^-$ tracer on the $\sigma_\theta = 26.8$ density surface



The Si* tracer shows that SAMW (Subantarctic Mode Water) fills the entire main thermocline except the north Pacific with high nitrate-low silicic acid water from the Southern Ocean.

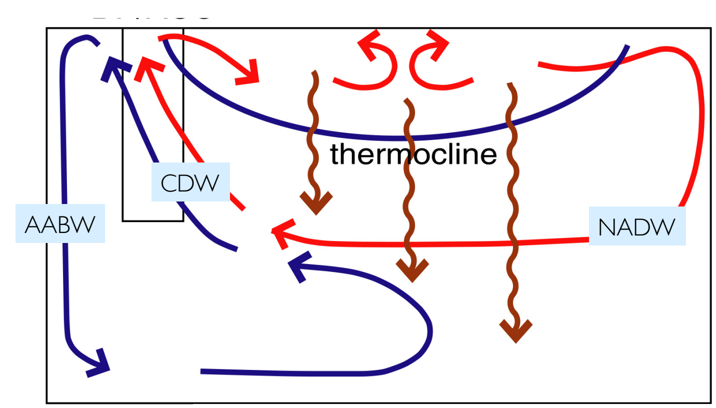
Zonally integrated biological productivity in the world ocean (Pg C/degree/yr)



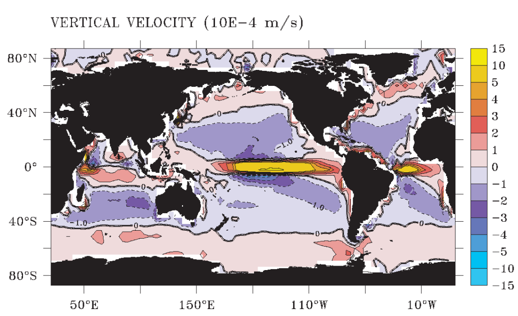
Southern Ocean surface nutrient depletion blocks the SAMW nutrient resupply pathway & reduces low latitude biological productivity by ~75%.

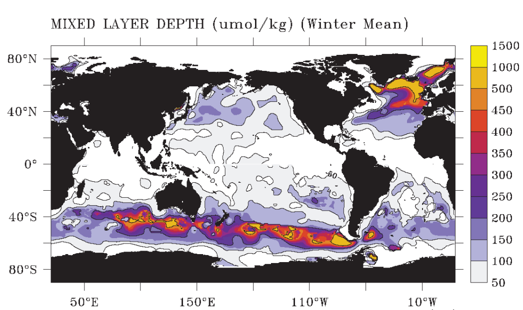
Marinov et al. (2006)

How do nutrients get from the main thermocline into the surface layer?



Sarmiento et al. (2004). Figure from Marinov et al. (2006)





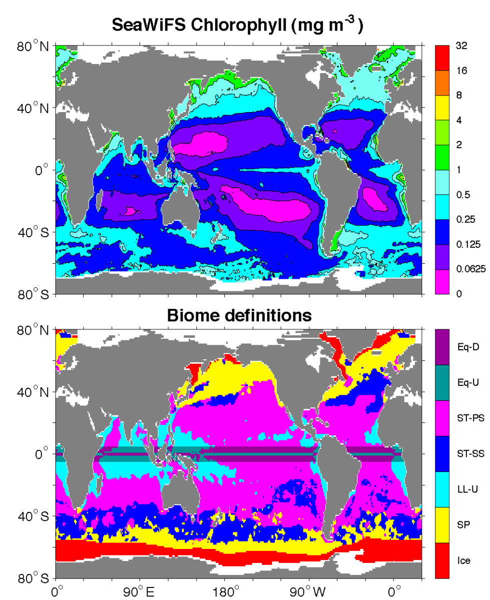
Physical processes controlling nutrient supply to the surface ocean

-- Upwelling

--Deep wintertime mixing

--Vertical diffusion (stratification dependent)

Sarmiento & Gruber (2006)



Biological productivity as inferred from the chlorophyll distribution reflects primarily physical processes such as upwelling and deep wintertime mixing.

This motivates dividing the world up into six biomes:

(1) Seasonally ice covered

(2) Subpolar gyre (upwelling)

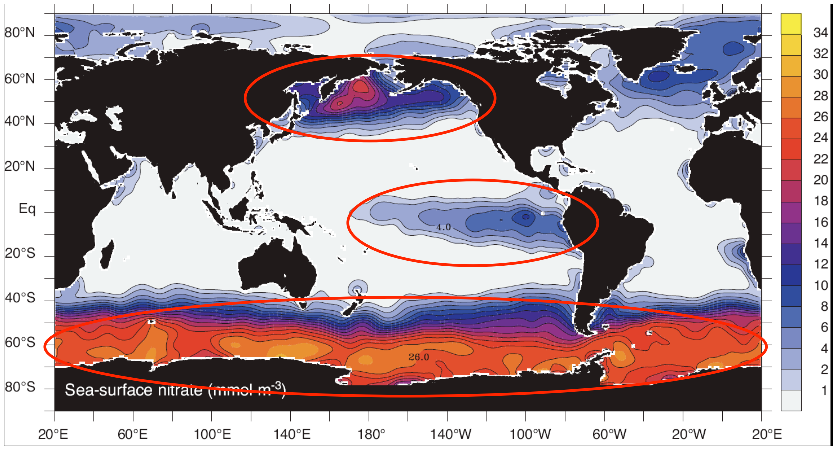
(3) Seasonally mixed subtropical (downwelling & winter ML > 150 m)

(4) Permanently stratified subtropical (downwelling & winter ML < 150 m)

(5) Low latitude upwelling

(6) Equatorially influenced (±5°)

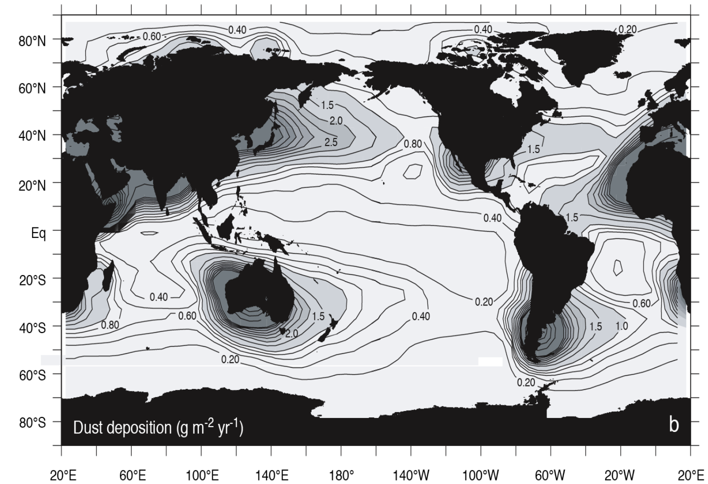
The biological pump efficiently depletes surface nutrients everywhere except in three major regions where the iron supply is insufficient



Note: iron is used in electron transport proteins involved in photosynthesis & respiration and in the enzymes nitrate & nitrite reductase and nitrogenase (required for N_2 fixation)

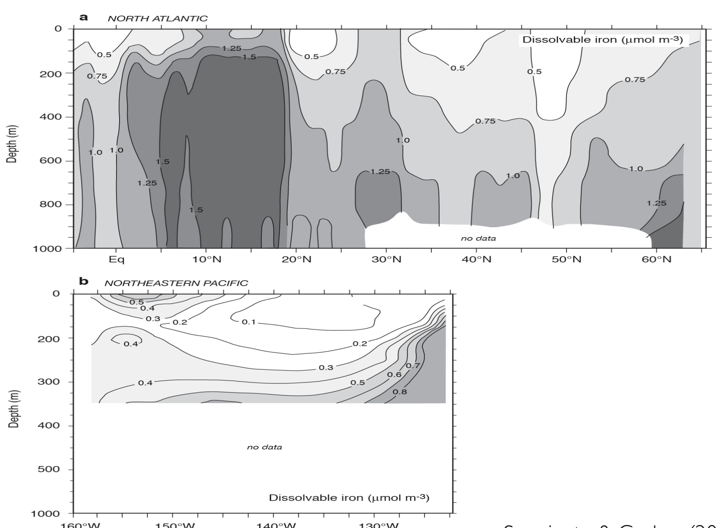
Sarmiento & Gruber (2006)

Supply of iron by dust also influences biological productivity

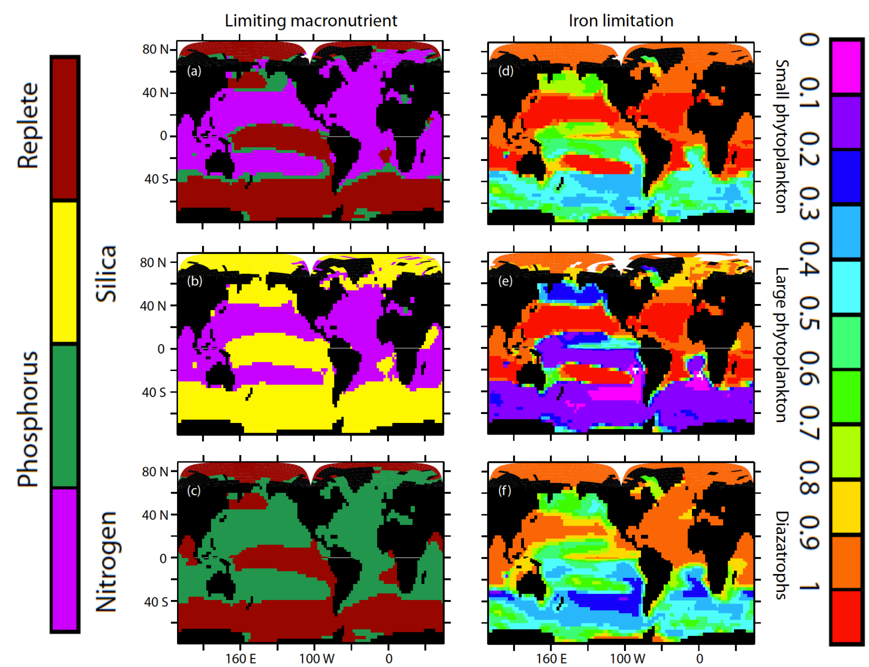


Sarmiento & Gruber (2006)

Supply of iron from below



Sarmiento & Gruber (2006)



II. Biome shifts

Climate change impact on physical processes

Sarmiento et al. (2004); Sarmiento group (Thomas Frölicher) and John Dunne of GFDL/ NOAA, including model results from IPCC AR4 & European CARBOOCEAN project

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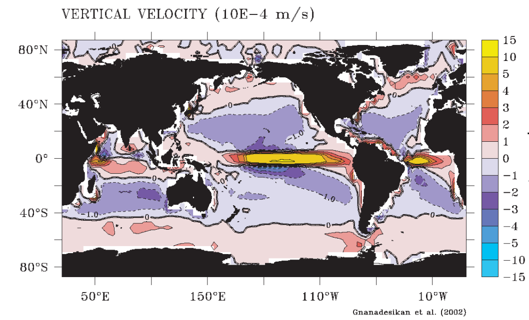
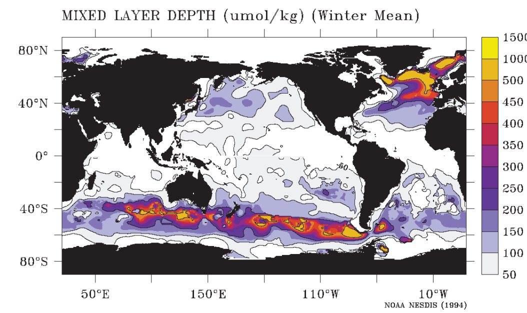
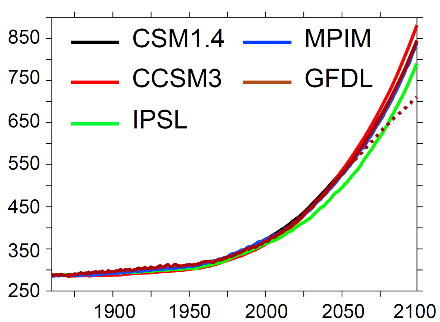


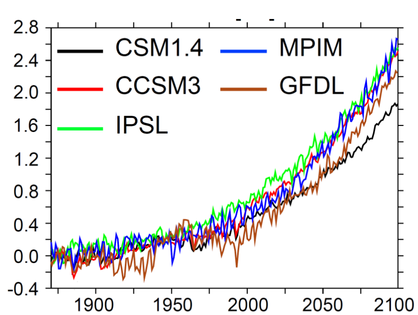


The physical processes controlling the nutrient supply to the surface ocean are all climate sensitive

Sarmiento & Gruber (2006)



Atmospheric pCO_2 (ppm)



Projected increase in sea surface temperature (°C)

Modeling response of ocean biology to climate warming using an empirical approach

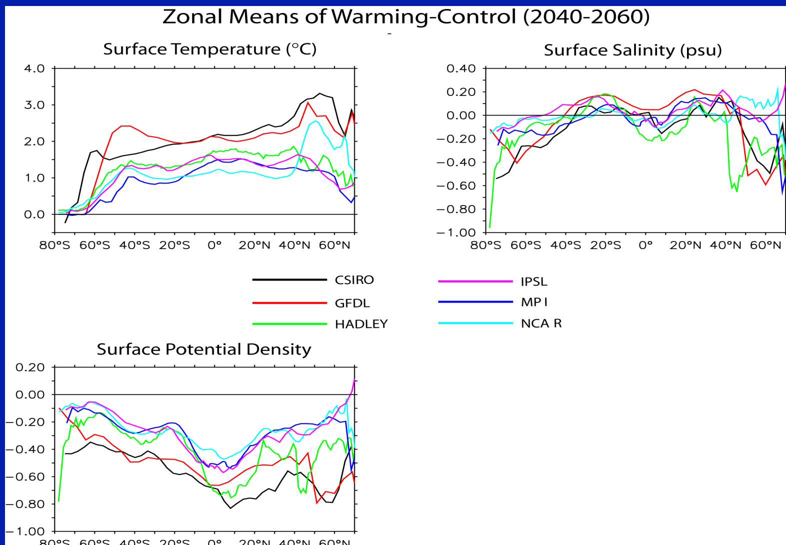
Original motivation: To develop a method to analyze the biological response to global warming in a wide range of climate models, most of which do not have an ecosystem model (Sarmiento et al., 2004):

Model	Co-authors	Warming in 2100
GFDL*	R. Stouffer	4.5
CSIRO*	A. C. Hirst & R. Matear	4.0
Hadley	S. Spall	4.0
IPSL	L. Bopp, P. Monfray, & J. Orr	3.1
NCAR	S. Doney & J. Kleypas	2.5
MPI*	U. Mikolajewicz & V. Soldatov	N/A

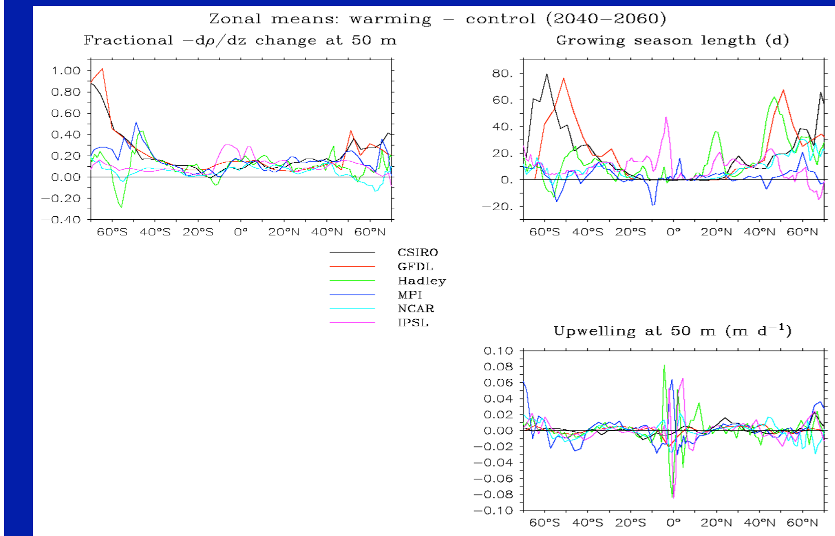
*These models are flux corrected.

Strategy: (a) develop physically based diagnostics for biomes and biogeographical provinces; (b) develop an empirically based model for primary production.

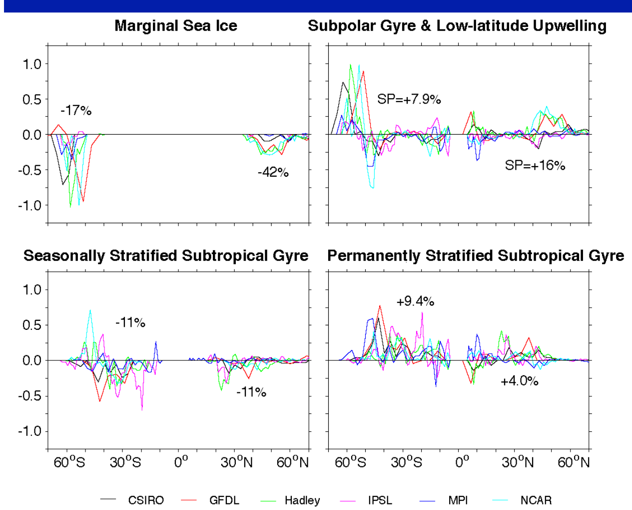
Global warming increases temperature, enhances hydrologic cycle, and decreases surface density



This increases vertical stability and lengthens the high lat growing season. Upwelling response varies.



Global warming generally increases low productivity biome areas at expense of high productivity biomes

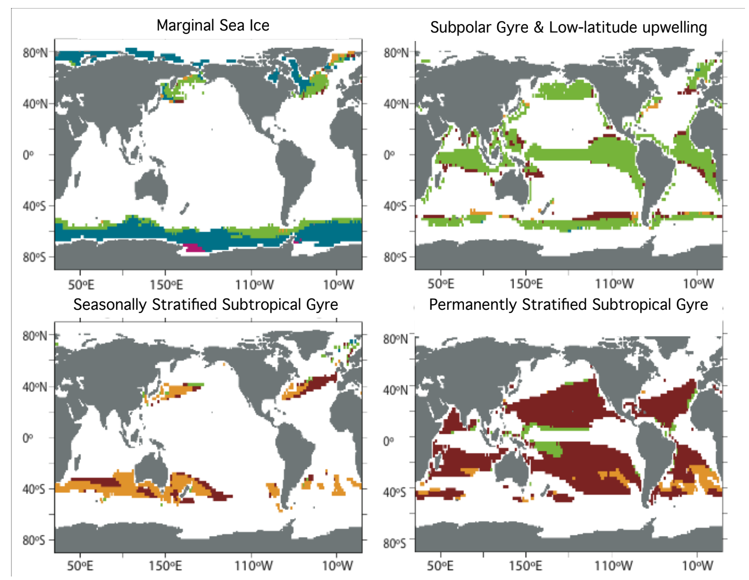


Each line represents the area change in 2040-60 of one of the six climate models.

The % change in area shown is the average of all six models.

All biomes also become more stratified

Response of biome areas to global warming in GFDL model in 2040 – 2060 versus control



Global Mean Response of Model Physics to Global Warming (2040-2060)

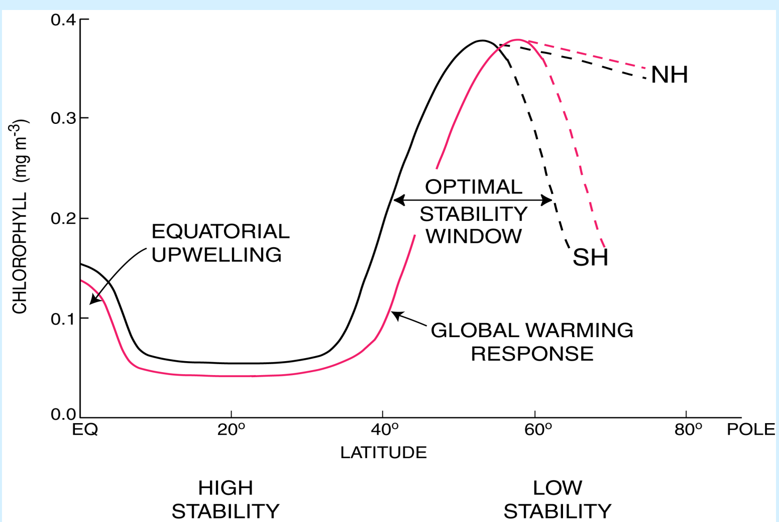
	Average	Range
Seasonally Stratified Regions		
Period when Mixed Layer < 100 m	+17 days (7%)	0 to 46 days
Permanently Stratified Subtropical Gyres		
Expansion of Area	8%	4% to 11%
Increase in Stratification	7%	5% to 10%
Equatorial + Low Latitude Upwelling (±15°)		
Change	-6%	-2% to -15%

III. Lower trophic level response

Model projections of the response of ocean biology to global warming

Sarmiento et al. (2004); Steinacher et al., (2010); Collaborative study between Sarmiento group (Thomas Frölicher) and John Dunne of GFDL/NOAA, including model results from European CARBOOCEAN project

Schematic of Expected Chlorophyll (and Primary Production) Response to Global Warming



Modeling the Response of Chlorophyll and Primary Production to Global Warming

Possible approaches:

- Extrapolating from present patterns of variability such as El Niño
- Empirical models based on extrapolating from present observations
- Ecosystem models

Previous research on impact of global warming on biological production

	Biological model	Coupled climate model
Sarmiento et al. (1998)	Empirical	GFDL model
Bopp et al. (2001)	Ecosystem	IPSL model
Sarmiento et al. (2004)	Empirical	Six models (climate sensitivity = 2.5 to 4.5°C)
Steinacher et al. (2010)	Ecosystem	Four models (climate sensitivity = 2.0 to 4.4°C)
This project	Ecosystem GFDL TOPAZ	GFDL ESM2.1 (climate sensitivity = 3.4°C)

Climate sensitivity is the warming that occurs in response to $2xCO_2$

III. A. Empirical model

From Sarmiento et al. (2004)

Empirical Model I - Primary Production

We calculated Primary Production using three different algorithms of the form:

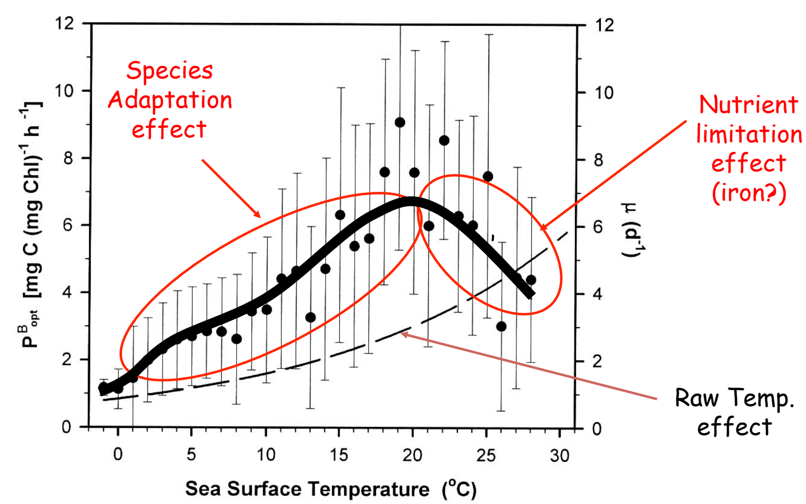
$$PP = f(P_{opt}^{B} \cdot Chl,\ light)$$

P_{opt}^{B} is *temperature dependent* optimal assimilation efficiency (mg C/mg Chl).

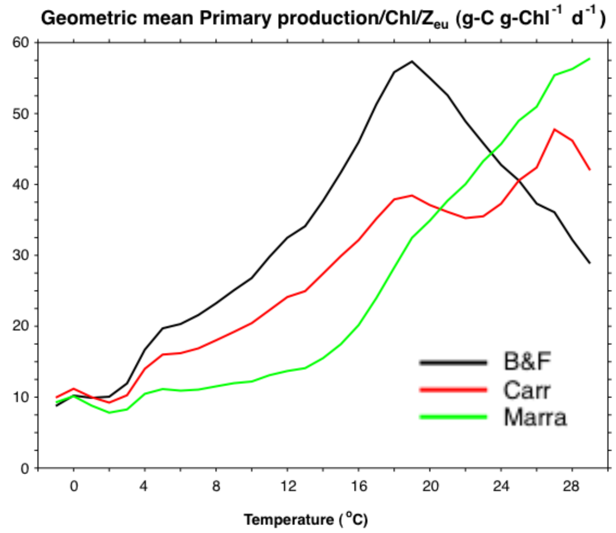
Chl is chlorophyll (mg Chl/m^3).

Note: *Nutrients* are not explicitly included in the PP model. Chl and P_b^{opt} serve as proxies for it.

Optimal assimilation efficiency in Behrenfeld & Falkowski (1997) model



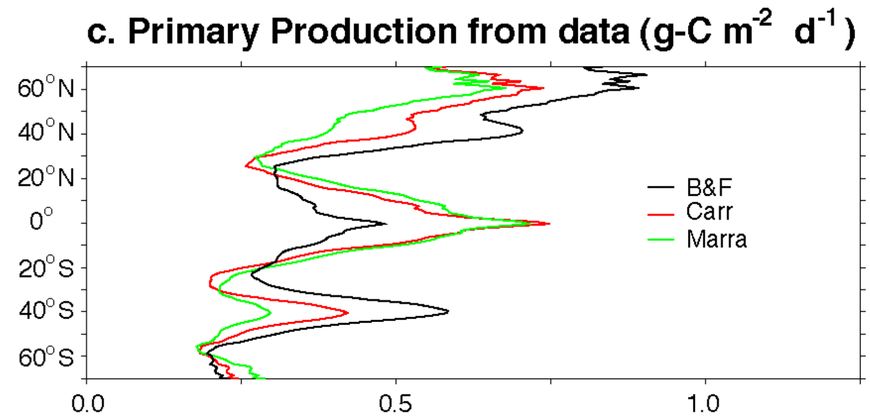
The global primary production (PP) predicted by three different PP models differs primarily in their temperature dependence



The figure shows global mean PP binned by temperature intervals

Behrenfeld & Falkowski, 1997; Carr, 2002; & Marra, et al., 2003)

A comparison of the three empirical primary production models (using SeaWiFS chlorophyll)d



Empirical Model Part II - Chlorophyll Estimation

A multiple linear regression of ln(Chlorophyll) observations in each biome using model predicted variables in that biome:

Water mass variables (most important):

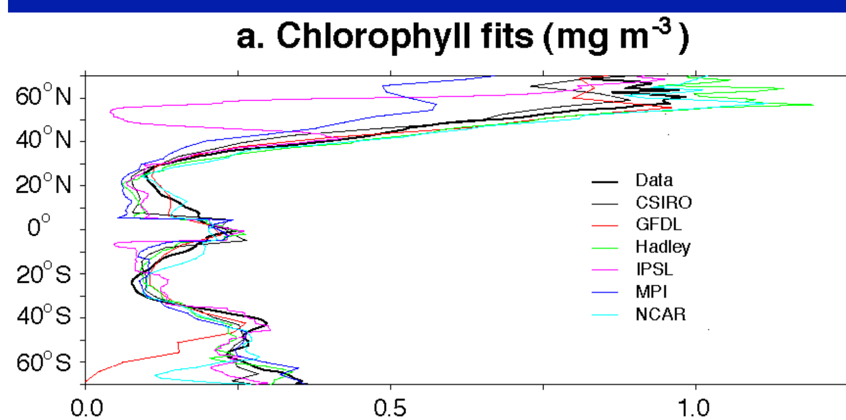
- •Sea surface temperature anomaly
- •Sea surface salinity anomaly

Variables that directly influence nutrient and light supply:

- •Maximum mixed layer depth (important)
- •Growing season length (time MLD < 100 m and light > 5 Einsteins; generally not important)

The model is "trained" using SeaWiFS Chlorophyll

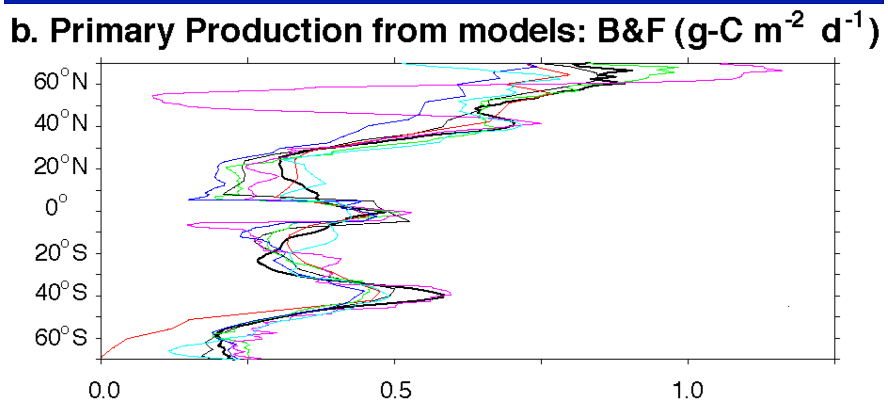
Empirical model prediction of present day chlorophyll (mg/l) using control climate variables



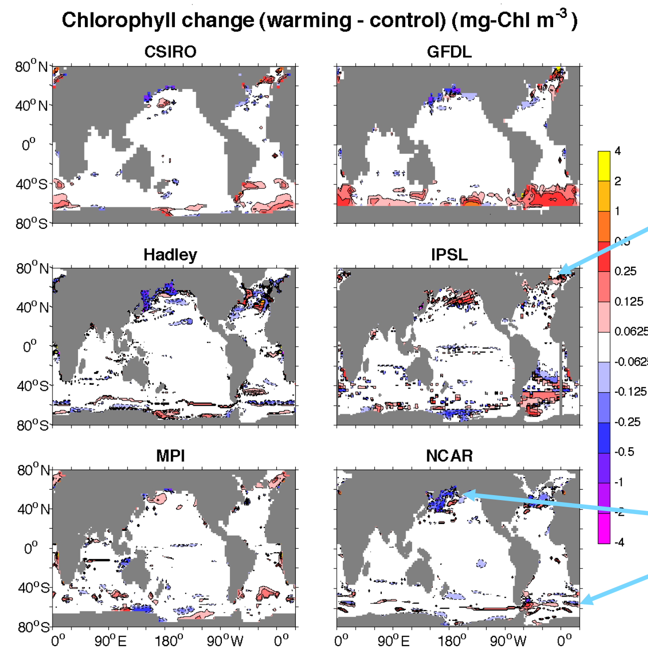
•Thick black line is zonal mean of SeaWiFS chlorophyll

•Thin lines are zonal means of each of the six models

Primary Production Estimate



- Thick black line uses SeaWiFS chlorophyll
- Thin lines use control climate chlorophyll from models



Average of 2040-2060

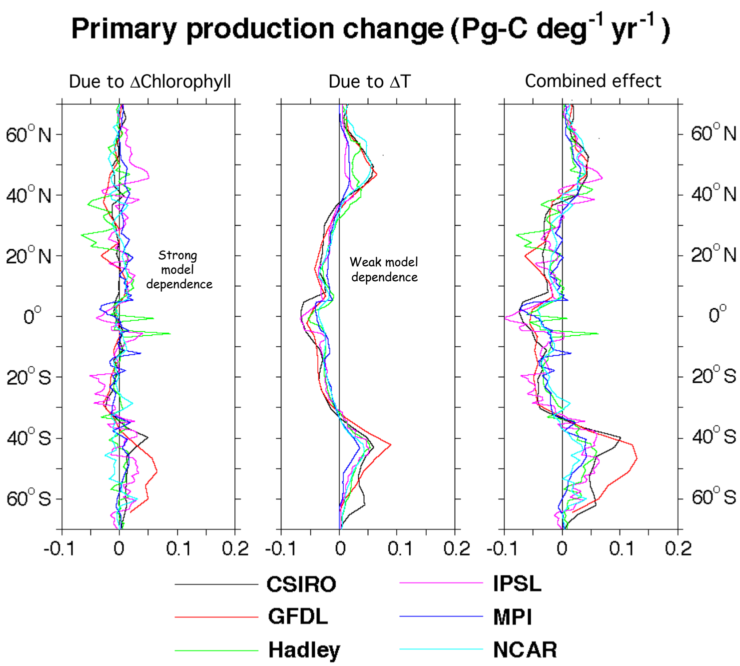
(<0.06 mg Chl/l in white)

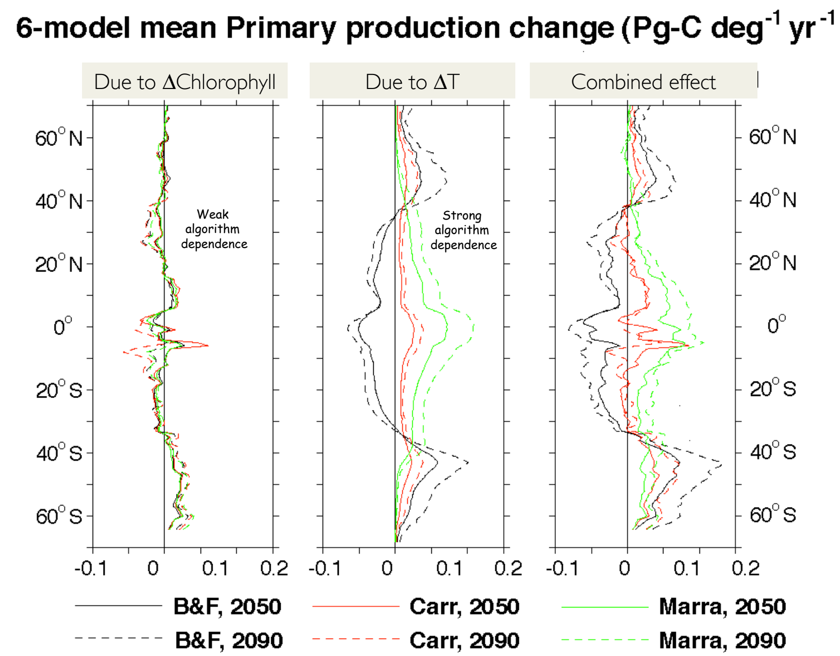
(1) N. Atl. Increases (complex combination of processes)

Changes due mostly to MIZ retreat:

(2) N. Pac

(3) S. Oc. (~60°S)





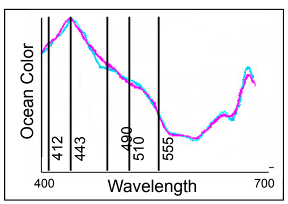
Conclusions - Response to global warming based on empirical model

- Biomes shift poleward, with a dramatic reduction in the seasonal sea ice biome
- Chlorophyll response to warming is modest
  - North Pacific drops
  - North Atlantic increases
  - Southern Ocean (~60°S) increases
- Primary production response is very sensitive to temperature dependence of optimal assimilation efficiency
  - More observations are needed!

Future Directions

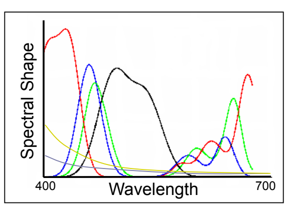
- Improved coupled atmosphere-ocean climate models of global warming
- Response of ocean biology to global warming
  - More objective methods for determining biomes (Jacobson & Sarmiento)
  - Improved empirical models of productivity (Jacobson, Schultz, Hiscock, Sarmiento & Behrenfeld)
  - Empirical models of functional group distribution (Jin, Gruber, Dunne, Sarmiento & Armstrong)

Controversial ocean color inversions by Behrenfeld et al. (2005) give carbon biomass directly
(as well as chlorophyll and estimates of growth rate)



Net Spectrum

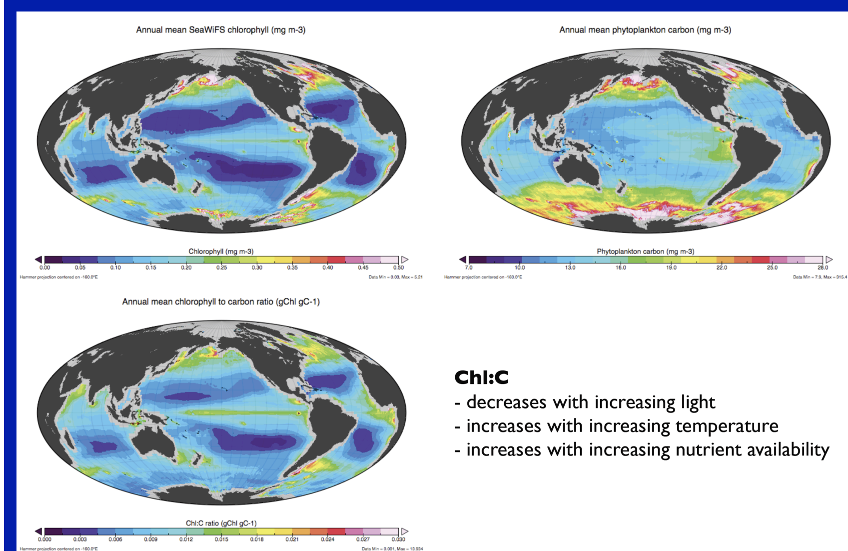
Reconstruction

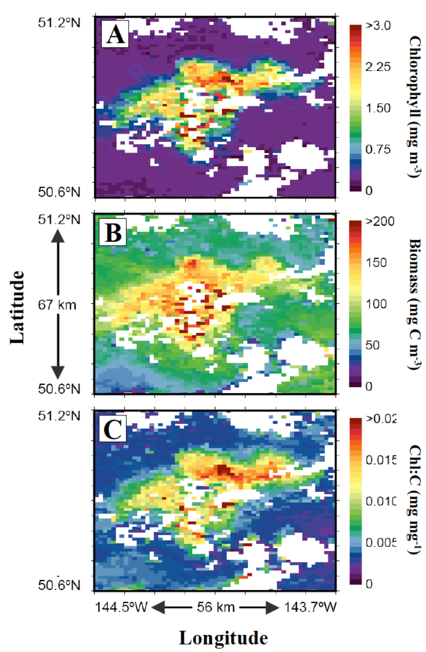


Chlorophyll-a
Chlorophyll-b
Chlorophyll-c
Carotenoids
Particulate backscatter
CDOM

Phytoplankton Absorption

Algal C Biomass
CDOM



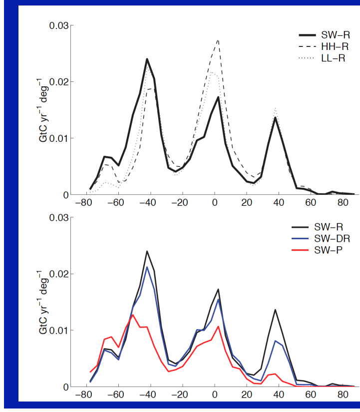


Day 19 of SERIES iron enrichment near OSP

SERIES study described by Boyd et al. (2004)

First Steps towards a functional group empirical model (Jin et al., 2006)

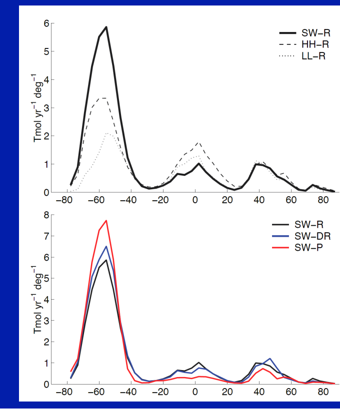
Diagnosed $CaCO_3$ export from alkalinity distribution



Sensitivity to ocean circulation

Sensitivity to biogeo-chemical model

Diagnosed opal export from silicic acid distribution



Empirical models for $CaCO_3$ and opal export

$$CaCO_3 = -0.081 + 0.0163 \cdot NPP + 0.0037 \cdot [Si(OH)_4]$$

$$Opal = -0.35 + 0.0298 \cdot [Si(OH)_4] + 0.168 \cdot Chlorophyll$$

Units = mol m^{-2} yr^{-1}

Note: In their present form, these equations require knowing the silicic acid concentration, but it should be possible to represent this using physical parameters (e.g. ML depth).

Modeling the Response of Chlorophyll and Primary Production to Global Warming

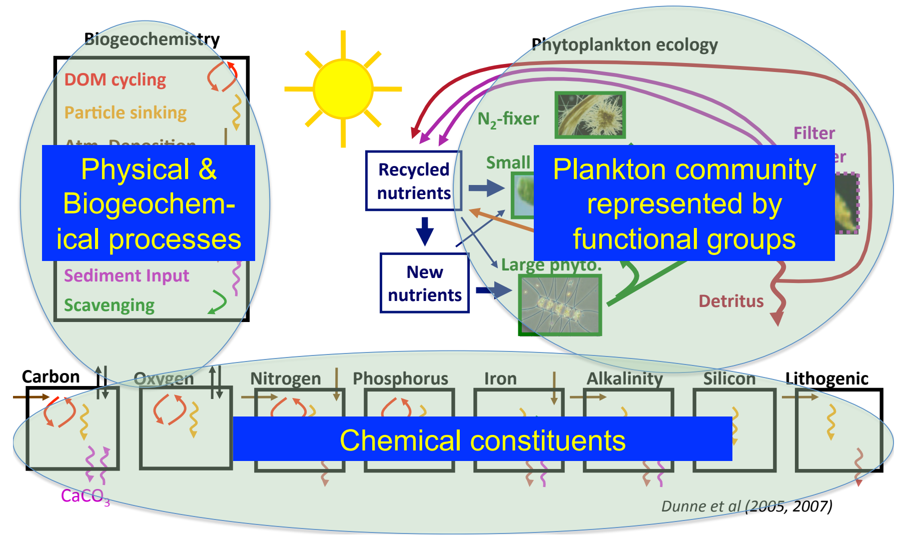
Possible approaches:

- Extrapolating from present patterns of variability such as El Niño
- Empirical models based on extrapolating from present observations
- Ecosystem models

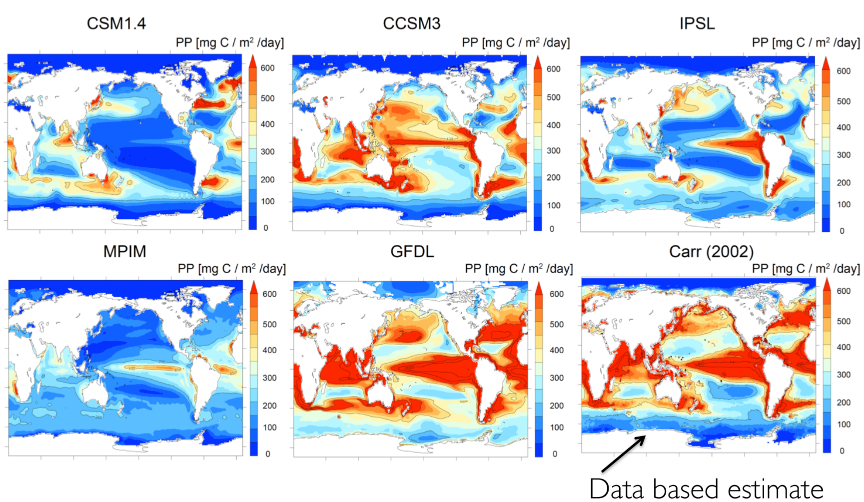
III. B. Ecosystem model

Steinacher et al. (2010) and collaborative study between Sarmiento group (Thomas Frölicher) and John Dunne of GFDL/NOAA, including model results from European CARBOOCEAN project

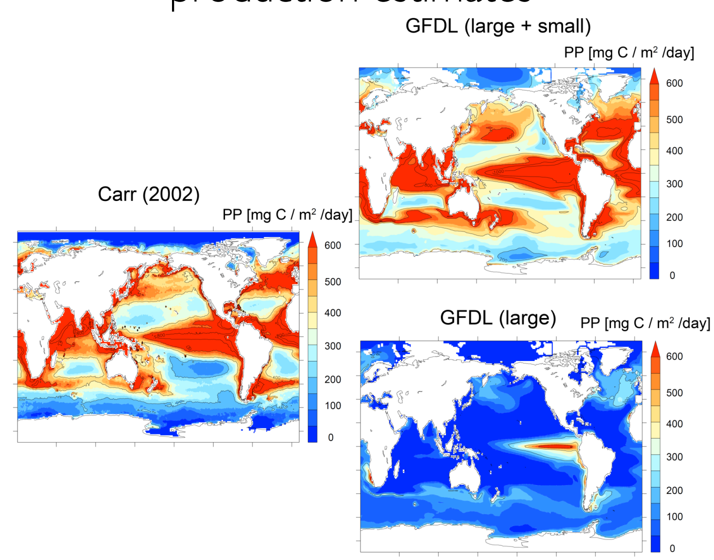
A typical model of biological contributions to the great biogeochemical loop (GFDL TOPAZ)



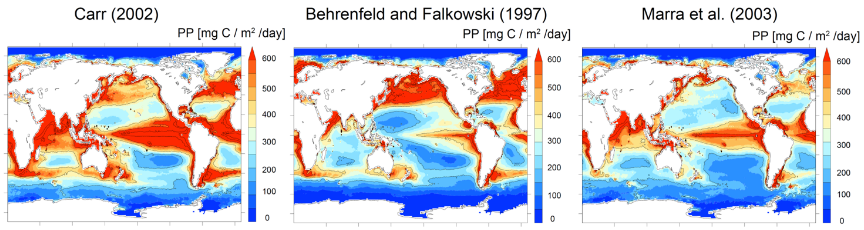
Present-day decadal mean model primary production compared with satellite-based estimate



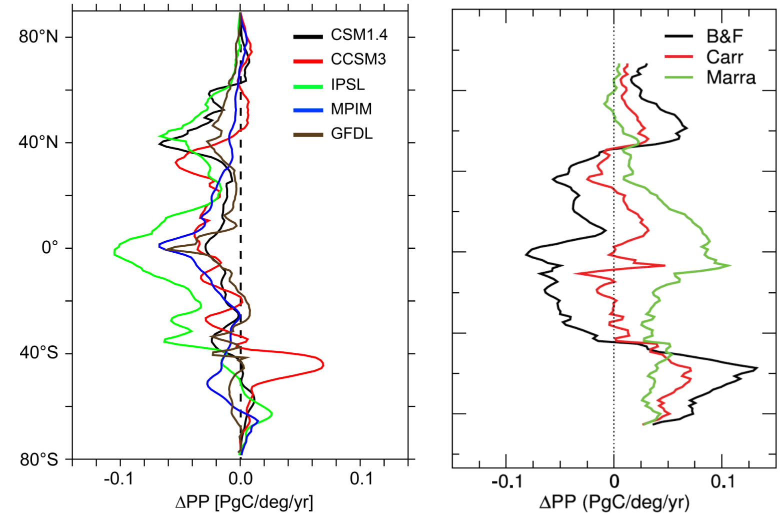
Uncertainty in satellite-based primary production estimates



Primary production estimated from satellite estimates of chlorophyll using the three different algorithms



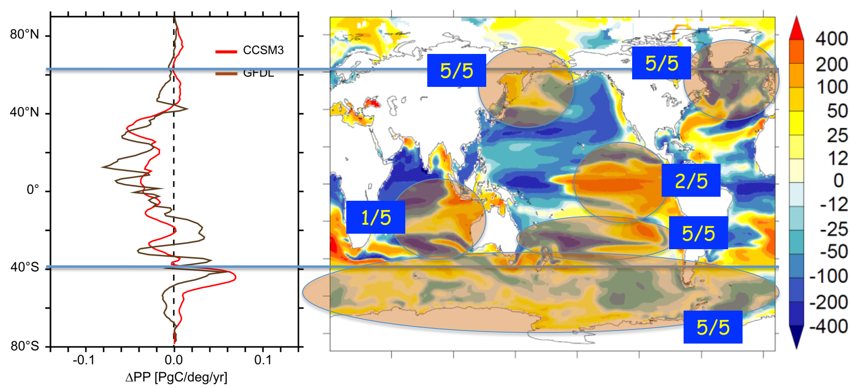
Comparison of PP in empirical versus ecosystem models



Projected decadal mean change in primary production from 1860s to 2090s

Zonal mean increase (Pg C yr $^{-1}$ degree^{-1})

GFDL model (mg C m^{-2} day^{-1})

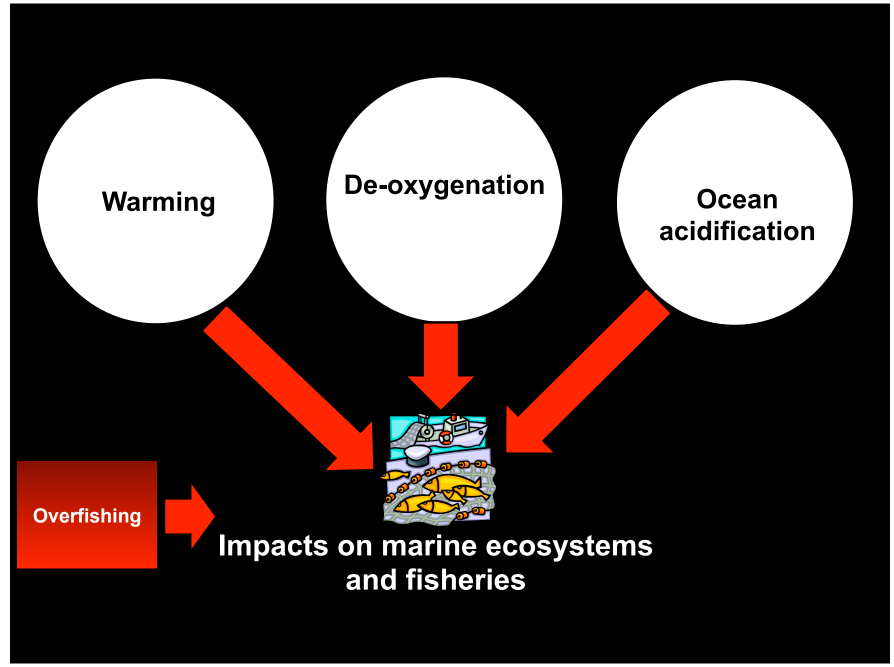


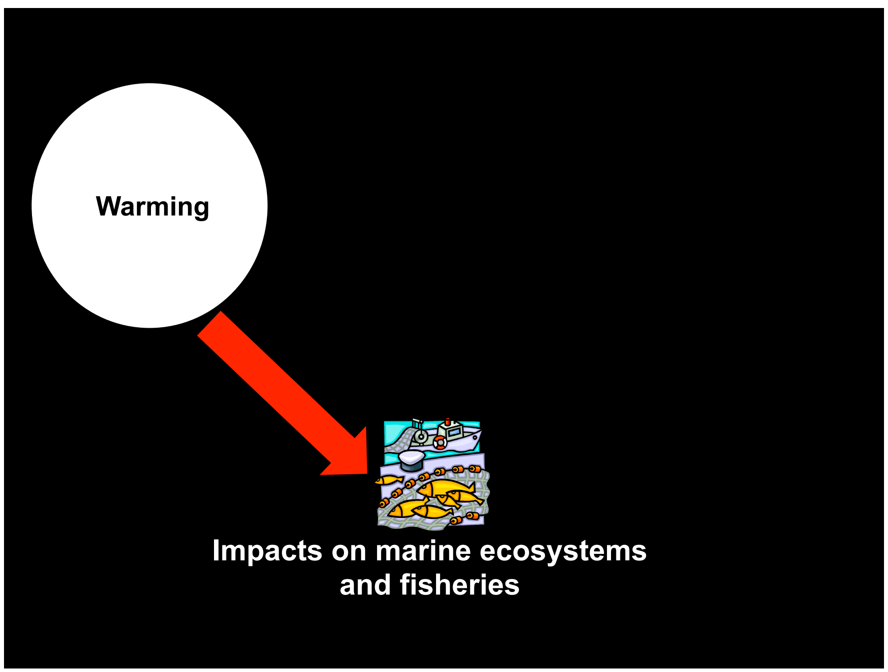
Conclusions: lower trophic level response

- Global warming leads to increased temperature & stratification
  - This tends to reduce nutrient supply & primary production in low latitudes
  - It contributes to increased light supply & primary production in high latitudes
  - The overall pattern of the responses is consistent between different models on a broad scale but differs in detail
- Sources of uncertainty
  - disagreements in estimates of present magnitude and distribution of primary production.
  - wide range of model estimates due both to climate simulations and biological models.

IV. Fisheries response

Cheung et al. (2009, 2010, 2011); collaboration of Sarmiento (Princeton University) and Pauly (University of British Columbia) groups as part of Nereus Project





Cheung (2009) bioclimate envelope model applied to 1066 species

Environmental variables considered:

- Sea surface and bottom temperature
- Salinity
- Sea ice cover
- Advection
- Bathymetry

- Habitat preferences
  - Coral reef
  - Estuary
  - Seamounts
  - Coastal upwelling

Cheung (2009) relative abundance calculation

Uses an empirical model for 30' x 30' cells predicting relative abundance as a function of:

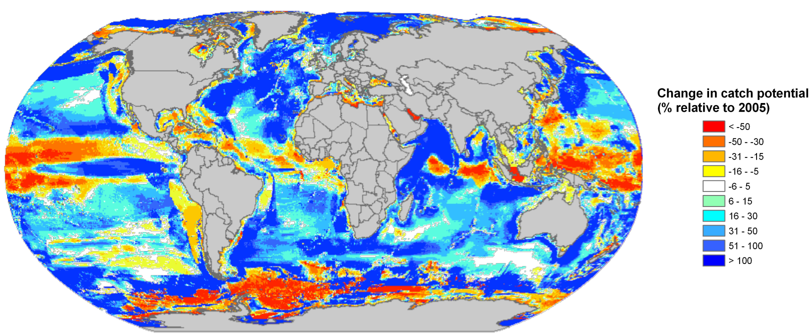
- Logistic population growth with carrying capacity being related to habitat suitability
- Immigration of larvae from surrounding cells using an advection diffusion reaction model (Gaylord & Gaines, 2000)
- Migration of adults to surrounding cells along increasing habitat suitability gradients.
- Predation and food availability are not considered.

Cheung et al. (2010) Maximum catch potential (MSY) estimate

Calculated from an empirical model as a function of

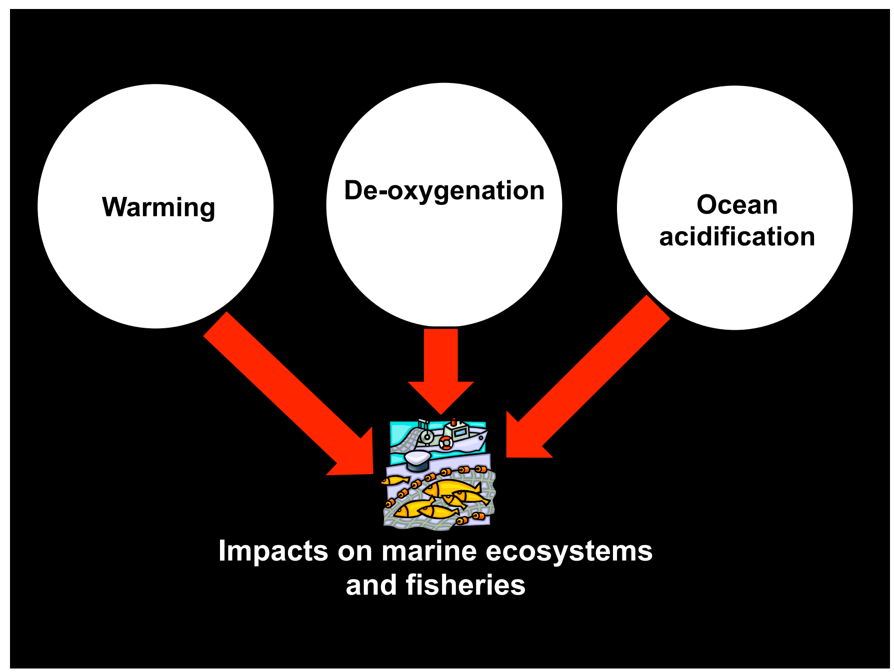
- Primary production in exploitable range
- Area of geographic range
- Trophic level
- Number of years of exploitation
- Catch reported as "higher level taxonomic aggregations"

Projected change in catch potential by 2055 Scenario: "Business-as-usual" scenario



- High latitude regions are projected to gain in catch potential while regions in the tropics may suffer from losses.

Source: Cheung, Lam, Sarmiento, Kearney, Watson, Zeller, Pauly 2010. Global Change Biology

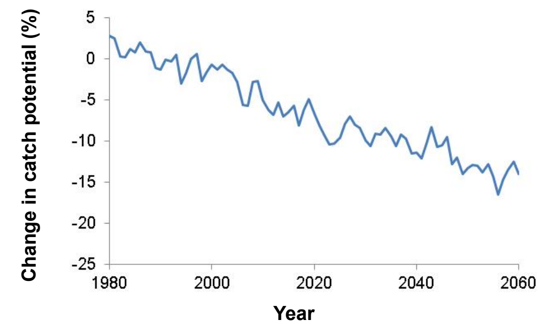


Cheung et al. (2011) integration of ecophysiology into MSY predictions

Uses a model algorithm derived from the Von Bertalanfy growth function including the following effects:

- Arrhenius temperature effect on both the anabolism and catabolism coefficients (Q_{10} = 2.4)
- Oxygen effect on the anabolism coefficient
- pH effect on oxygen demand to parameterize its influence on ionic balance regulation and increased $CaCO_3$ formation.

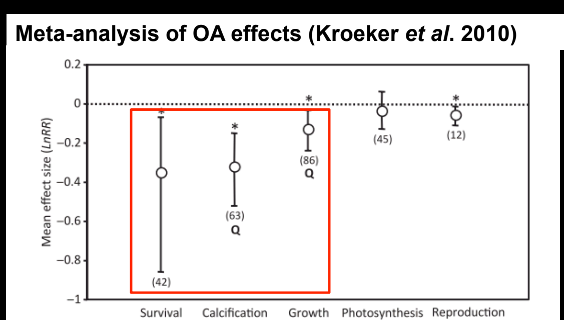
By 2050, warming and de-oxygenation combined are predicted to decrease catch potential



- This analysis considered 610 exploited species.

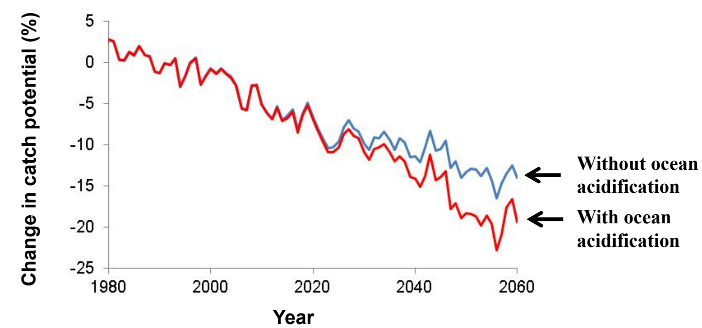
Source: Cheung, Sarmiento, Frölicher, Pauly (in prep.)

Testing key hypotheses of OA effects on population dynamics



- **Base metabolic rate increases by 15% when [H+] (measure of acidity) is doubled;**
- **Larval mortality increase by 25% when [H+] is doubled.**

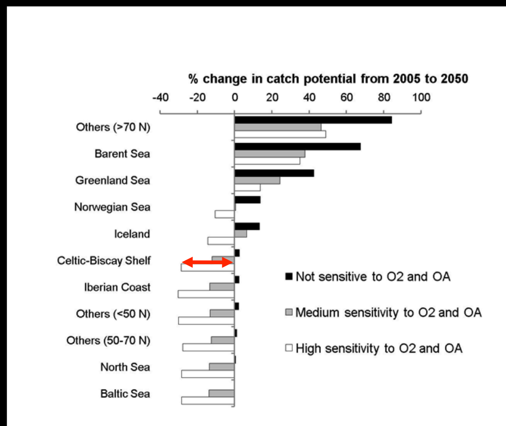
With OA as an additional stressor, by 2050 catch potential is predicted to decrease even more



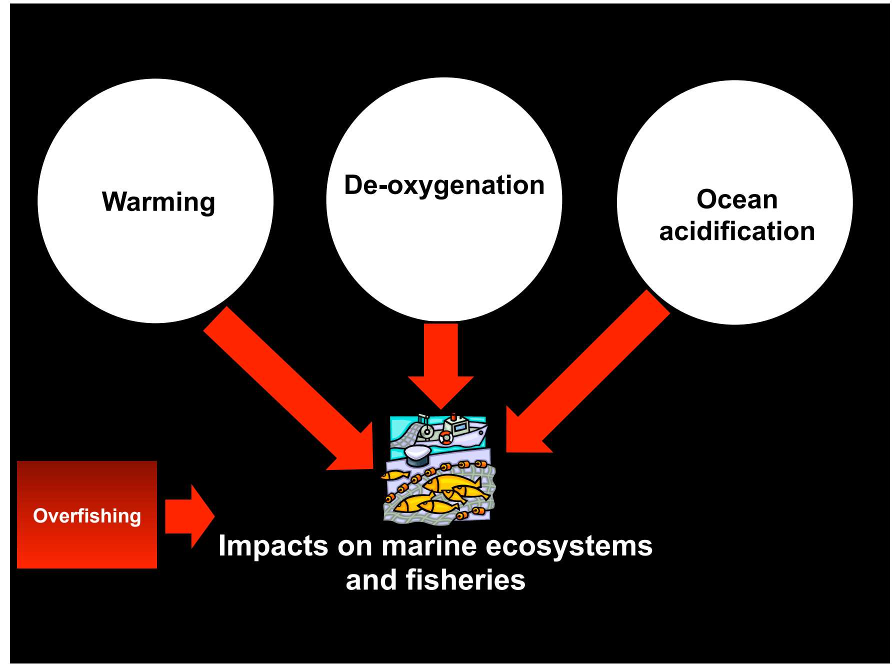
Source: Cheung *et al.* (in prep.)

Ocean acidification may turn some of the perceived 'winners' of warming to 'losers'

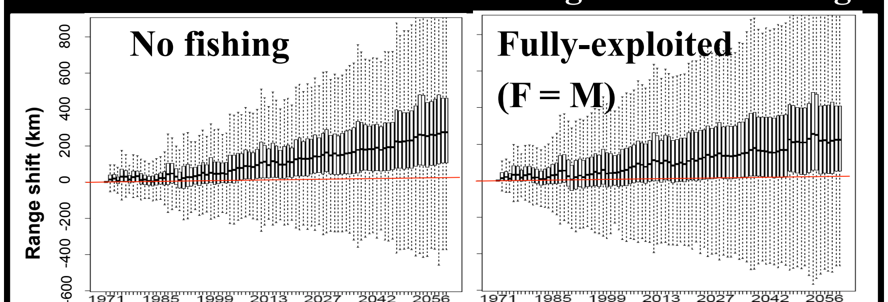
Example: Northeast Atlantic



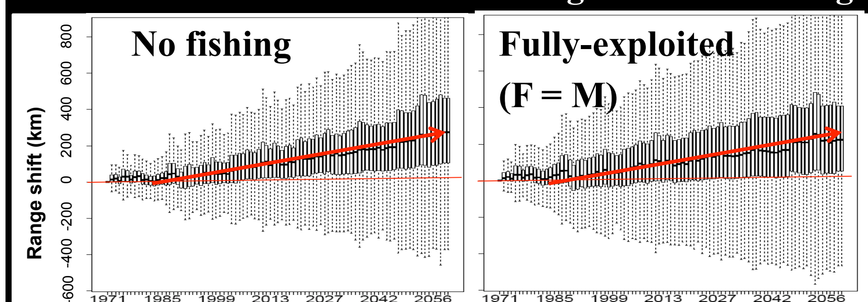
Source: Cheung, Dunne, Sarmiento and Pauly (2011) ICES Journal of Marine Science

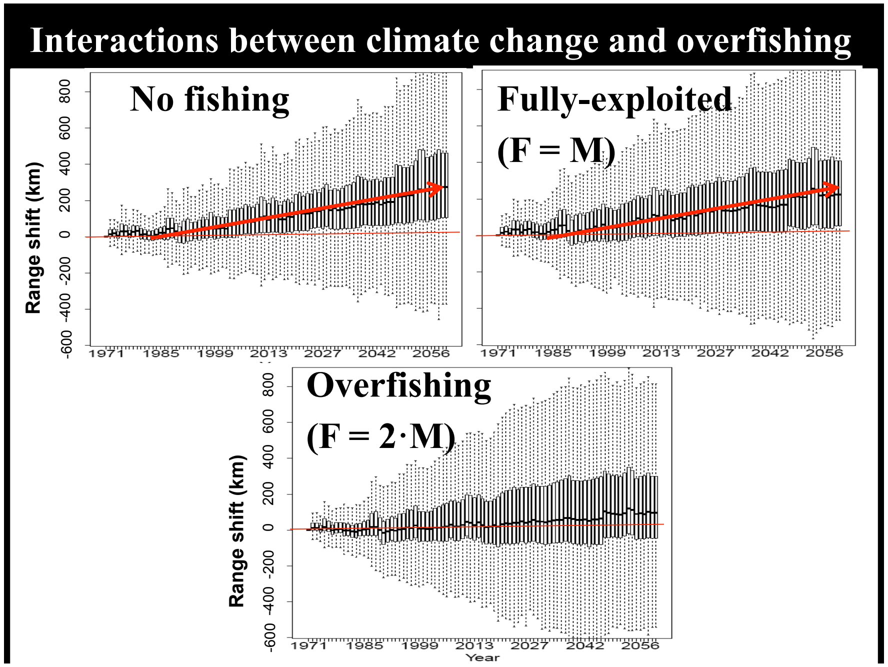


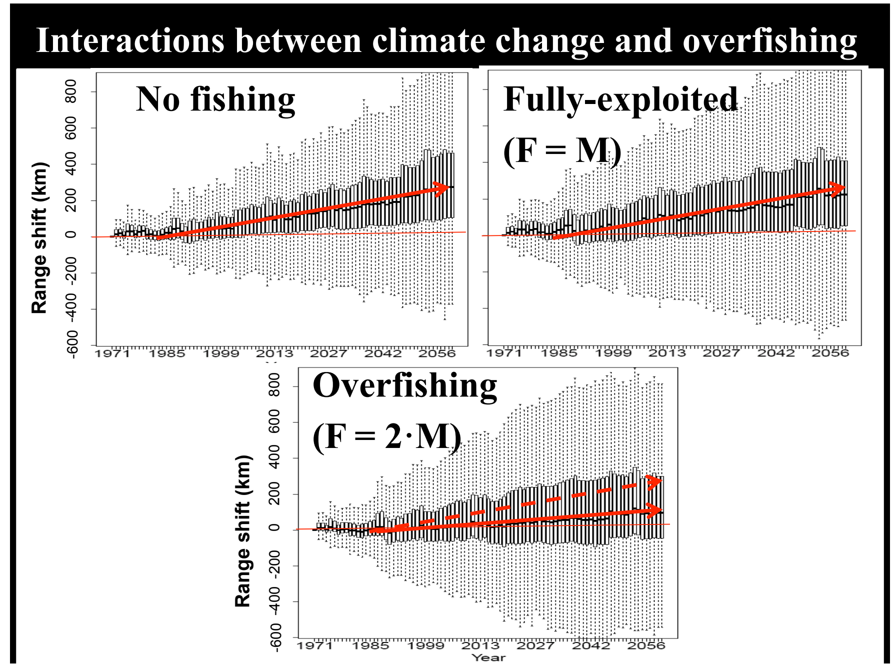
Interactions between climate change and overfishing



Interactions between climate change and overfishing




Interactions between climate change and overfishing
No fishing
Fully-exploited
(F = M)
Overfishing
(F = 2·M)
Range shift (km)
Year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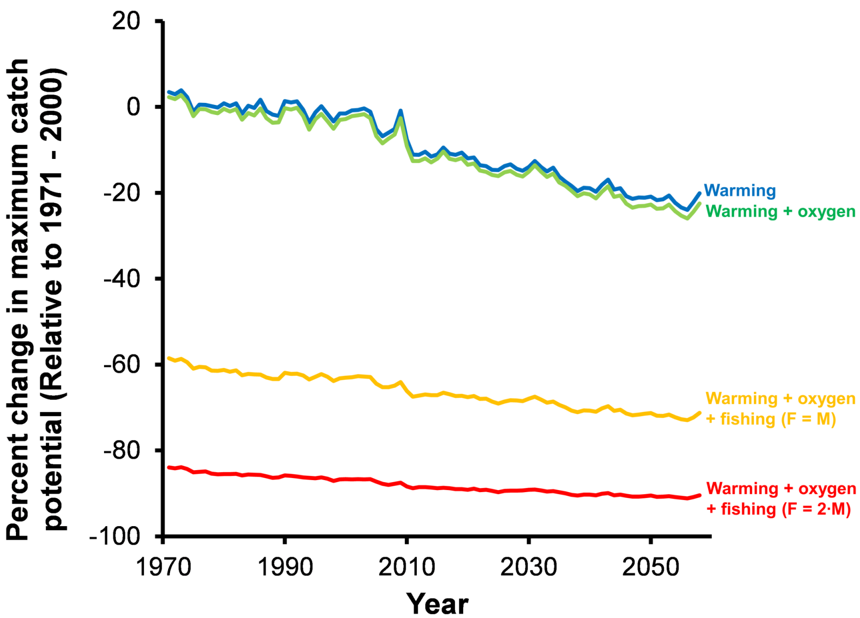
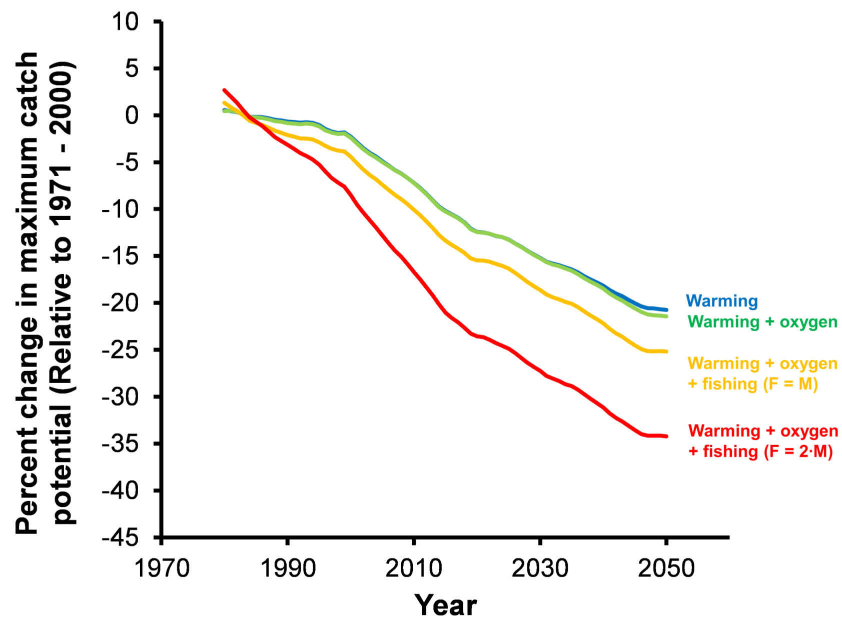
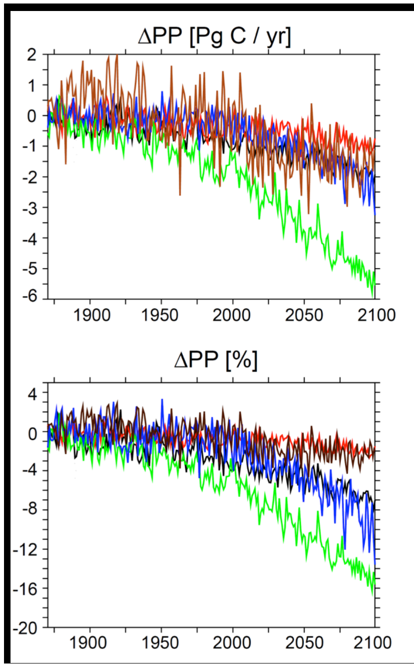
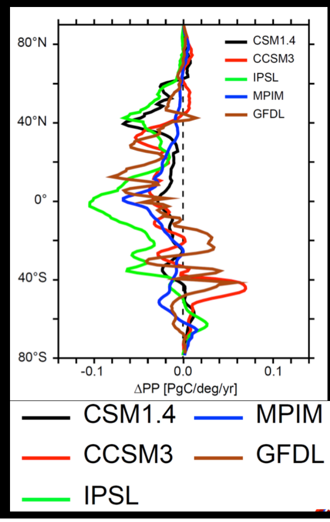

Percent change in maximum catch potential (Relative to 1971 - 2000)
Year
Warming
Warming + oxygen
Warming + oxygen
+ fishing (F = M)
Warming + oxygen
+ fishing (F = 2·M)


Percent change in maximum catch potential (Relative to 1971 - 2000)
Year
Warming
Warming + oxygen
Warming + oxygen
+ fishing (F = M)
Warming + oxygen
+ fishing (F = 2·M)

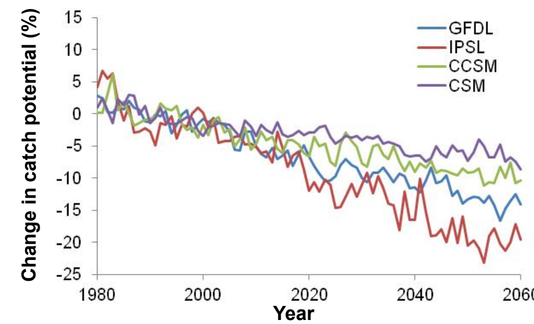


Projected decadal mean changes in marine primary production from 1860s to 2090s



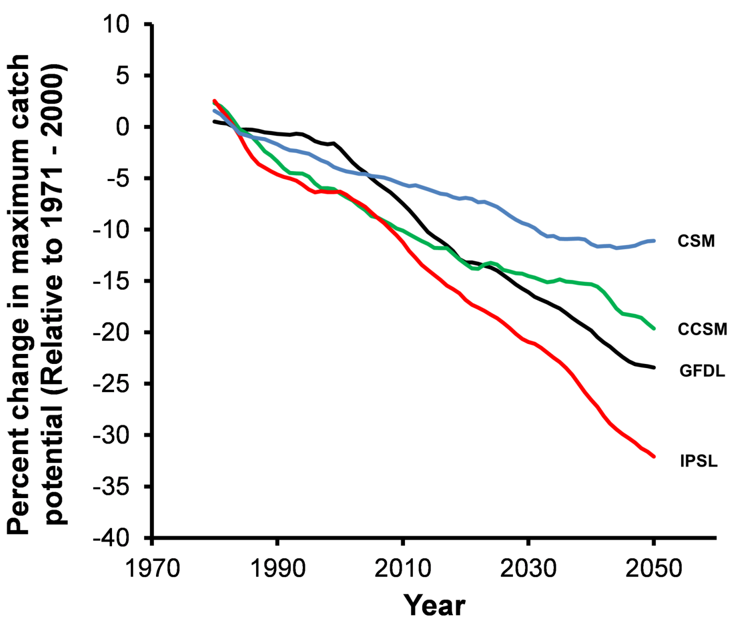
Predicted maximum catch potential between models

(with size structure +O_2)



- All models project decrease in overall maximum catch potential, ranging from 5 to 20% decrease by 2050 relative to 1980 – 2000.

Source: Cheung, Sarmiento, Froölicher, Pauly (in prep.)



Conclusions: fisheries response

- Climate change is expected to be one of the key drivers of changes in marine ecosystems and fisheries
- Changes include species distribution, individual and community body size, structure, and productivity.
- Marine fisheries are projected to be seriously affected through reductions and redistribution of fisheries resources and may in turn reduce the adaptive capacity of fish stocks.
- Ocean deoxygenation and acidification may exacerbate climate change impacts on marine ecosystems.

Additional considerations

- Detection of climate change impacts may be extremely challenging. Henson et al. (2010) and Henson et al. (in preparation) show that because of interannual variaibility it will take of order 40 years to detect global warming trends in satellite chlorophyll.
- Possibility of tipping points. Are our equations and models biased in favor of stable behavior? Do they include processes that may lead to tipping points?

The end