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Biogeochemical Modelling in the North Atlantic

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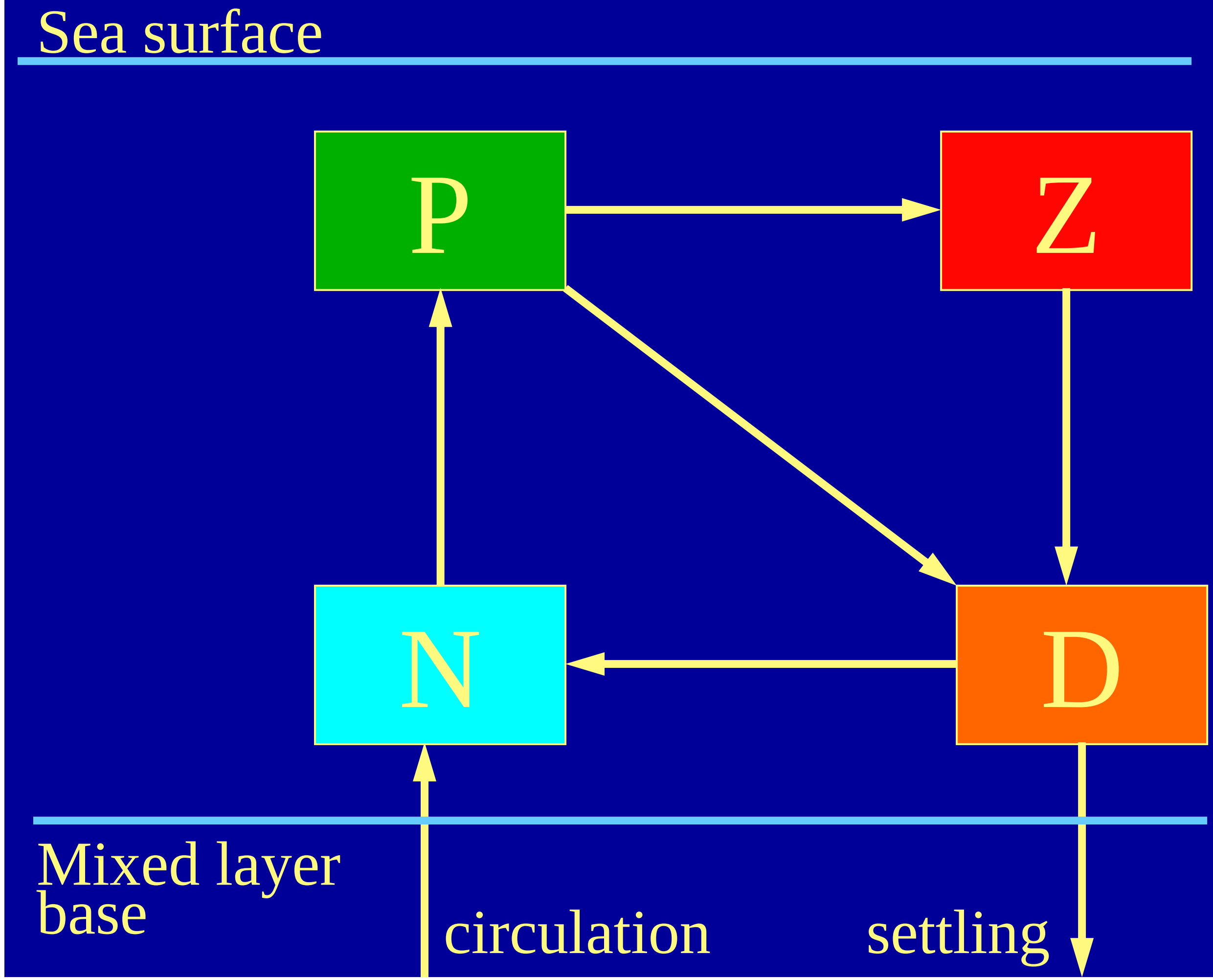
Overview

- Biogeochemical modelling in the North Atlantic - State of the art
- Model assessment and lessons from data assimilation studies
  - Discrepancy between lab results and models
  - Discrepancy between field data and models
  - Portability
  - Predictability
- Challenges and opportunities
  - Adaptive modelling
  - Property variables versus material variables

State of the art: Empirical Models

pre-JGOFS type



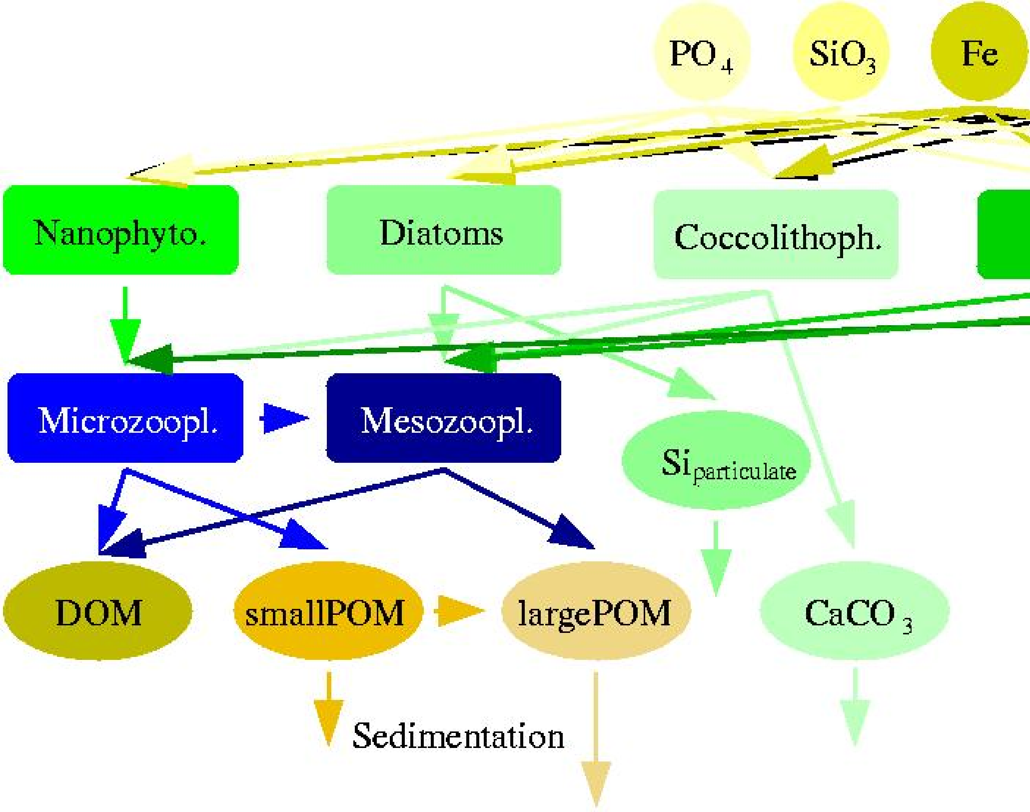
Steele (1958)

Wroblewski (1977)

Evans & Parslow (1985): spring bloom

Fasham *et al*. (1990): microbial loop

State of the art:
Functional-group type models



O(100) Parameters:

- uptake, loss rates
- remineralisation profiles
- multiple elements (N,P,C,Si,Fe)

Examples:

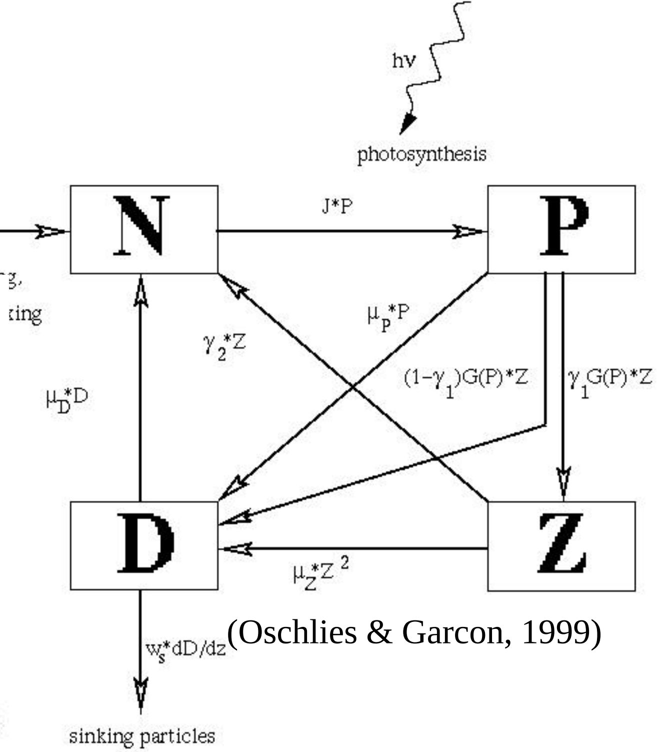
- Moore et al. (2002)
- Aumont et al. (2003)
- Gregg et al. (2003)
- “Dynamic Green Ocean Model“ consortium

The “cost” of ecological complexity

Ecosystem model	**stoichiometry**	**Number of adjustable parameters**
Restoring	usually Redfield	O(1)
NPZD-type	usually Redfield	O(10)
Multiple functional groups, multiple elemental cycles	prognostic	O(100)

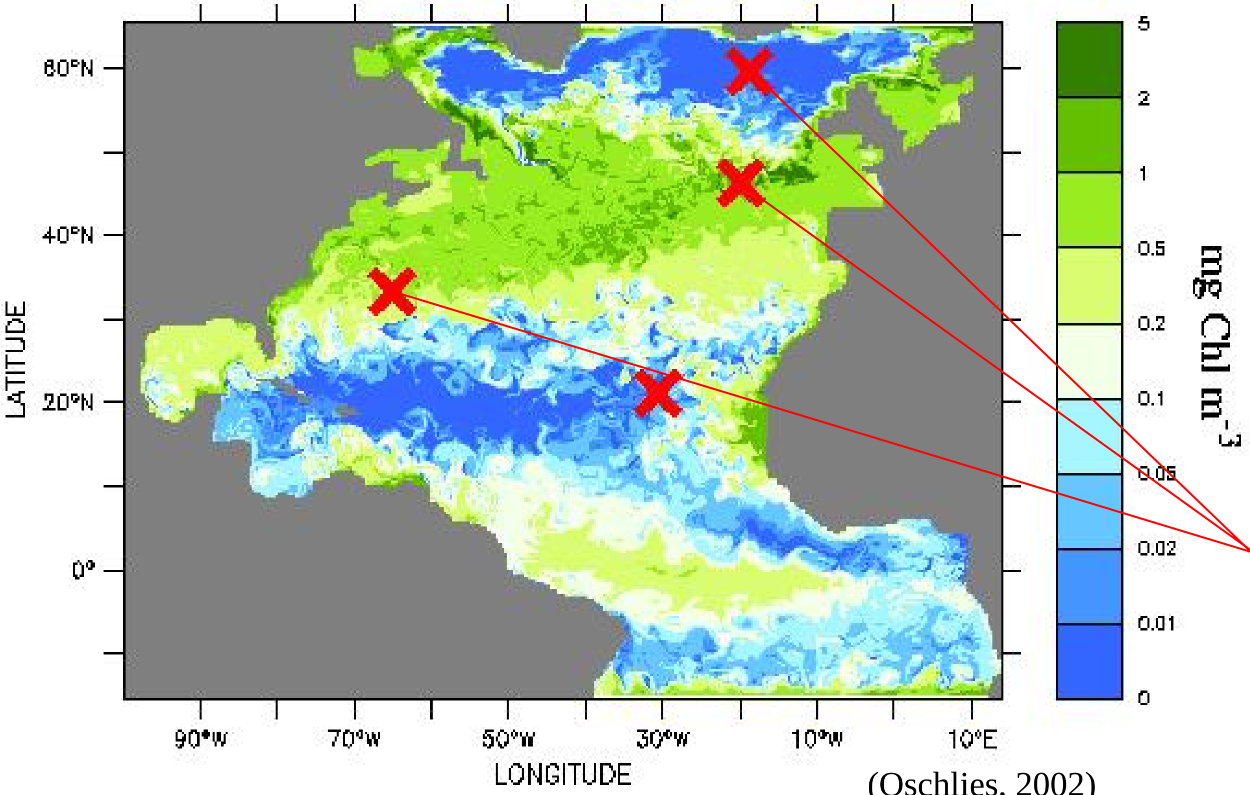
Eddy-resolving Modelling

N-based ecosystem model



(Oschlies & Garcon, 1999)

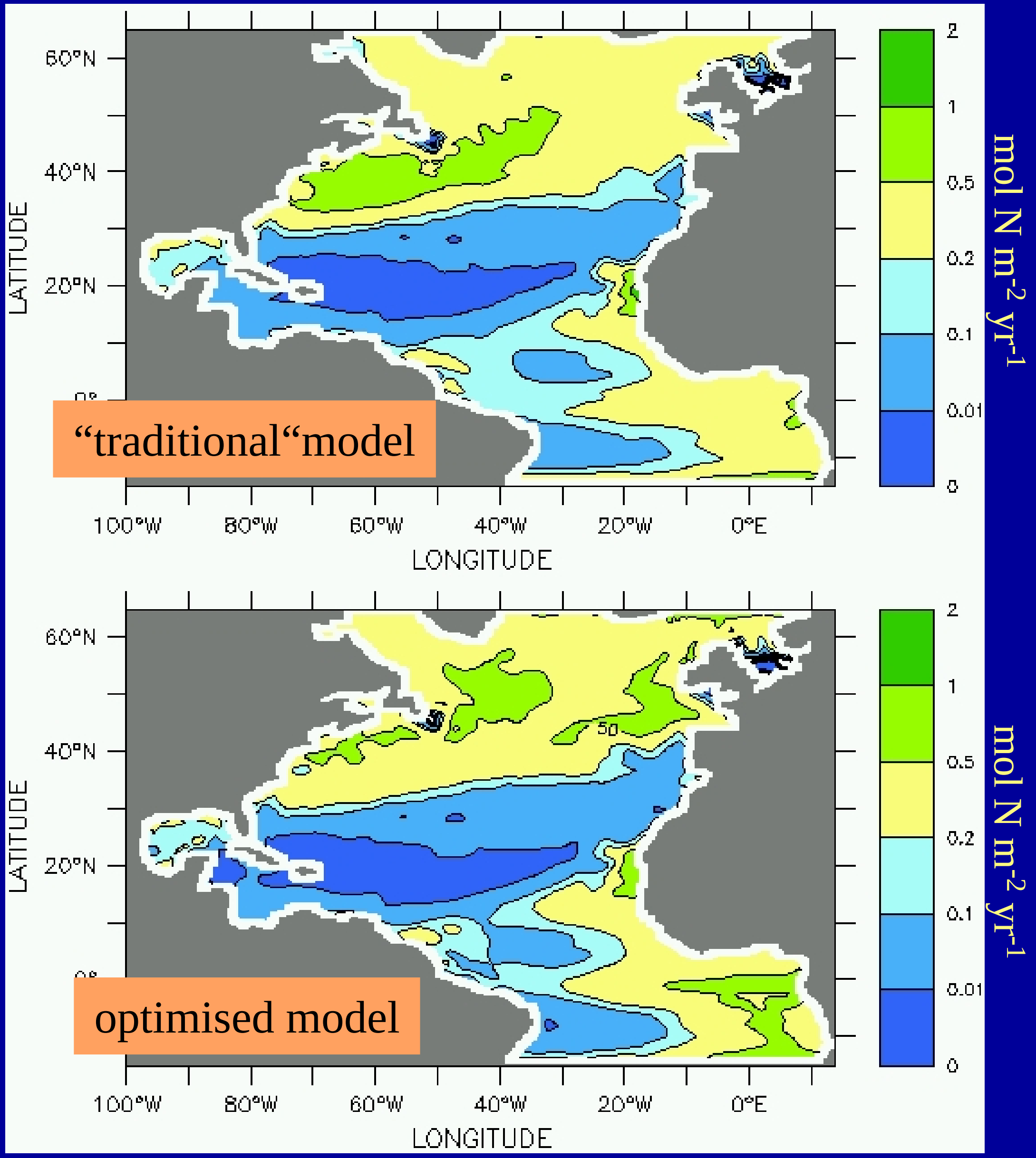
Simulated spring bloom at (1/9)º resolution



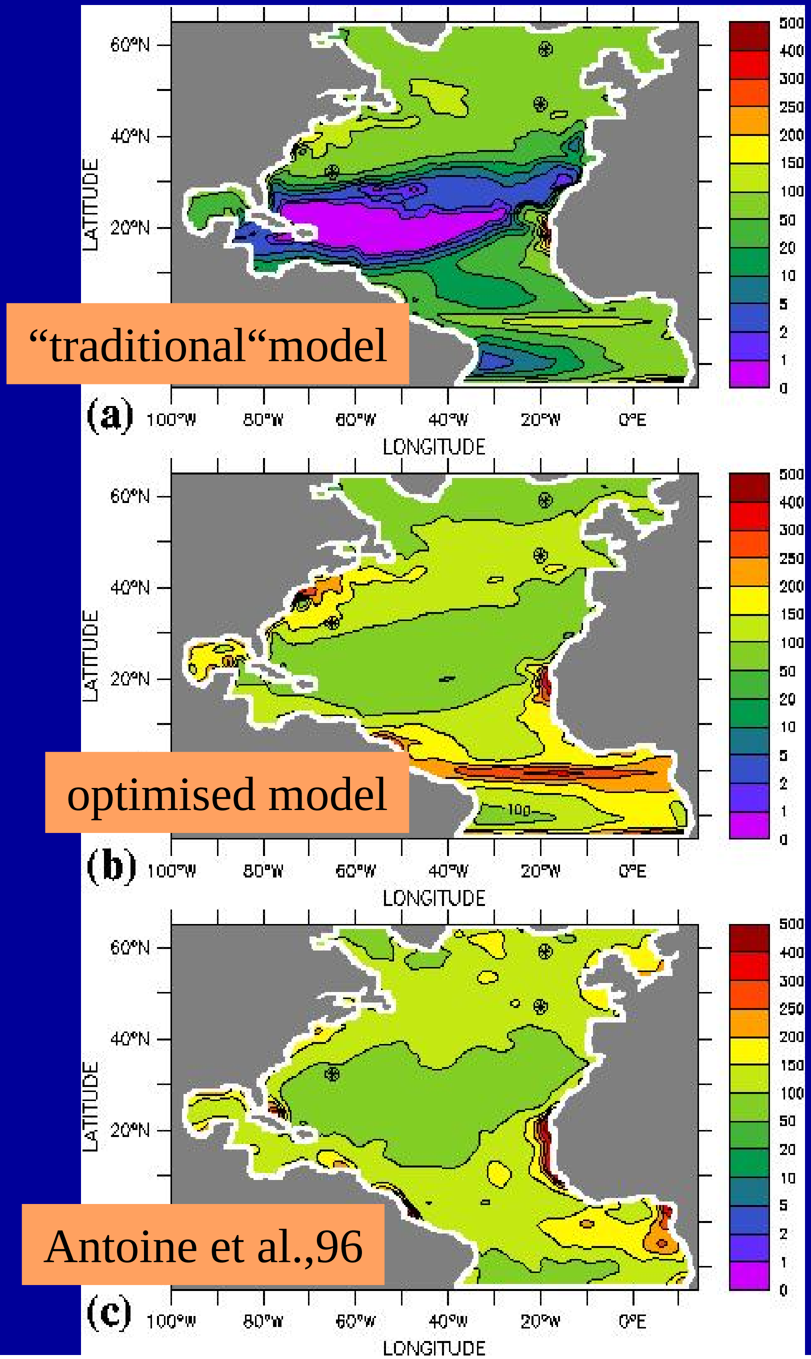
(Oschlies, 2002)

Model optimisation by data assimilation.
(genetic algorithm,
Schartau & Oschlies, 2003a,b)

Results: Very little change in export production



Annual Primary Production (gC m^{-2})

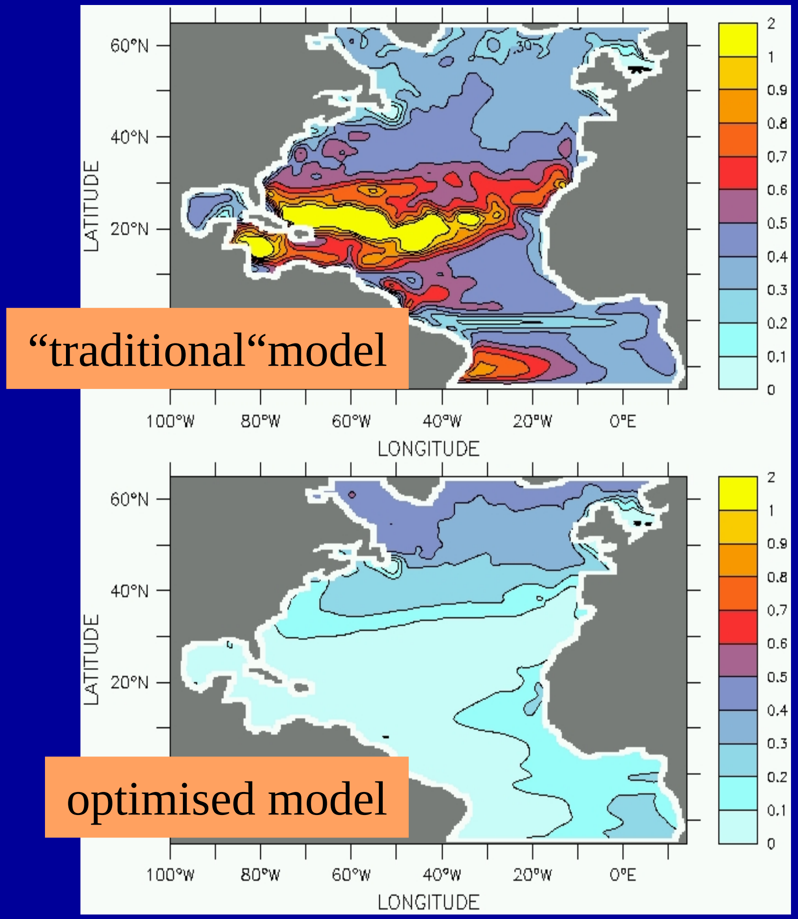


“traditional“model

optimised model

Antoine et al.,96

Simulated Export Ratio



“traditional“model

optimised model

1D-calibration of poorly known model parameters results in significant improvements in PP, ef-ratio and ecosystem dynamics even in 3D.

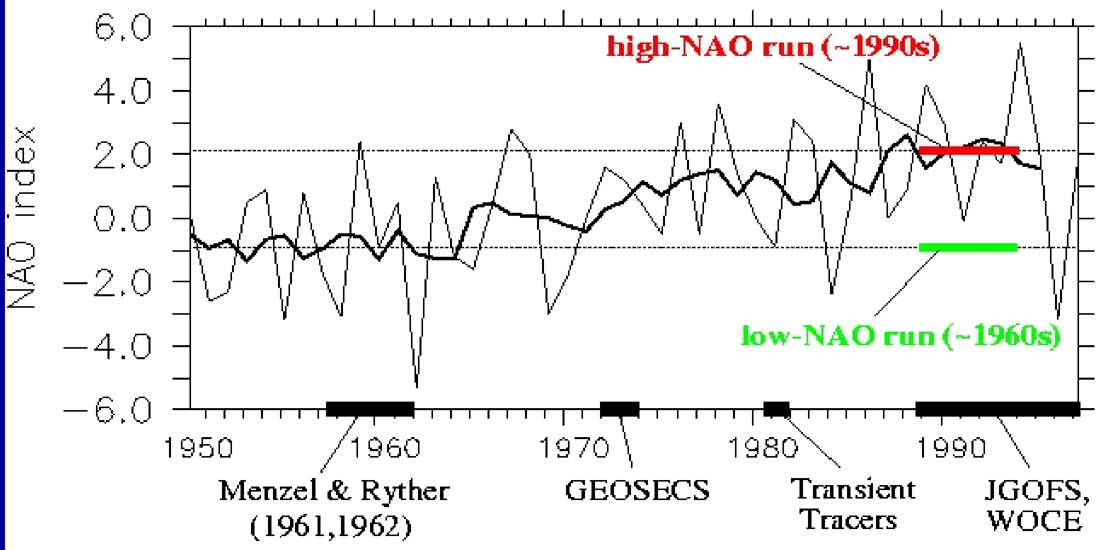
(Oschlies & Schartau, 2005)

How to simulate biogeochemical cycles in the anthropocene?

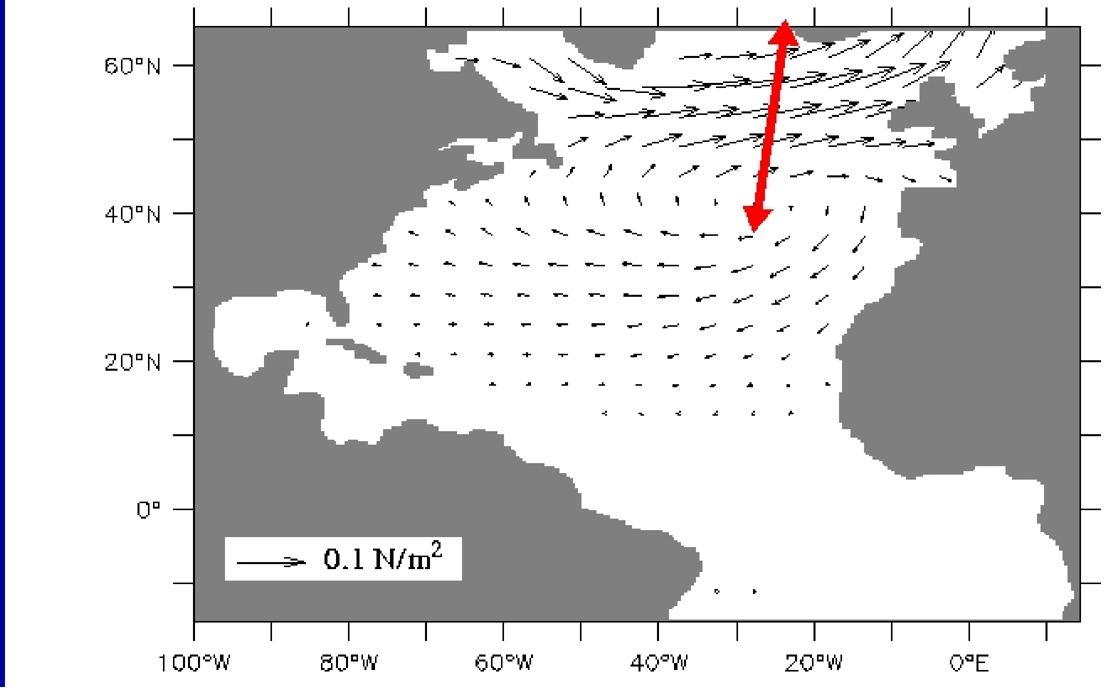
- Shifts in biogeographical provinces
  - Temperature
  - Stratification, mixing
  - Sea ice

Should -in principle- be OK with current models.

Example: NAO related variability



NAO index



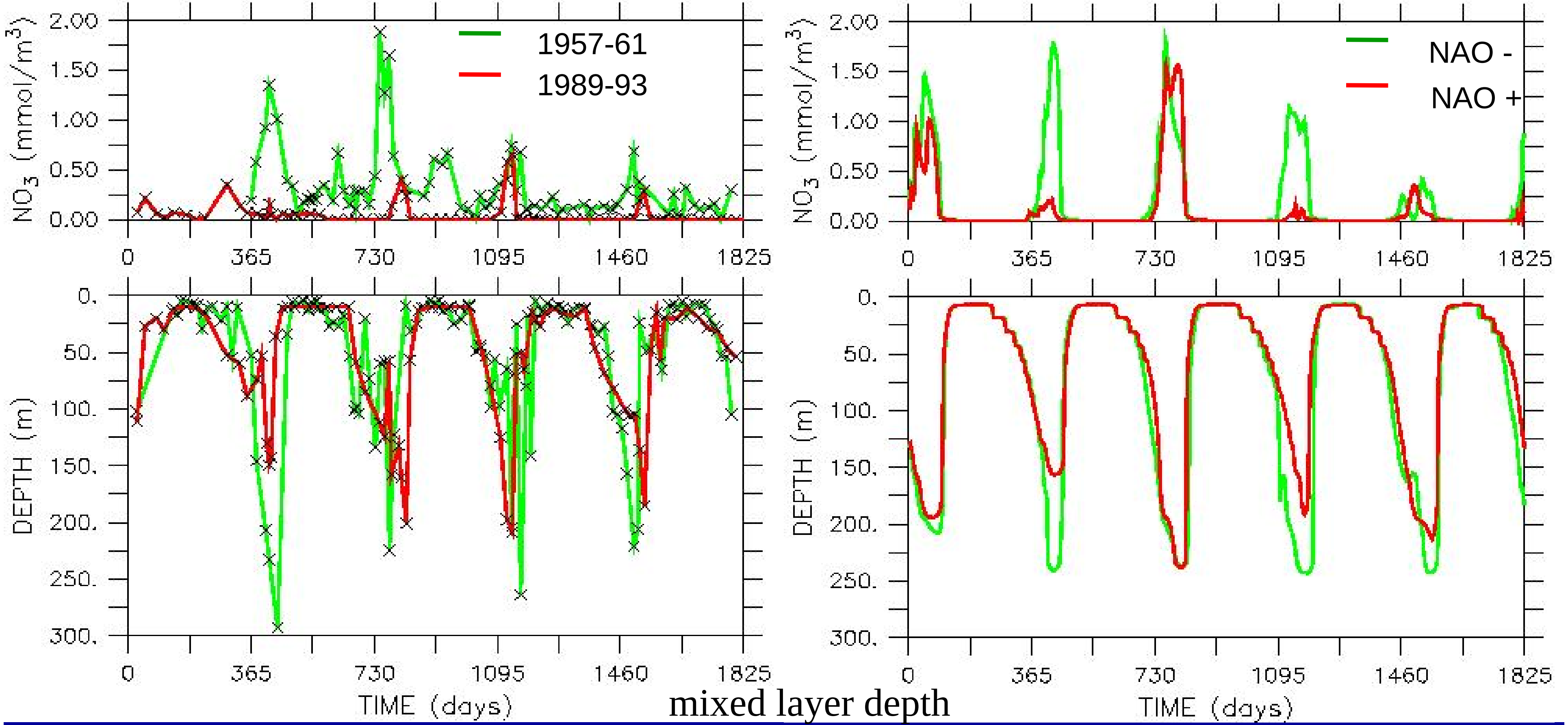
Wind stress difference:
(high NAO) minus (low NAO)

NAO related variability at BATS

Observations

Simulation

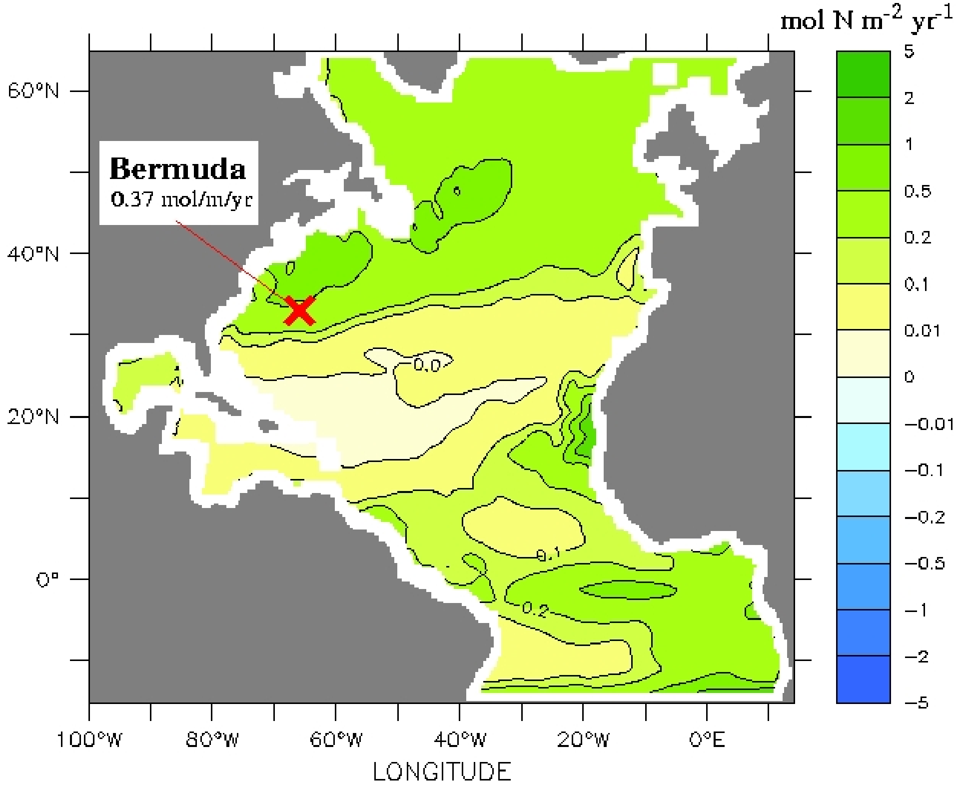
surface NO_3



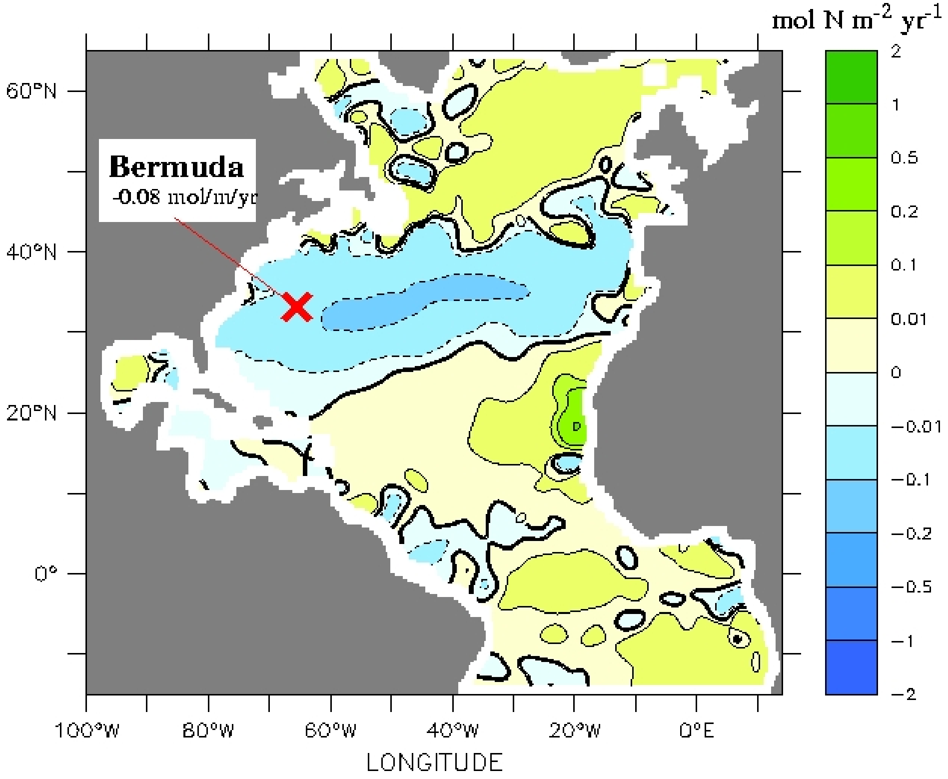
mixed layer depth

NAO-related PON export variations

PON export z_{euph},
high NAO



ΔPON export z_{euph},
high NAO minus low NAO

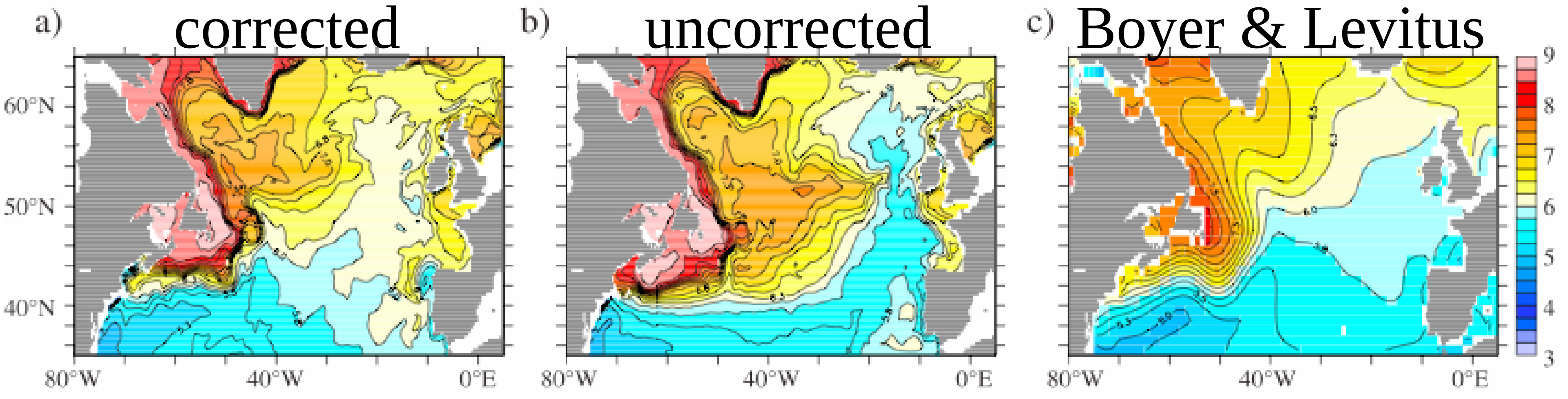


(Oschlies, 2002)

Correcting for physical model biases

Semi-prognostic, adiabatic correction method

Dissolved O_2 [ml/l]



corrected

uncorrected

Boyer & Levitus

(Eden & Oschlies, 2006)

How to simulate biogeochemical cycles in the anthropocene?

- Shifts in biogeographical provinces
  - Temperature
  - Stratification, mixing
  - Sea ice

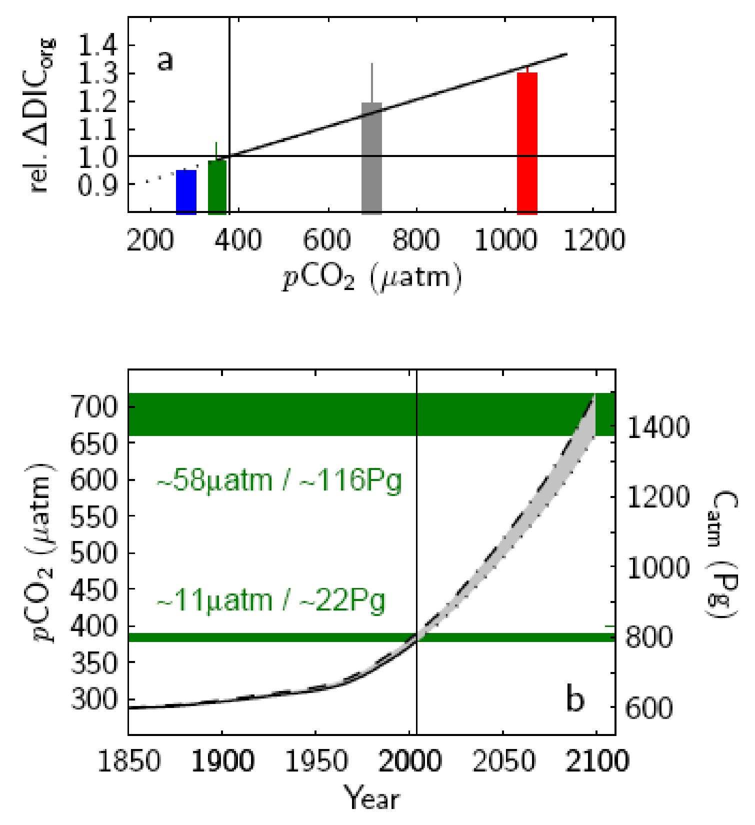
  Should -in principle- be OK with current models.

- Extrapolating to new conditions
  - Increasing temperatures of warmest waters
  - Acidification

  Questionable with current models!

Example: pCO_2-sensitive stoichiometry

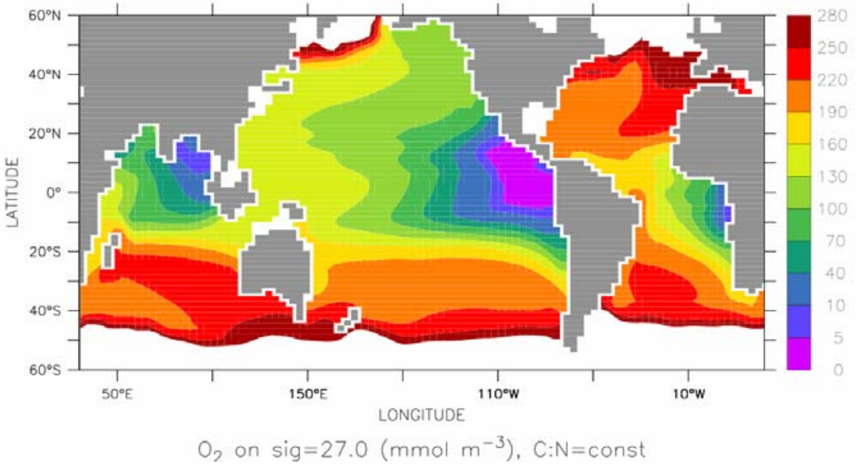
- Mesocosm experiments suggest increase of C:N in export

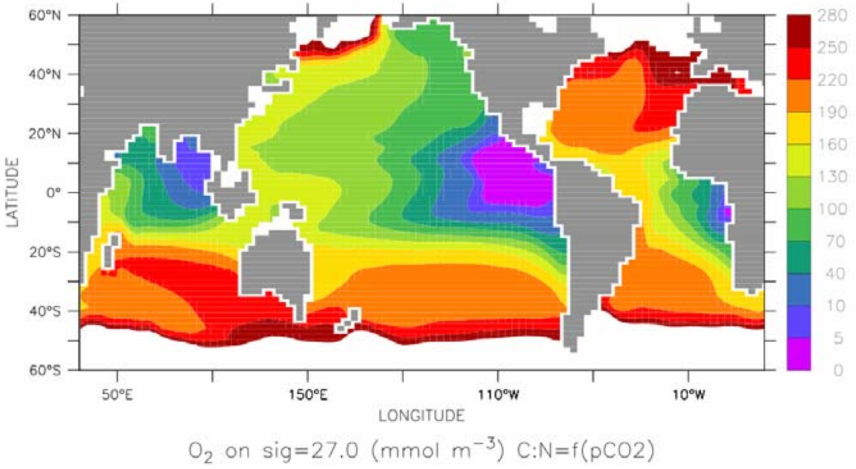


(Riebesell et al., subm)

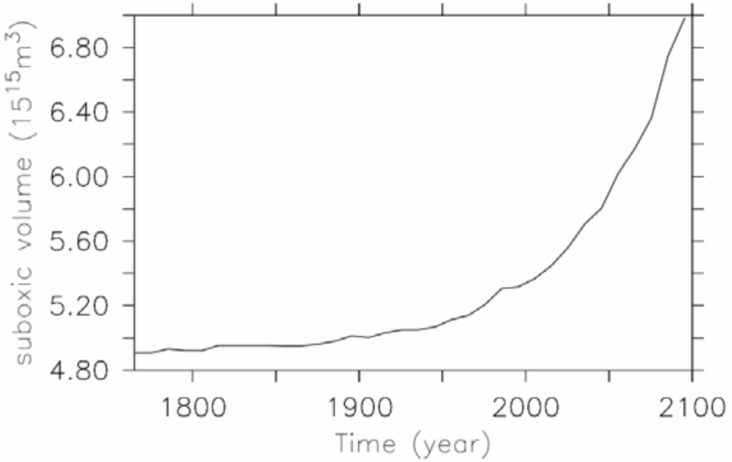
Simulated increase in suboxic areas

O_2 on 27.0 isopycnal

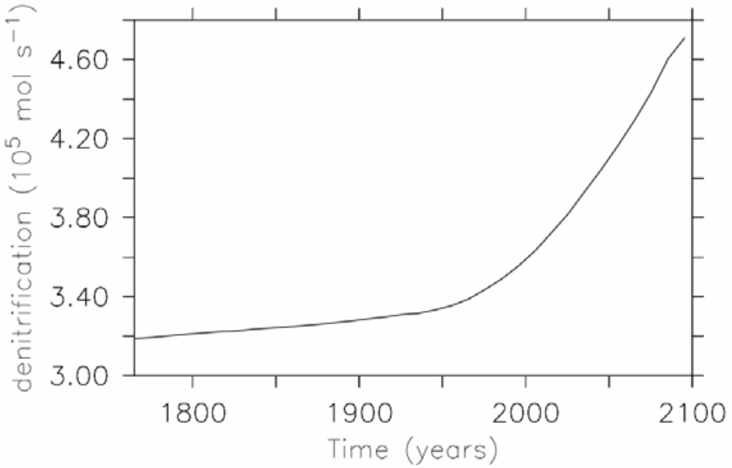




Suboxic volume



Denitrification



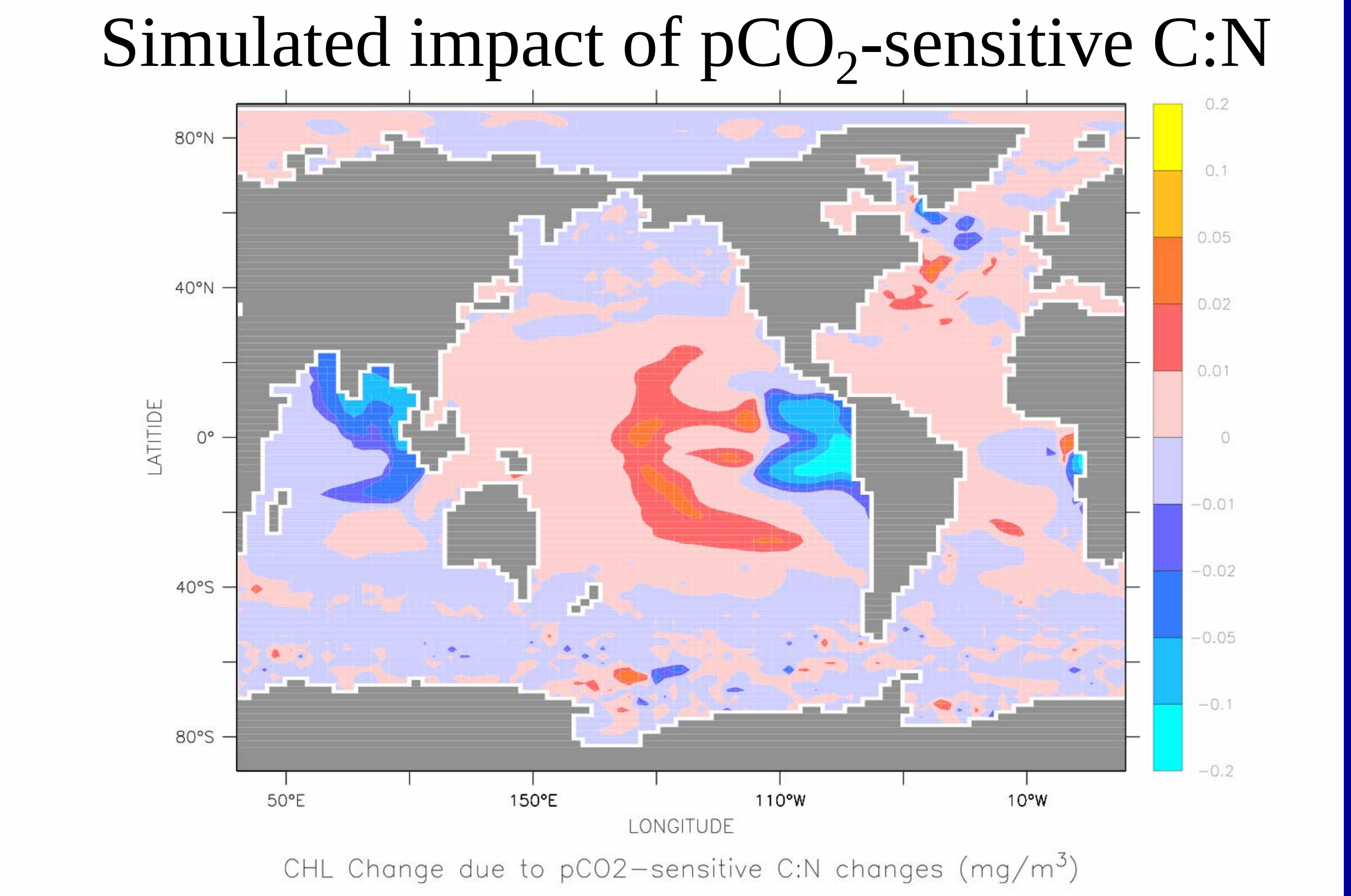
Change in surface chlorophyll

Satellite-derived changes 2003-1998

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

(Gregg et al., 2005)

Simulated Changes in Chlorophyll



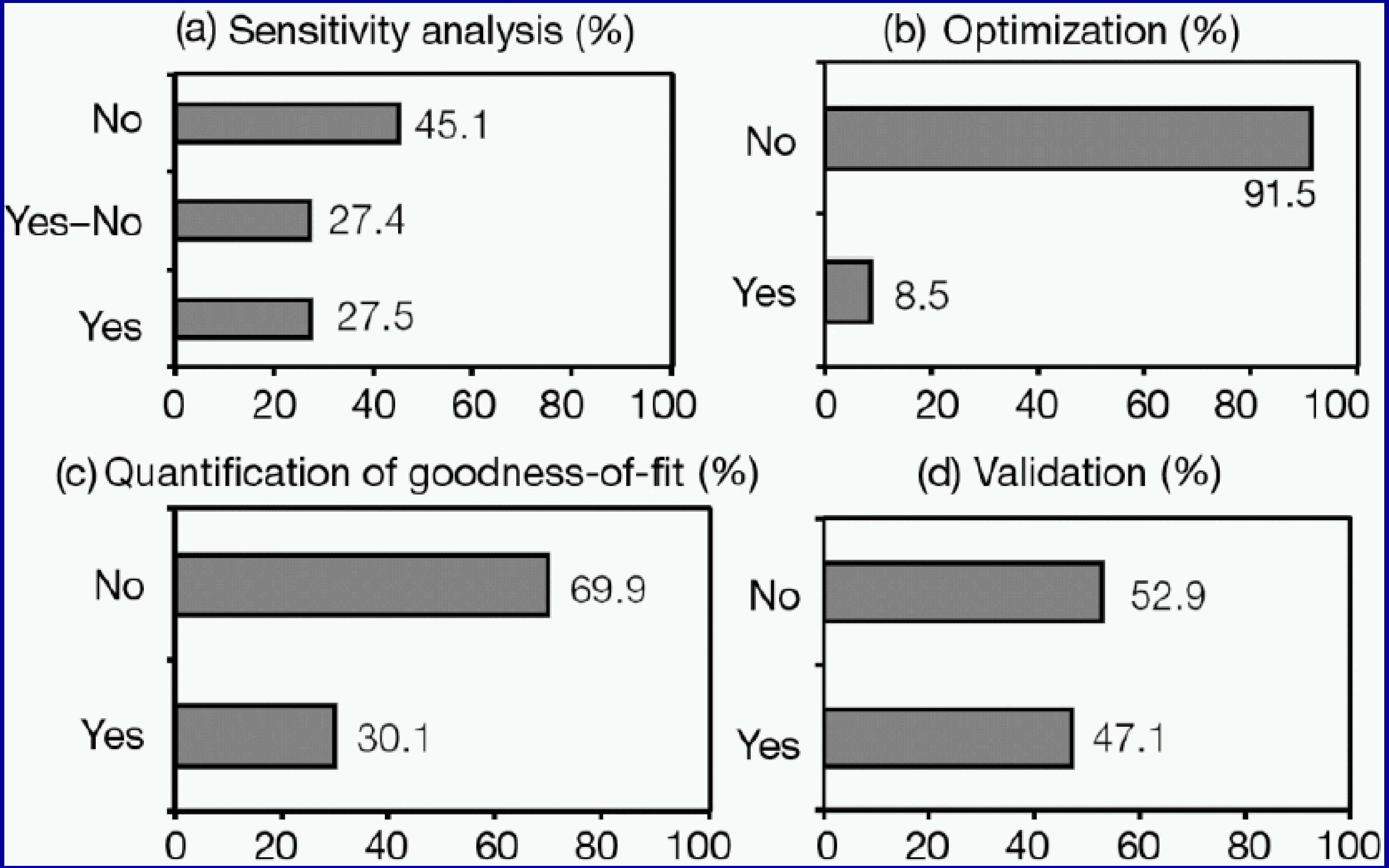
Zooplankton utilise C and N but not Chl!

Part II

How can we assess our models?

Crisis in marine ecological modelling

Analysis of 153 publications of aquatic ecosystem models (1990-2002)



(Arhonditsis & Brett, 2004)

Modellers’ Codex

- State underlying assumptions
  (“a model is not more than you put into it“)

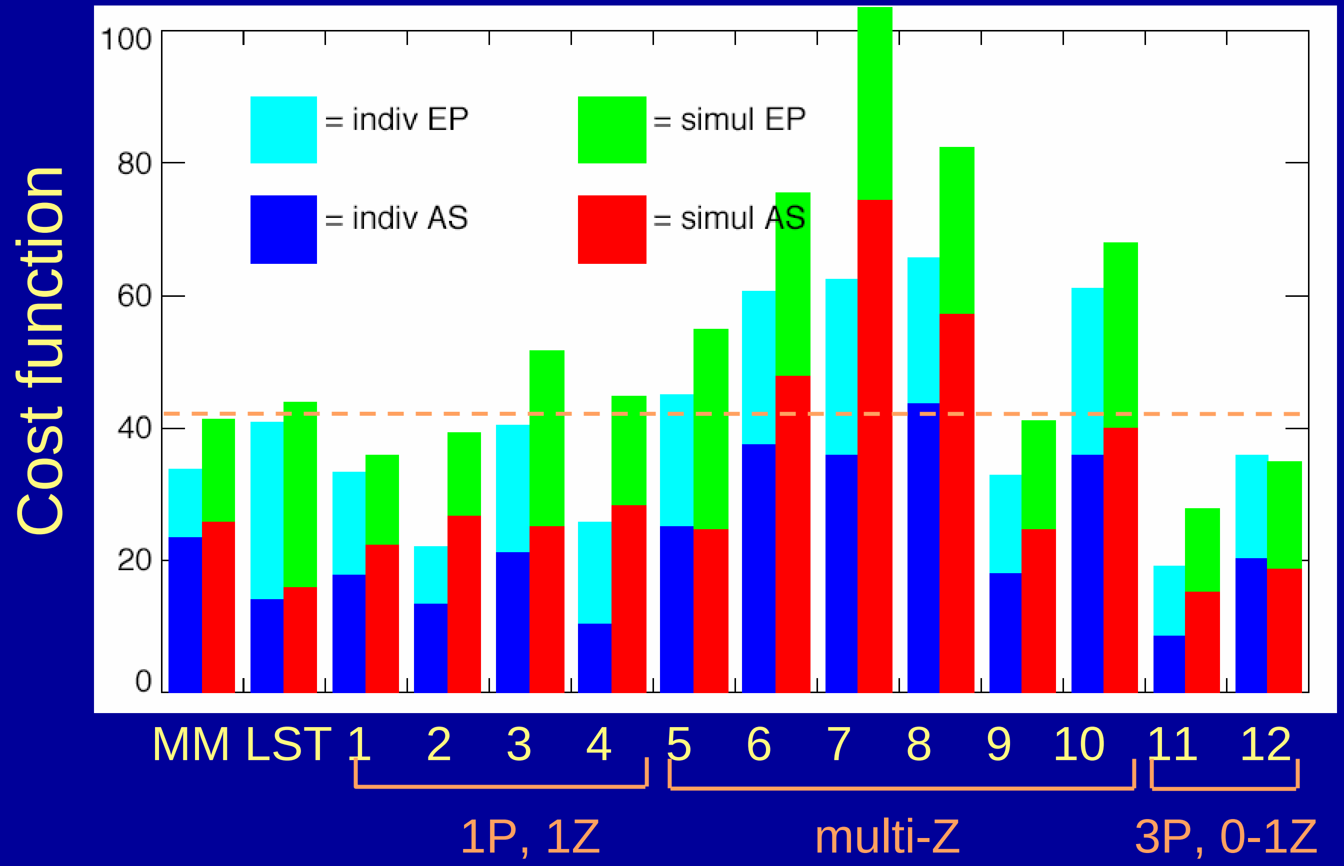
- Aim for quantitative model evaluation
  (goal function, cost function)

U.S. JGOFS test-bed project: Ecosystem model descriptions

- Models 1-4: N, P, Z, D (NH_4,DOM, C:chl, T) (CCMA, McCreary, Hood, Anderson/McGillicuddy)
- Models 5-6: 2P, 2Z, Fe (Christain, Wiggert)
- Model 7: 2P, 2Z, Si (Chai)
- Model 8: 2P, 3Z, Si, DOM (Fujii)
- Model 9: 2P, 4Z, DOM (Laws/Hood)
- Model 10: C, Alk, P, Z, 2DOM (Schartau)
- Model 11: 3P, 0Z, 3DOM, Si, Fe (Dunne)
- Model 12: 3P, 1Z, 4DOM, Si, Fe (Dusenberry/Doney/Moore)
- MM: Mean Model
- LST: Least Squares Test (N,P,Z,D) (Friedrichs/Hood/Wiggert/Laws)

(courtesy Raleigh Hood)

First results of U.S. test-bed project



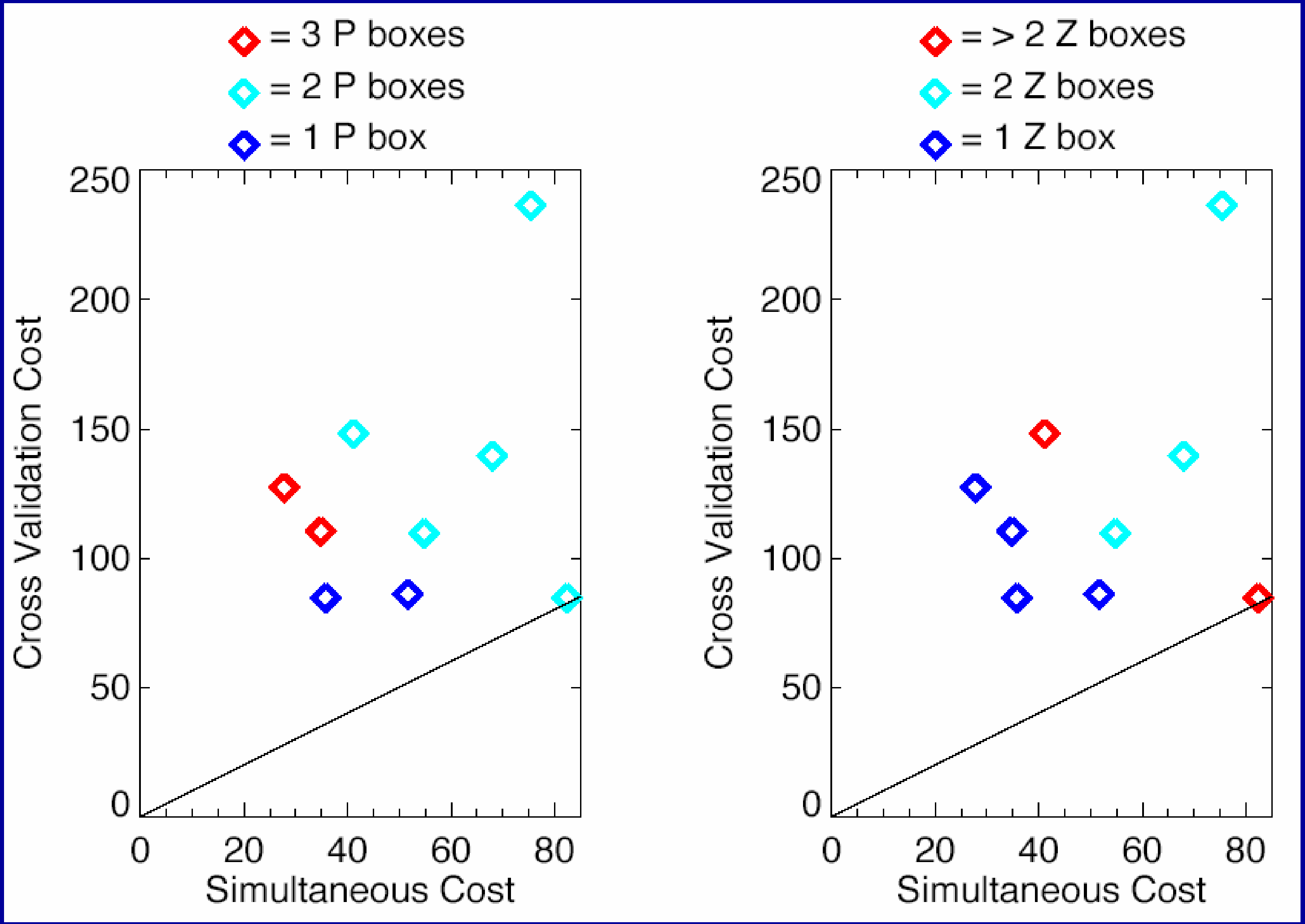
-Most models do significantly better for individual assimilation

-Only 4 models do substantially better than MM = ‘Mean Model’

-More complex models (#5-12) show greater variability in performance and they do not necessarily perform better than the simple NPZD models (#1-4)

(courtesy Raleigh Hood)

Portability



- More complex models are not always more portable (e.g. to different climate regimes).

(courtesy of Raleigh Hood)

Lessons from data assimilation studies (so far mainly NPZD-type models)

(Fasham & Evans, 1995; Matear, 1995; Prunet et al., 1996; Hurtt & Armstrong, 1996/1999; Spitz et al., 1998/2001; Fennel et al., 2001; Schartau et al., 2001; Friedrichs, 2002; Schartau & Oschlies, 2003; Oschlies & Schartau, 2005; U.S. JGOFS testbed project....)

- Only 10-15 parameters can be constrained.
  - Lots of unconstrained degrees of freedom. Makes extrapolation to different climate conditions problematic.
    - models too complex?
- Model-data fits remain relatively poor.
  - Errors in physical forcing.
    - models not complex enough?

Do we yet have the right model structures?

Part III

How can we improve our models?

Strategy I:
increase complexity

- Reduce misfits
  - Add degree of realism
  - Add degrees of freedom

- How to constrain model?
  - More (and more detailed) observations
  - Physiological information

Strategy II:
reduce model complexity

- Statistical approaches
  - Attractor in phase space
  - Dominant modes

  - Assumption of stationarity?
  - Biological meaning of model variables? (so what?)

- Aggregation of model compartments
  - Uses complex model results as reference solution
  - Assumes overall model structure to be OK

Strategy III: Mechanistic Models

Search for governing equations

Conservation equations:

- nutrients (N, P, Si, Fe, etc.)
- energy (light, C_{org})

Membrane physics:

- transport processes

Thermodynamics:

- chemical potential differences
- Basic metabolic equations + non-equilibrium thermodynamics

Physiological invariants:

- DNA, RNA, proteins, amino acids
- Dynamic Energy Budget theory

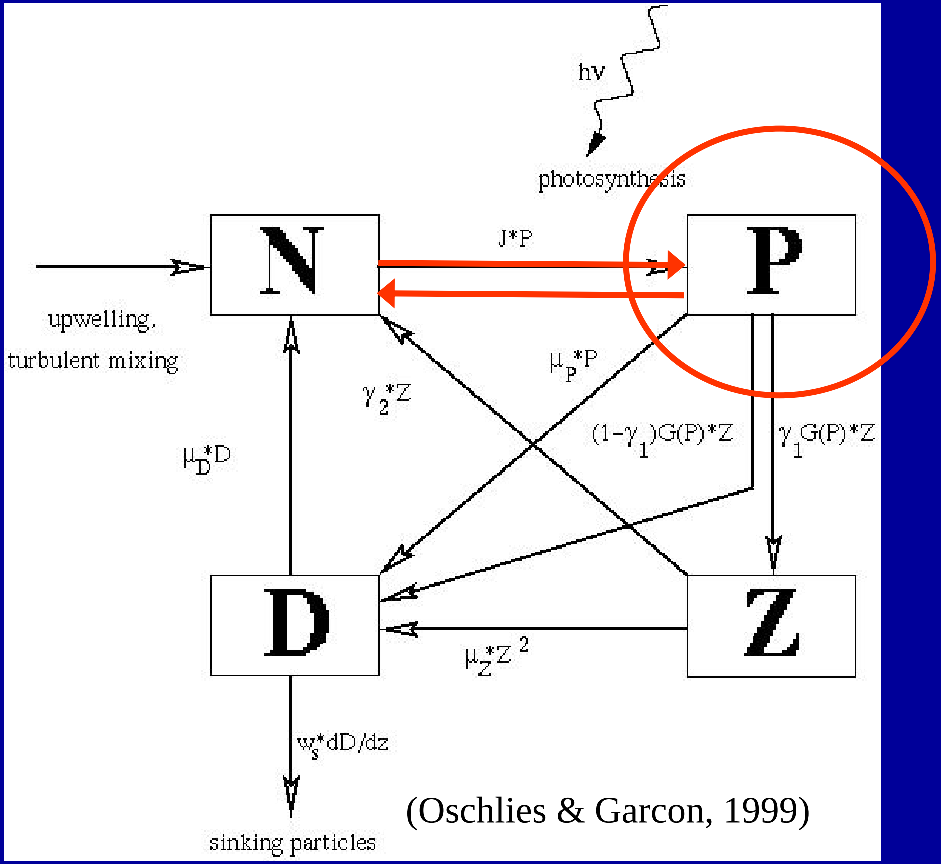
Strategy IV: Adaptive Models

Acknowledge uncertainties: adaptive modelling

1. Material variables
   (e.g., DIN, PHY(N), PHY(C), ZOO,…)

2. Property variables
   (e.g., T_{opt}, food preference, variance of Property distribution,…)

Example 1: Size as property



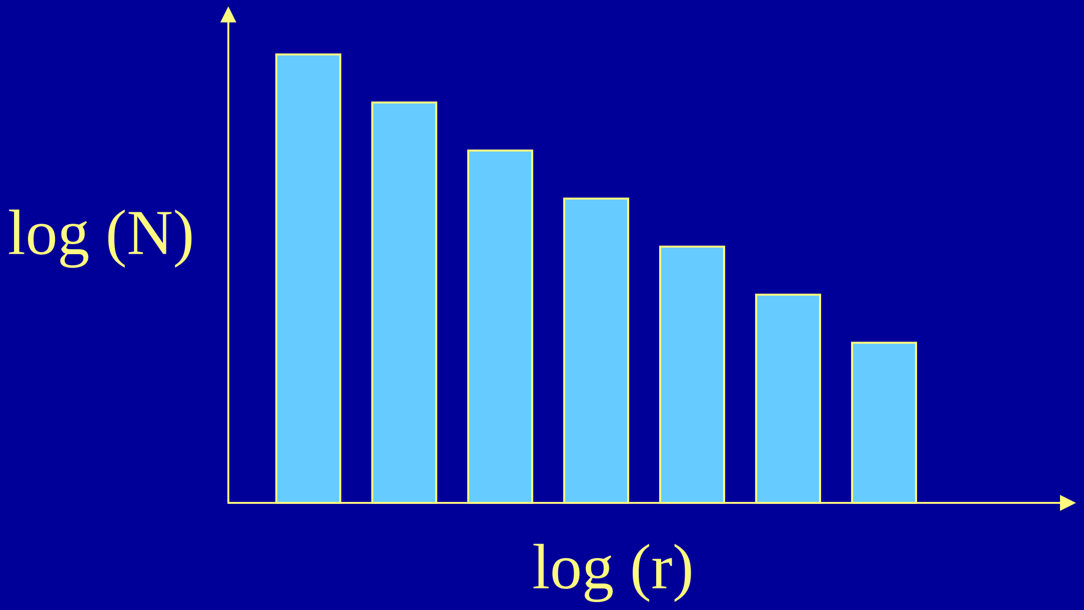
(Oschlies & Garcon, 1999)

N-based ecosystem model + equation for number of PHY cells

➔Diagnose spectral slope from phytoplankton biomass and cell number.

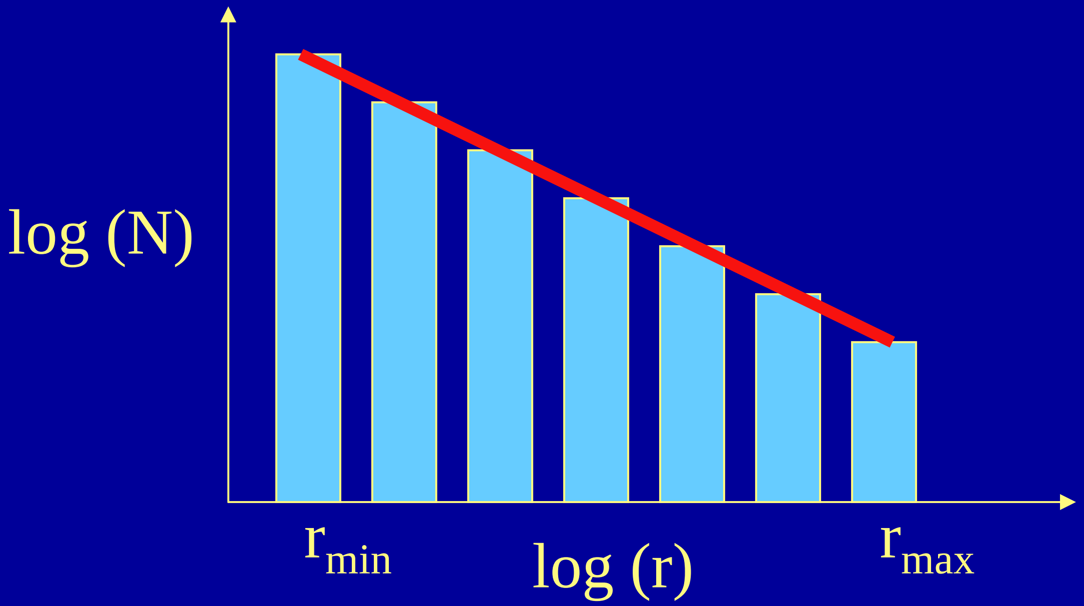
➔Integrate V(r) and λ(r) analytically over entire size spectrum.

Representing Size



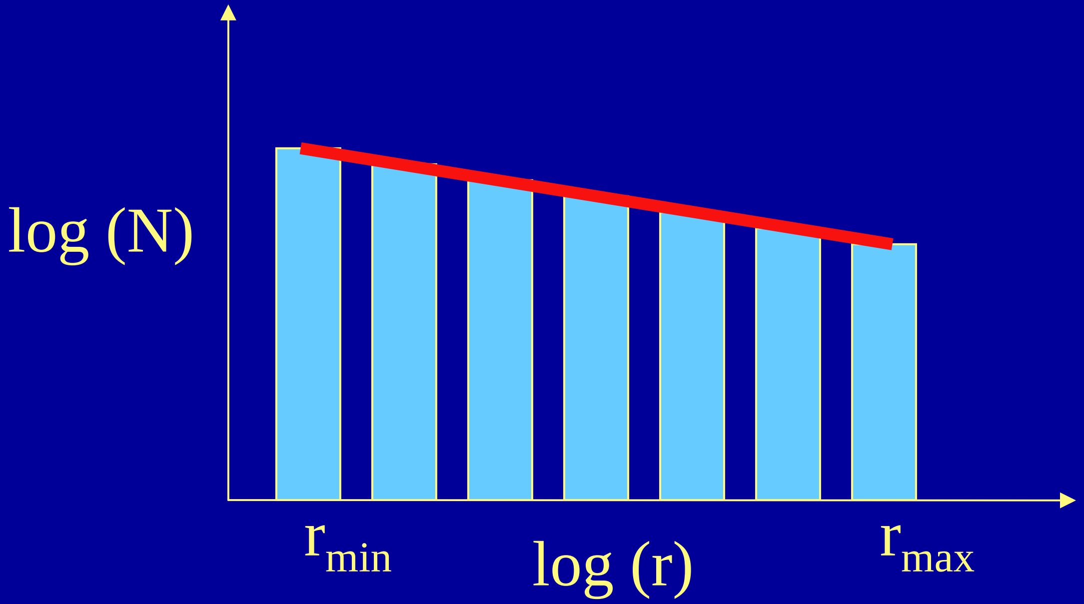
Discrete, explicitly resolved size classes

Representing Size



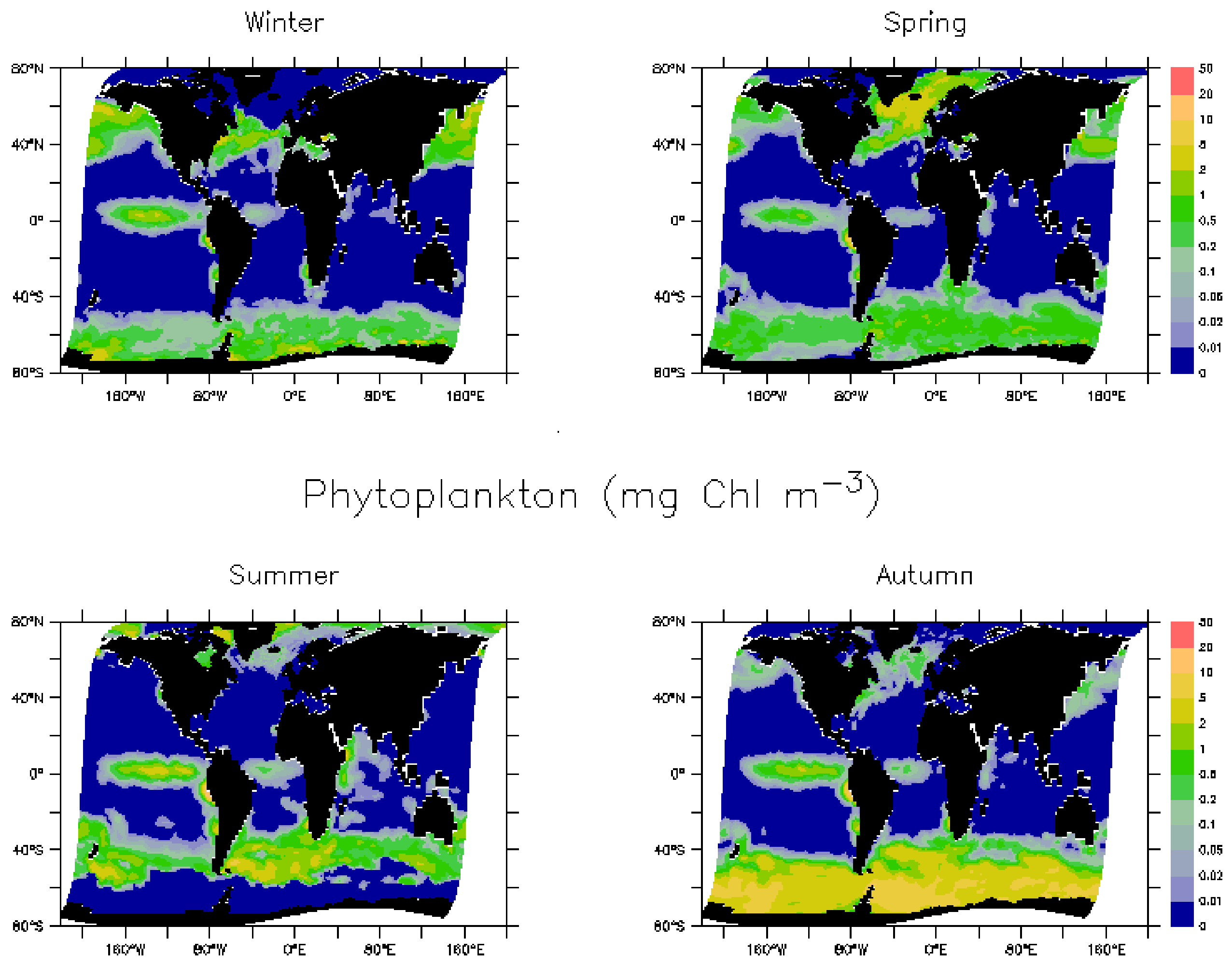
Continuous size spectrum (between r_{min} , r_{max})

Representing Size

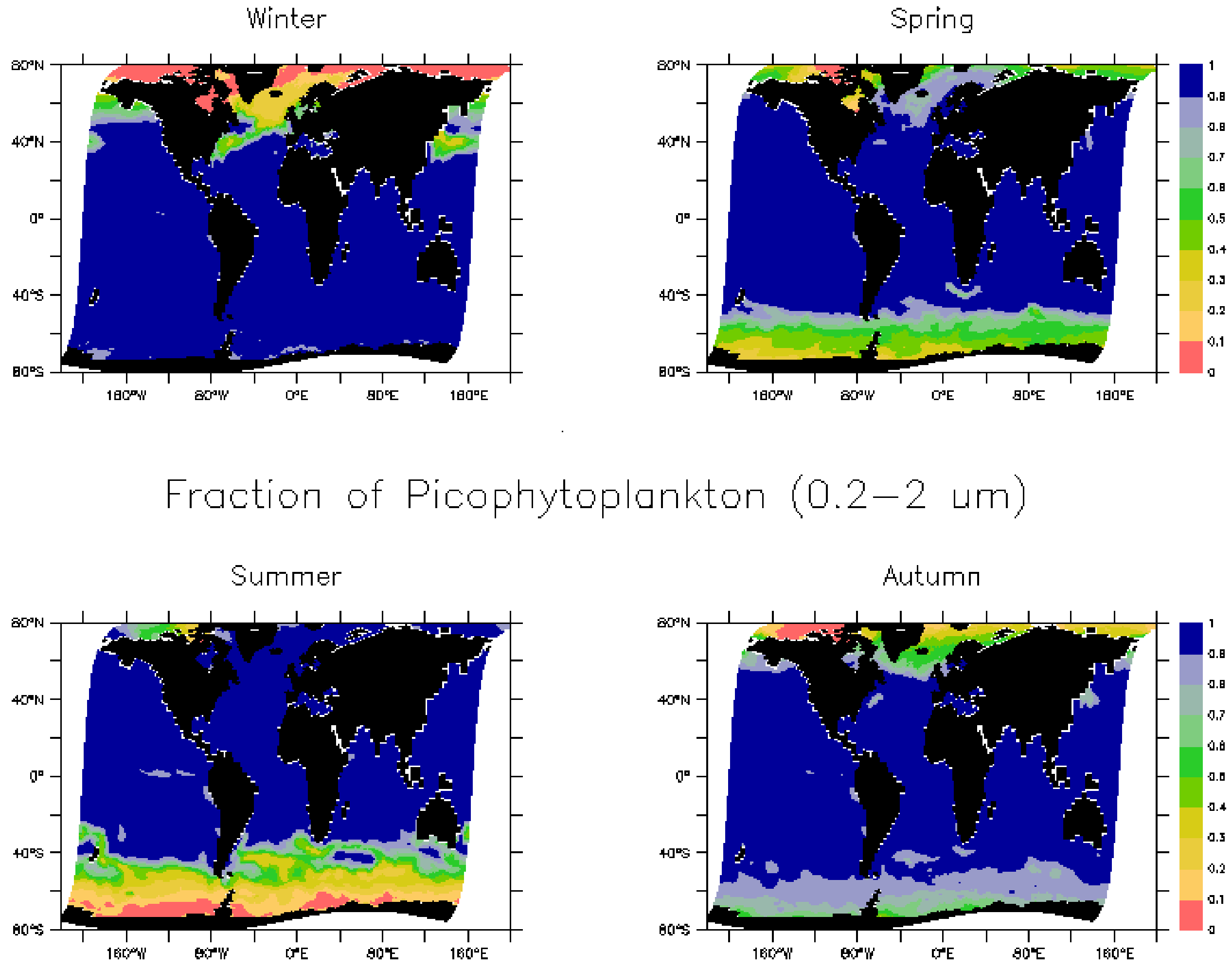


Continuous size spectrum (between r_{min} , r_{max})

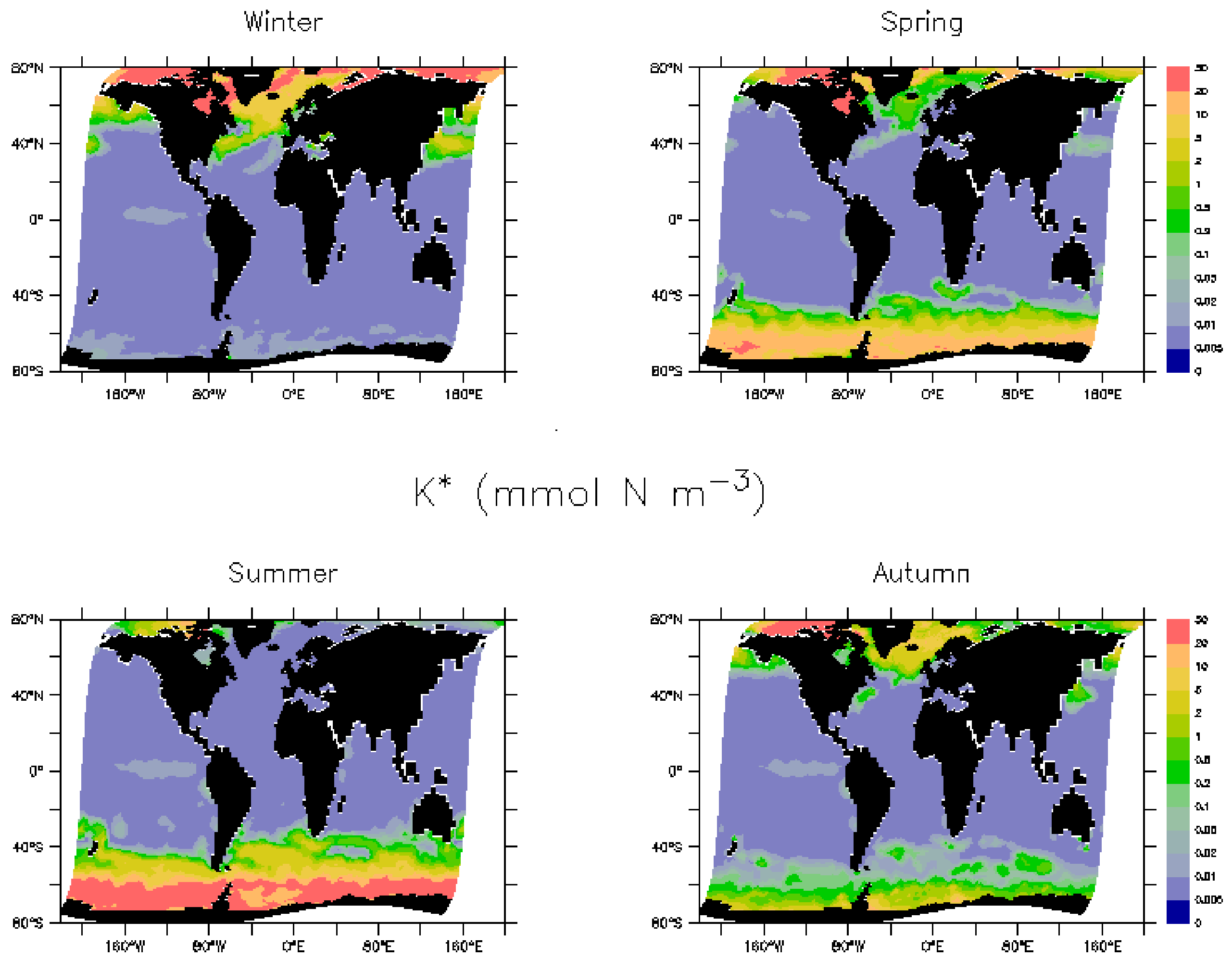
Global implementation of size-structured model



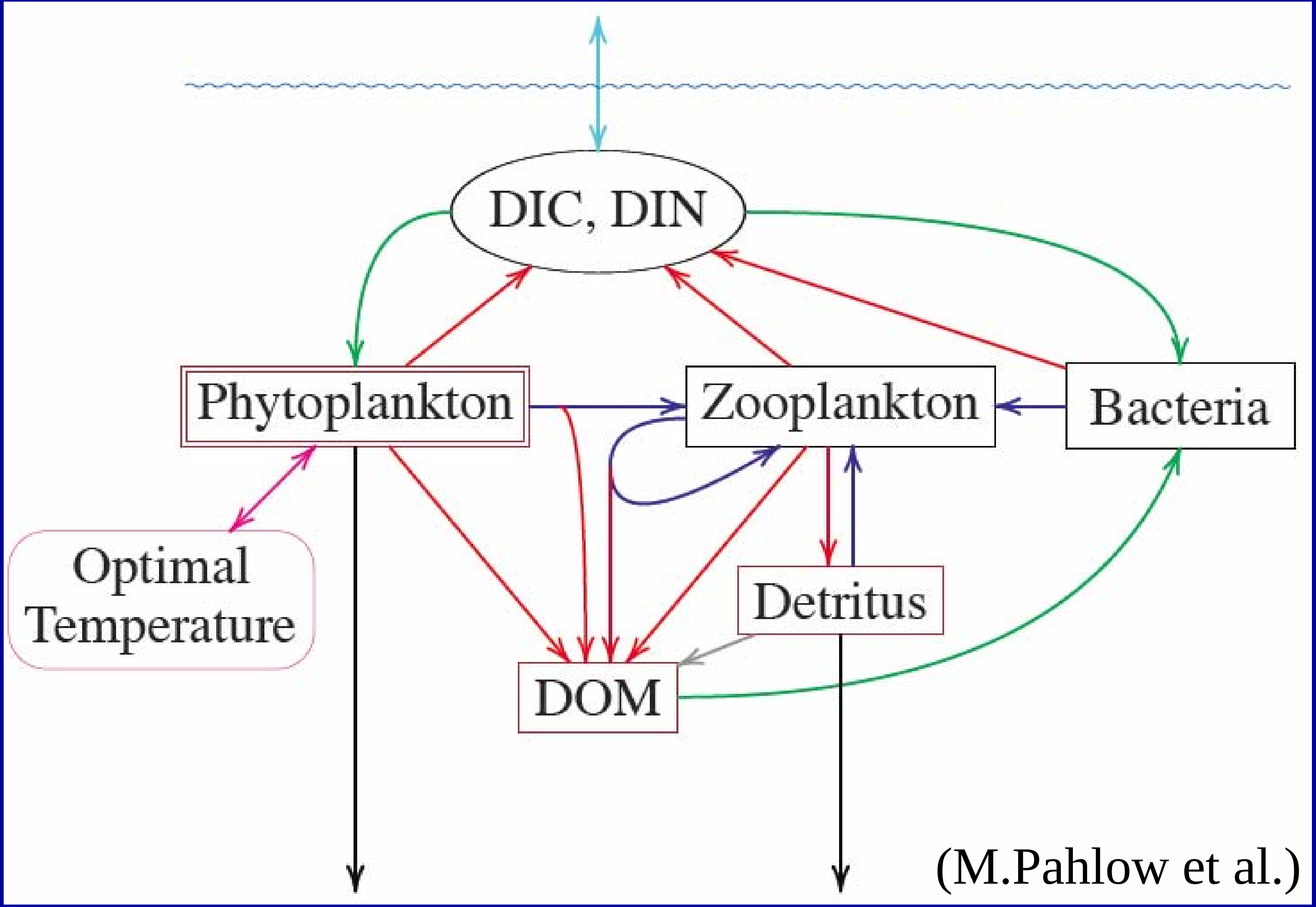
Fraction of Picophytoplankton (0.2-2μm)



Effective half-saturation “constant” for NO_3 uptake

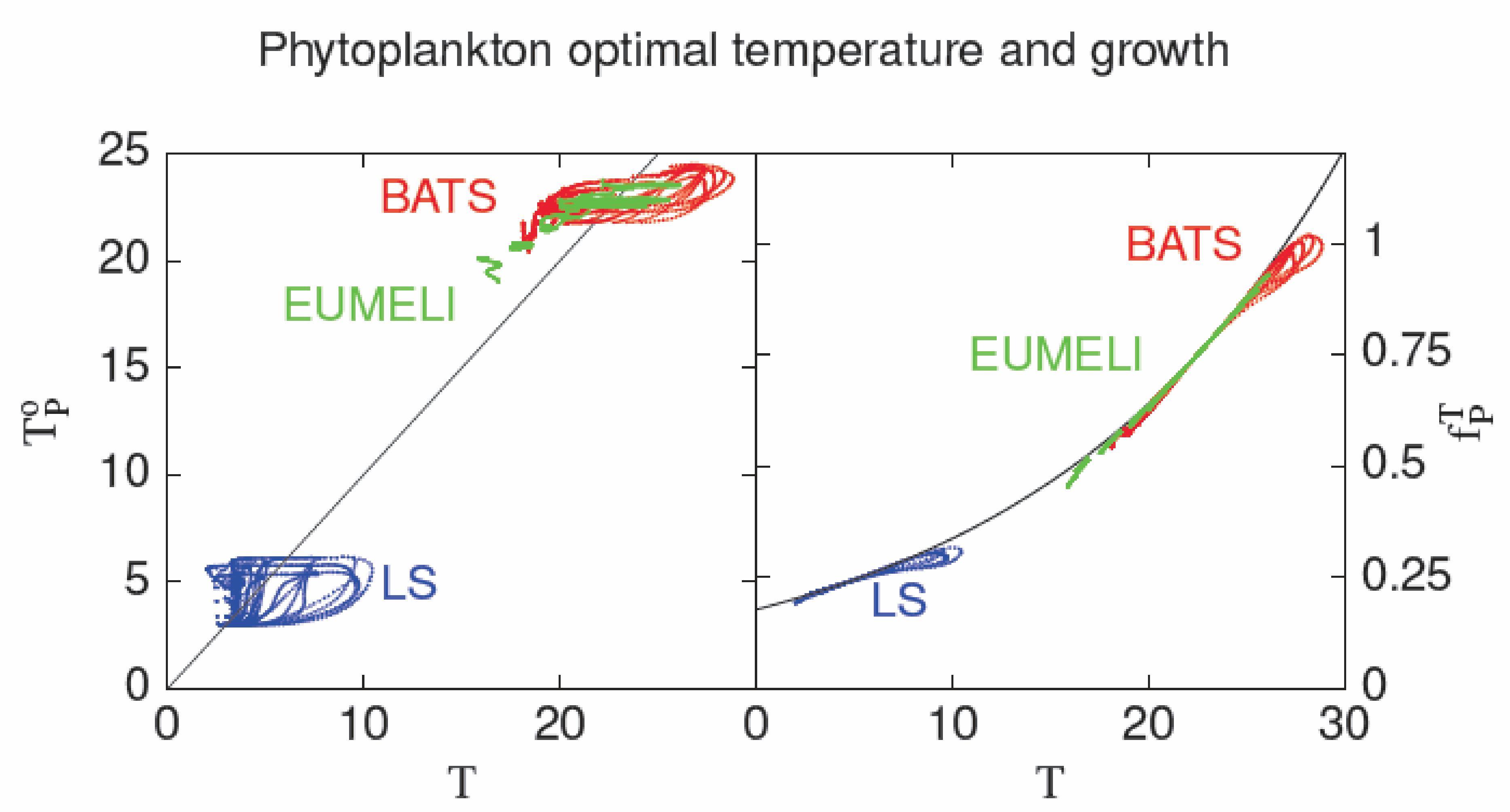


Example 2: optimal growth temperature as property variable



(M.Pahlow et al.)

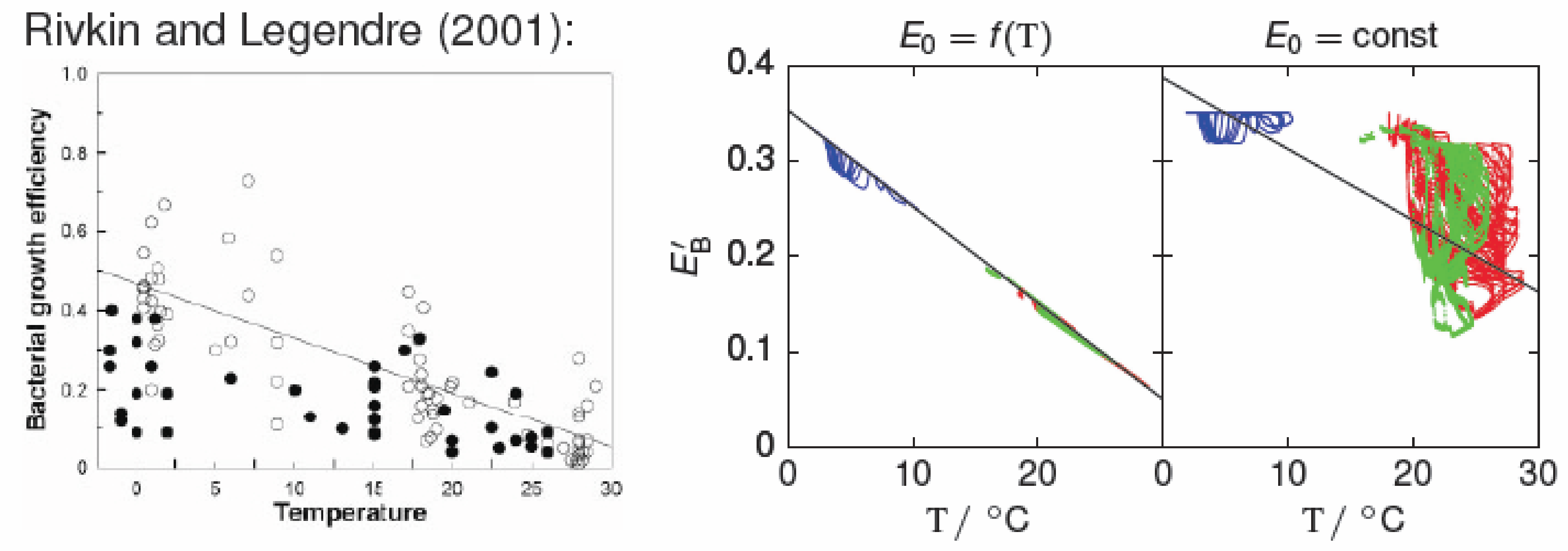
Temperature and growth



(M.Pahlow et al.)

Temperature and growth efficiency

Temperature dependence of growth efficiency


Rivkin and Legendre (2001):

- Model reproduces temperature dependence, whether prescribed or not!
- Emergent property?

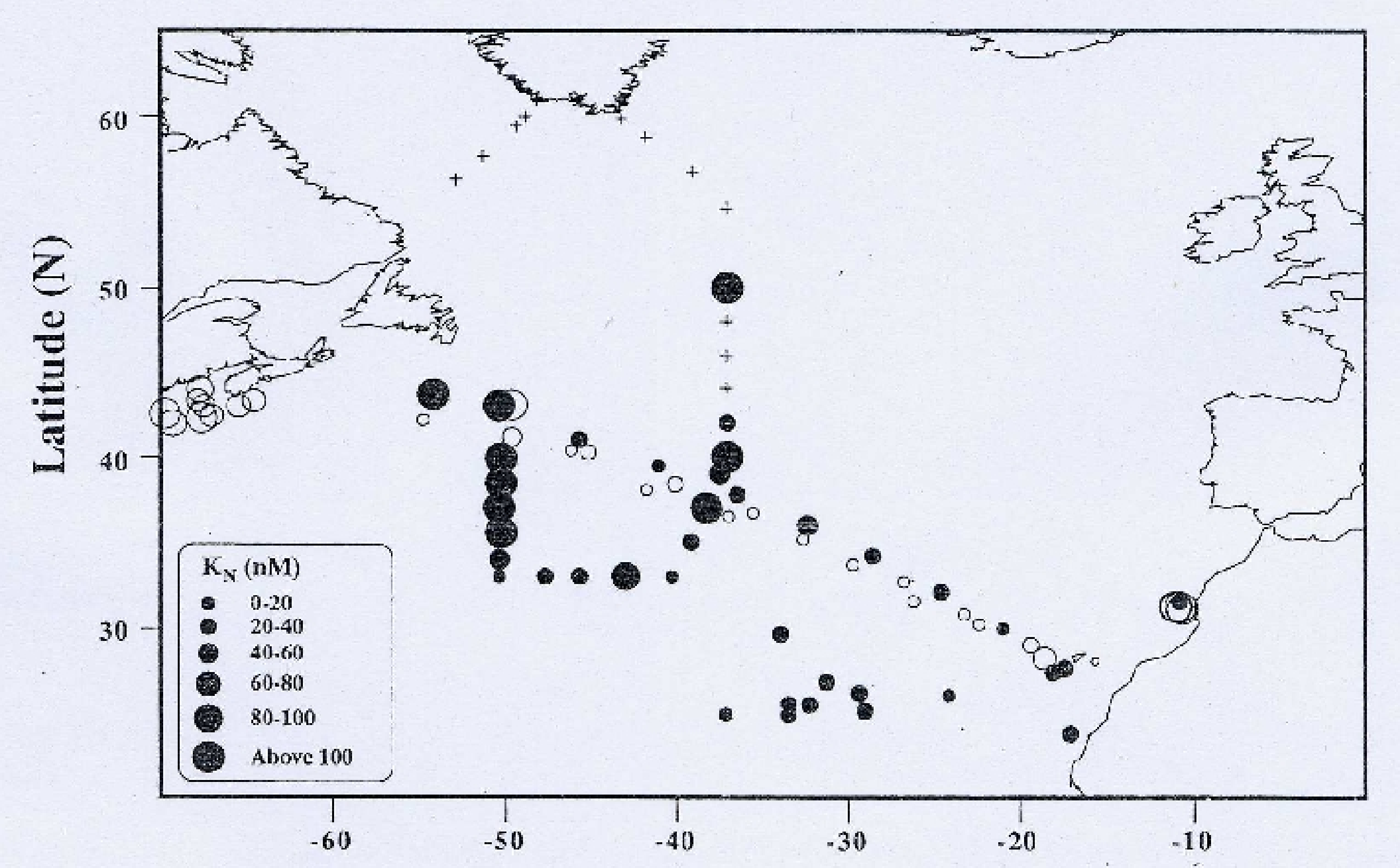
Summary

- Interannual to decadal variability in new production & export production to large extent controlled by physics
  - ⇒ can be modelled ~ well by current NPZD-type models
- Ecological variability
  - ⇒ complex models difficult/impossible to calibrate.
  - ⇒ large model-data discrepancies
  - ⇒ ∃ promising new modelling approaches!

The End

Hints for structural improvement

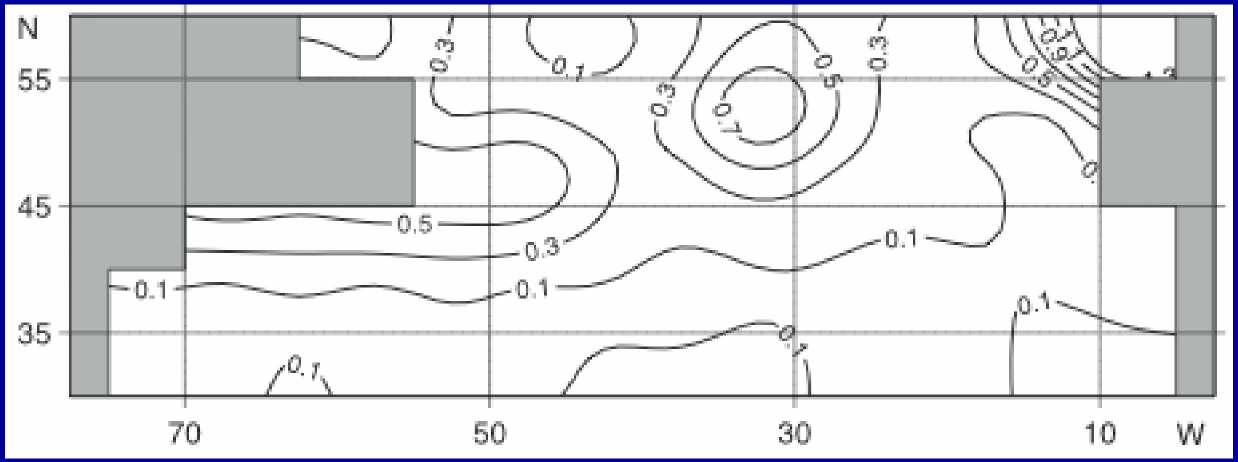
Observed variability of the half-saturation “constant” K_N.



(Harrison et al., 1996)

Results from data assimilation

Optimised half-saturation constant

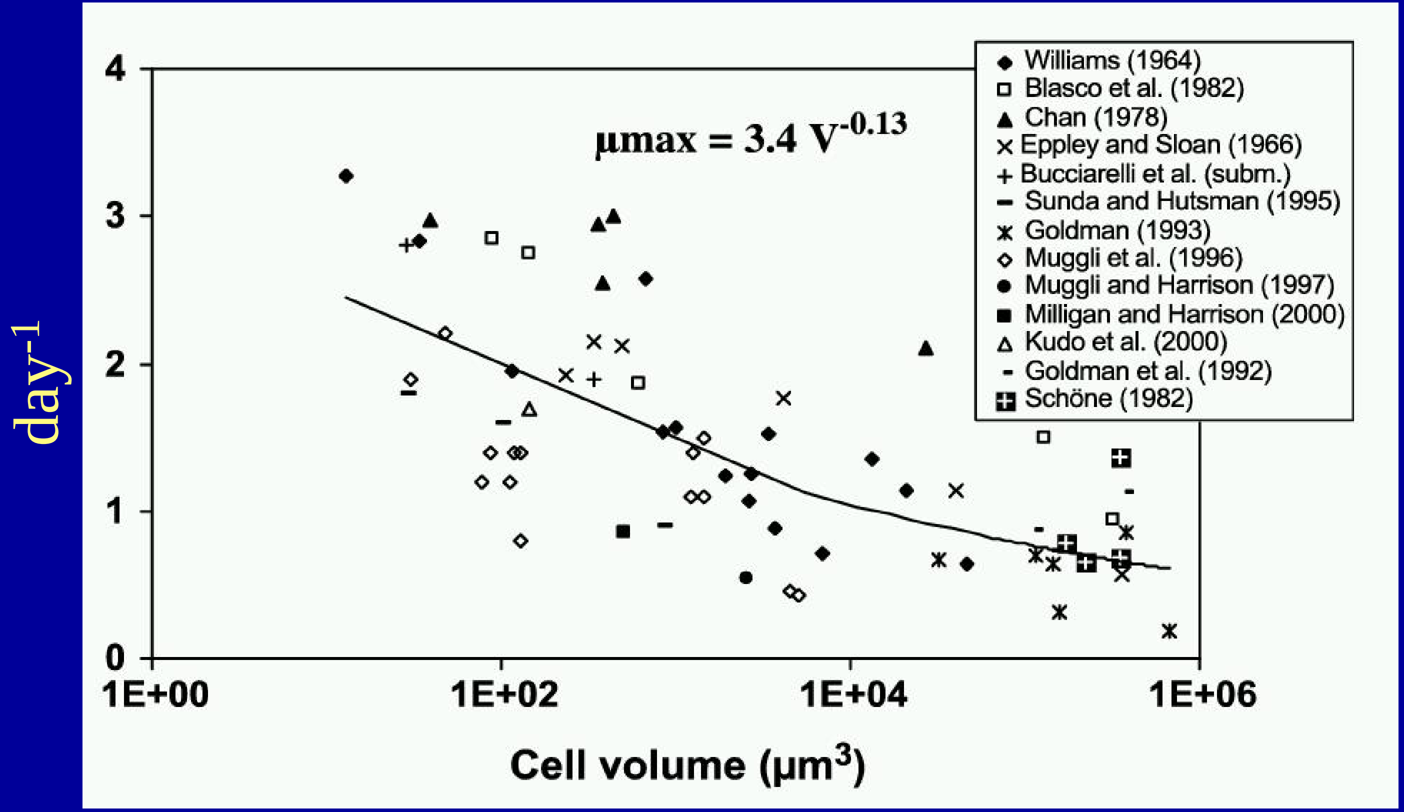


(Loza et al., 2004)

Role of size

Phytoplankton size range: ~0.2 - 200 µm.
Size determines surface:volume ratio
➔ affects exchange with surrounding medium.

Observational estimates of the maximum growth rate



(Sarthou et al., 2005)

“First principles”

NO_3 uptake rate:
$$V(r) = \frac{\mu(r) NO_3}{K(r) + NO_3}$$

Diffusion:
$$K(r) = K_1 \frac{r}{r_1}$$

Biomass:
$$b(r) = b_1 \left(\frac{r}{r_1} \right)^{\zeta} \quad , \quad \text{obs.:} \; 2 \le \zeta \le 3$$

Max. growth rate:
$$\mu(r) = \mu_1 \left(\frac{r}{r_1} \right)^{2-\zeta}$$

“First principles”

NO_3 uptake rate:

$$V(r) = \frac{\mu_1(I)\left(\frac{r}{r_1}\right)^{2-\zeta} NO_3}{K_1\left(\frac{r}{r_1}\right) + NO_3}$$

(Aksnes & Egge, 1991)

Small cells can grow faster
- why, then, do large cells exist?

Loss processes can depend on size as well!

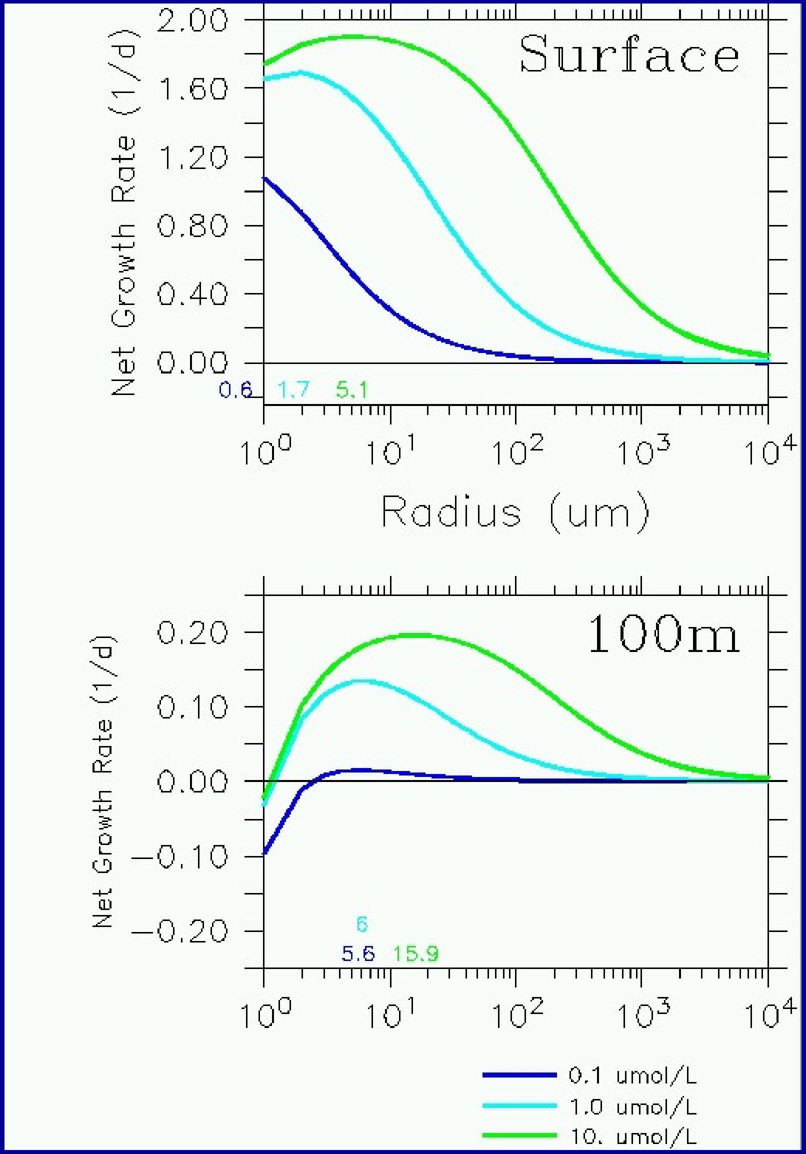
“First principles”

Exudation rate: $\lambda(r) = \lambda_1 r^{-1}$

(Bjornsen, 1988)

“Property tax” rather than “income tax”.

Simulated net phytoplankton growth

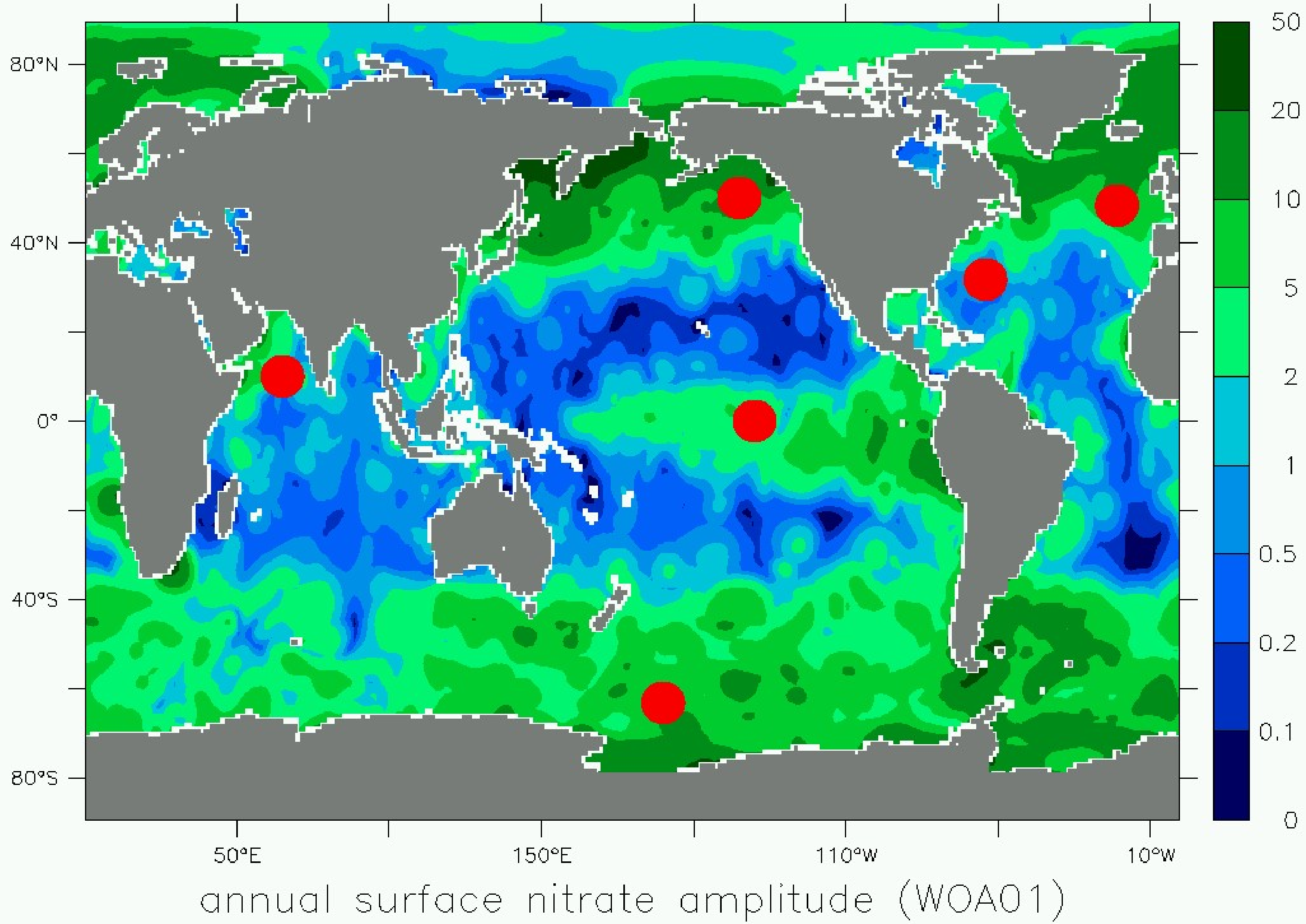


Net growth rate:

$$NGR(r) = \frac{\mu(I)NO_3}{K_1 r + NO_3} - \lambda_1 r^{-1}$$

- small cells in oligotrophic, well-lit regions
- medium cells in mesotrophic regimes
- large cells in eutrophic regimes
- Decreasing light causes an increase in optimum cell size.

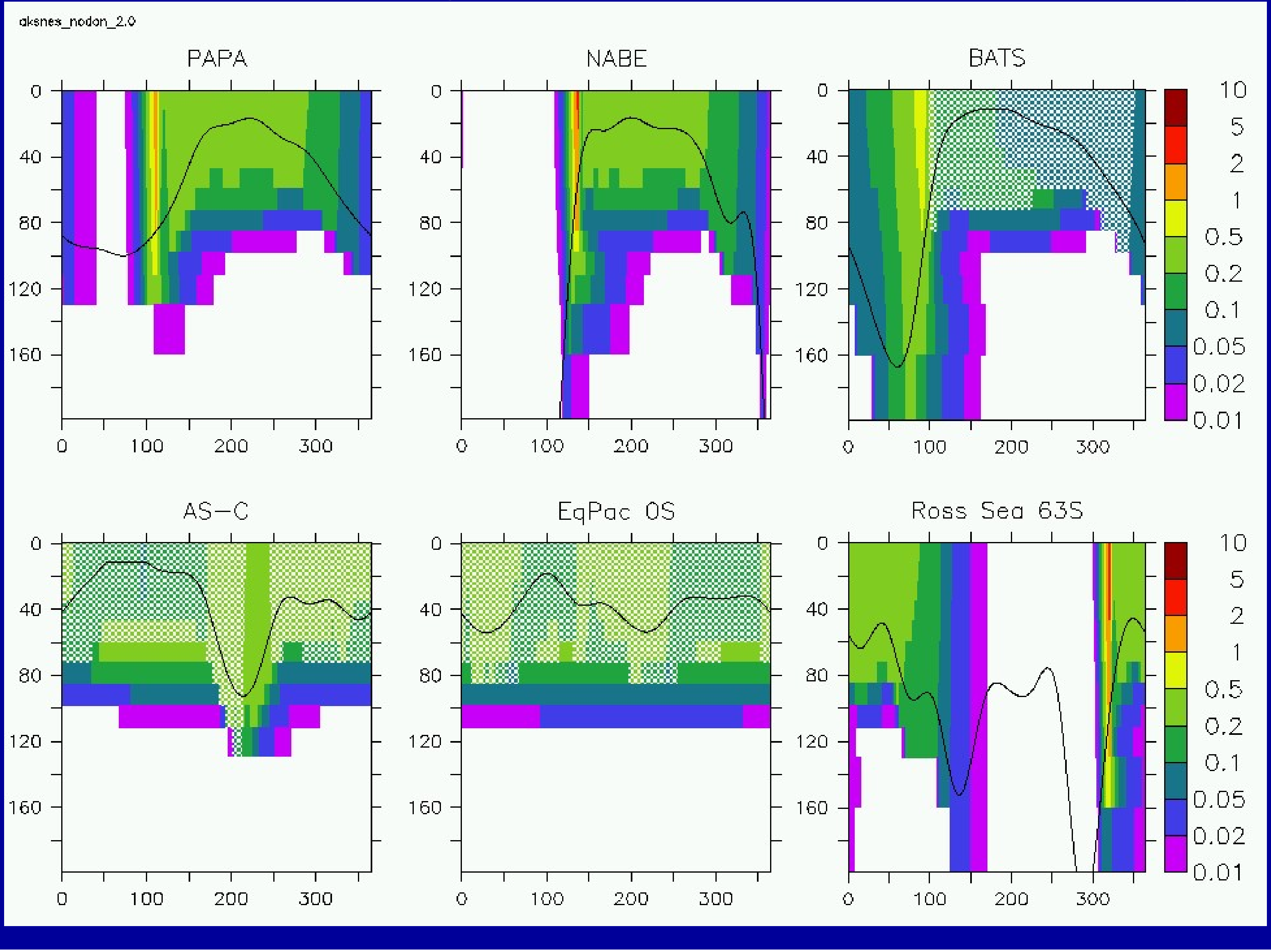
1D test sites



annual surface nitrate amplitude (WOA01)

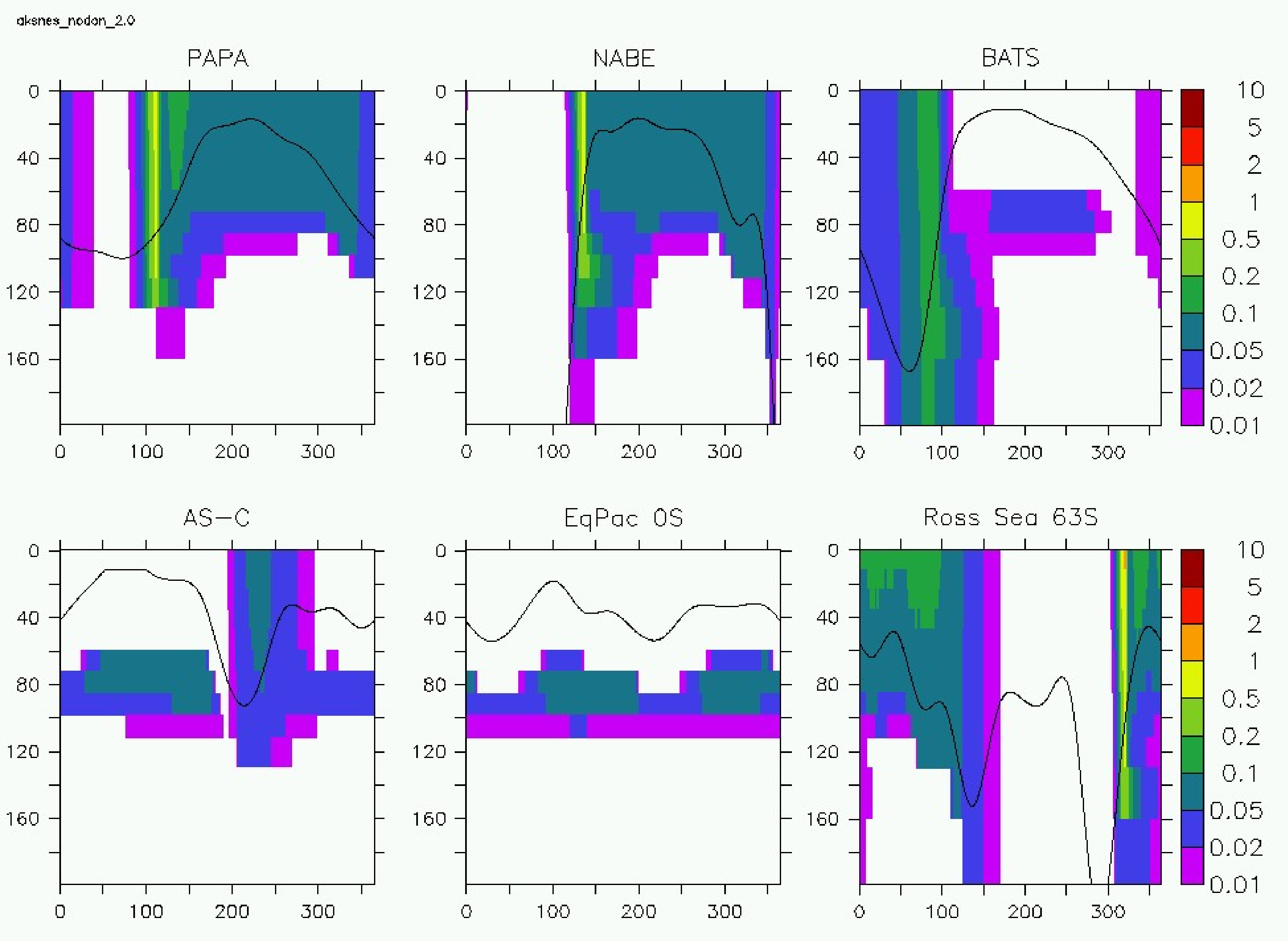
First 1D results

Simulated Chlorophyll, shaded areas: >50% of size < 5µm



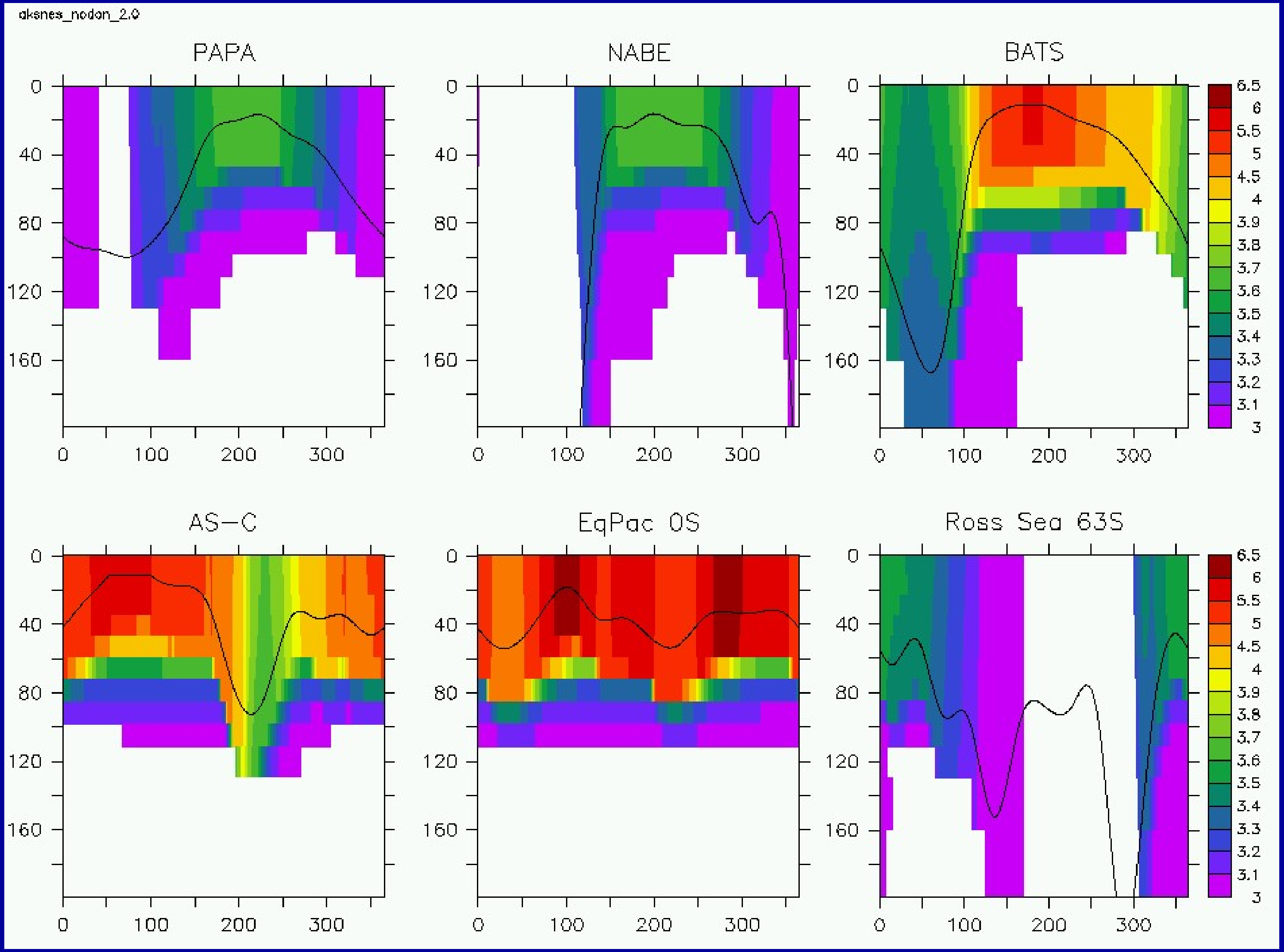
First 1D results

Simulated Chlorophyll of sizes > 20 μm



First 1D results

Simulated slope of log-log size spectrum



Ecological modelling - how can we proceed?

- Model development guided by data assimilation.
  Identify and remove redundancies.
  Add complexity after analysis of residuals.
  - Incubation experiments (sea & lab).
  - Mesocosm experiments.
  - time-series sites.
  - Paleo data.

Time & space
scale

- Do not disregard alternative model structures
  (e.g., based on size, energy, membrane surfaces, ...)
- Be ambituous Search for “Kepler‘s Laws“ instead of “Ptolomaic Epicycles“.

Is there an appropriate level of ecosystem-model complexity?

(An ecological equivalent of the Navier-Stokes equations is not known (yet?))

- Overview over current ecosystem-model categories
- Lessons from data assimilation studies
- First steps towards a transition from empirical to mechanistic ecosystem models

Example: pCO_2-sensitive N_2 fixation

- Culture experiments with *Trichodesmium* suggest
  - – increased N_2 fixation with increasing pCO_2
  - – Increased C:P
  - – Increased N:P

pCO_2-sensitive N_2 fixation

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

(Barcelos e Ramos et al., subm)