Modelling Biogeochemical Fluxes in the Ocean – How far have we gotten?

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Biogeochemical Modelling - How far have we gotten?

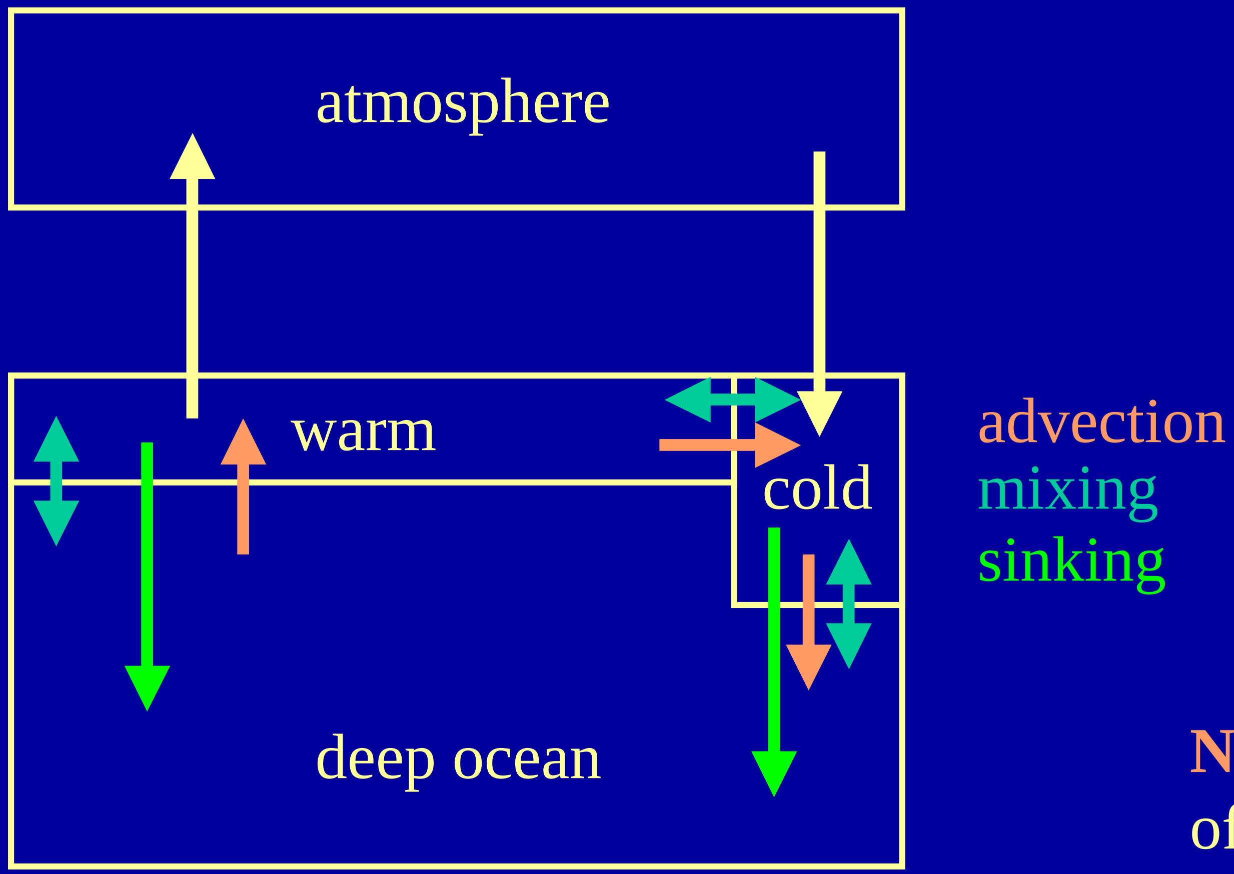
Modelling-related JGOFS goals:

- Determine fluxes of carbon in the ocean and exchange across boundaries.
- Develop capability to make predictions.

Situation at the end of JGOFS:

- Complexity of physical model component.
- Applicability of biological production concepts.
- Complexity of ecological model component.

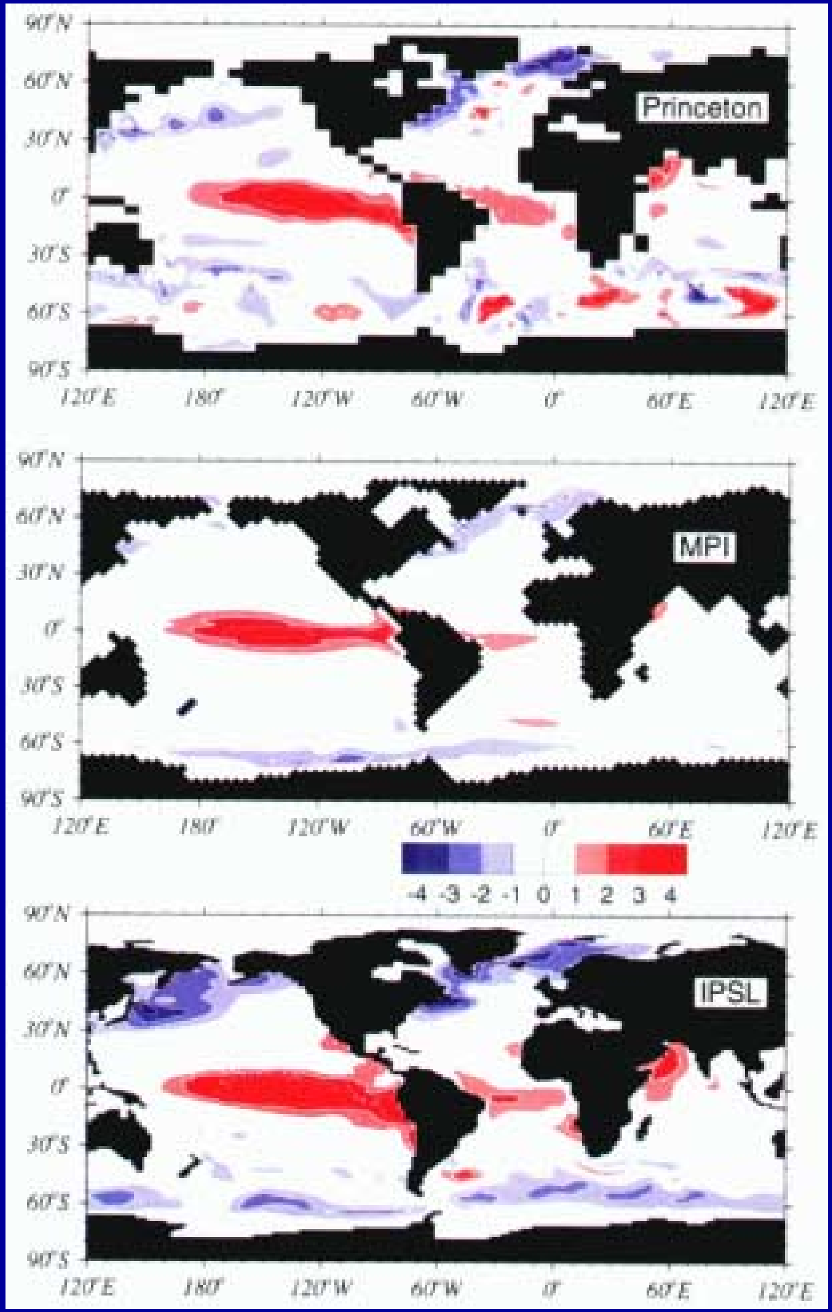
Part I: Physical Complexity: Pre-JGOFS Box Models



New Production: Restoring of surface nutrients.

Knox & McElroy (1984)
Sarmiento & Toggweiler (1984)
Siegenthaler & Wenk (1984)

Physical Complexity:
Carbon-Cycle OGCMs of the early JGOFS Period



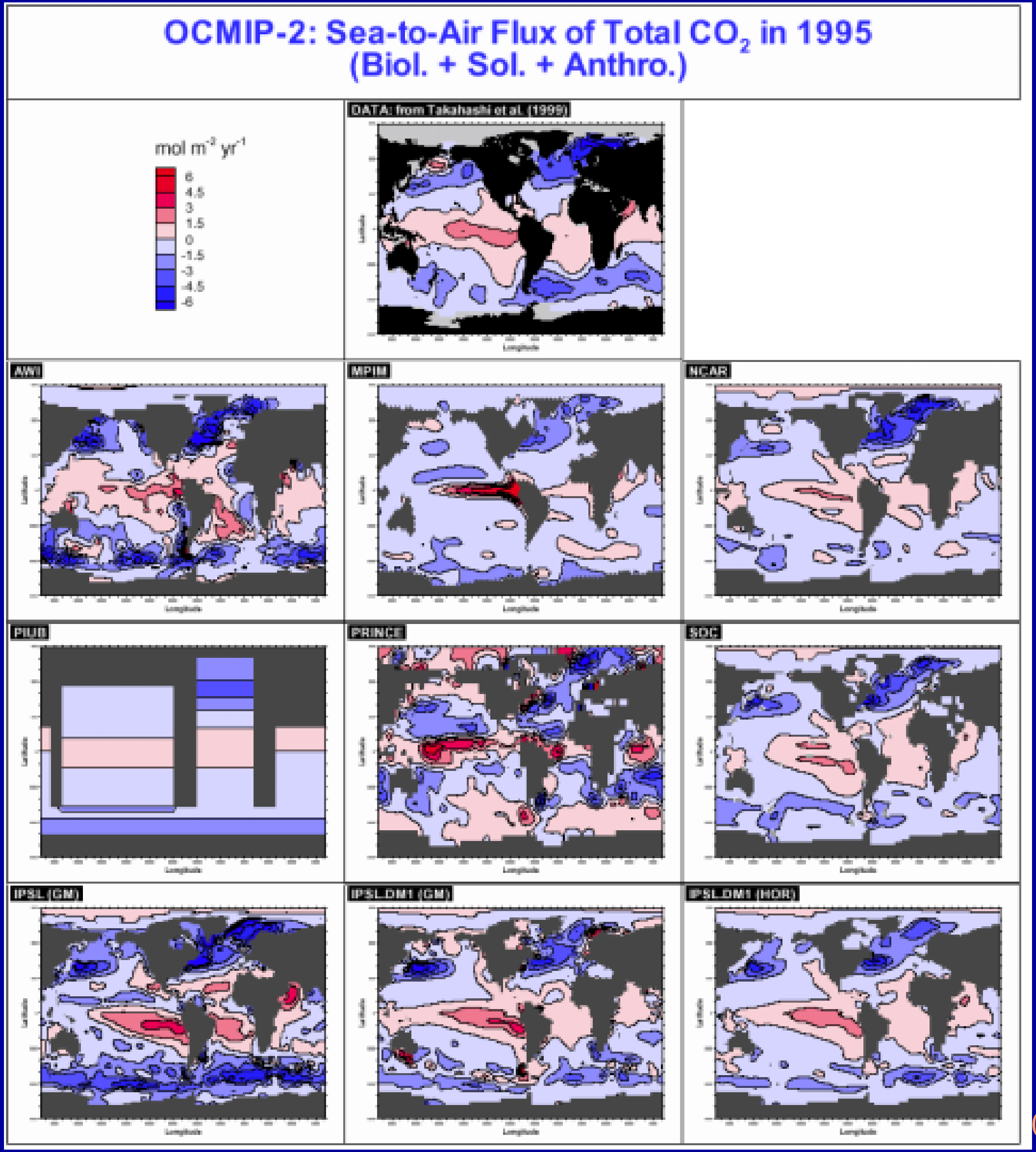
Simulated annual sea-air flux of pre-industrial CO_2
(OCMIP1, Sarmiento et al., 2000).

Look more realistic than box models.
Seem to converge w.r. t. integral properties.

New Production: Restoring of surface nutrients.
POM, DOM with fixed decay rates.

Bacastow & Maier-Reimer (1991)
Najjar et al. (1992)
:
OCMIP1, OCMIP2

Physical Complexity: OCMIP 2

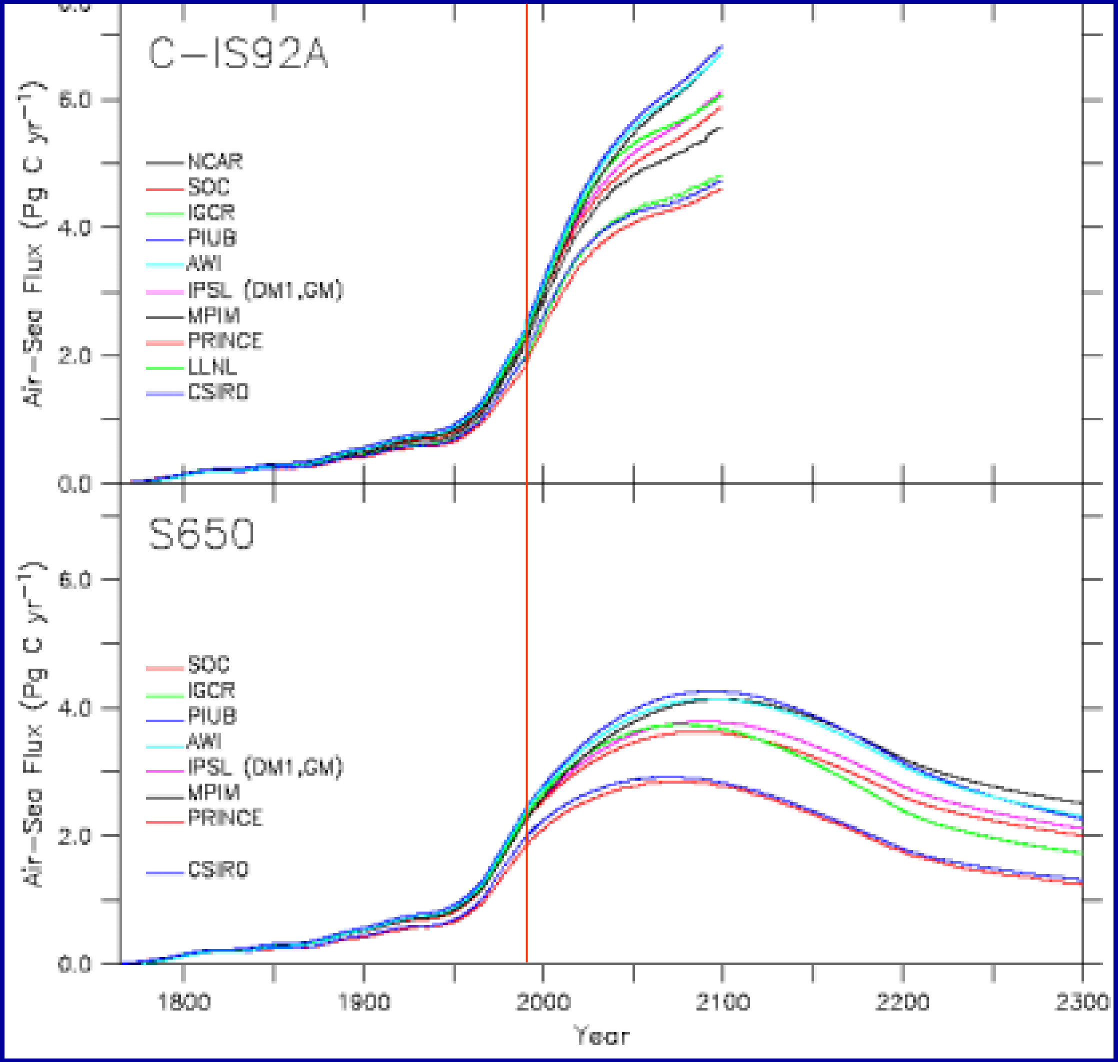


(J. Orr and OCMIP2 group)

Physical Complexity: OCMIP 2
Simulated Oceanic Carbon Uptake

Models were run with specified atmospheric CO_2 boundary conditions.

No future change in ocean circulation.

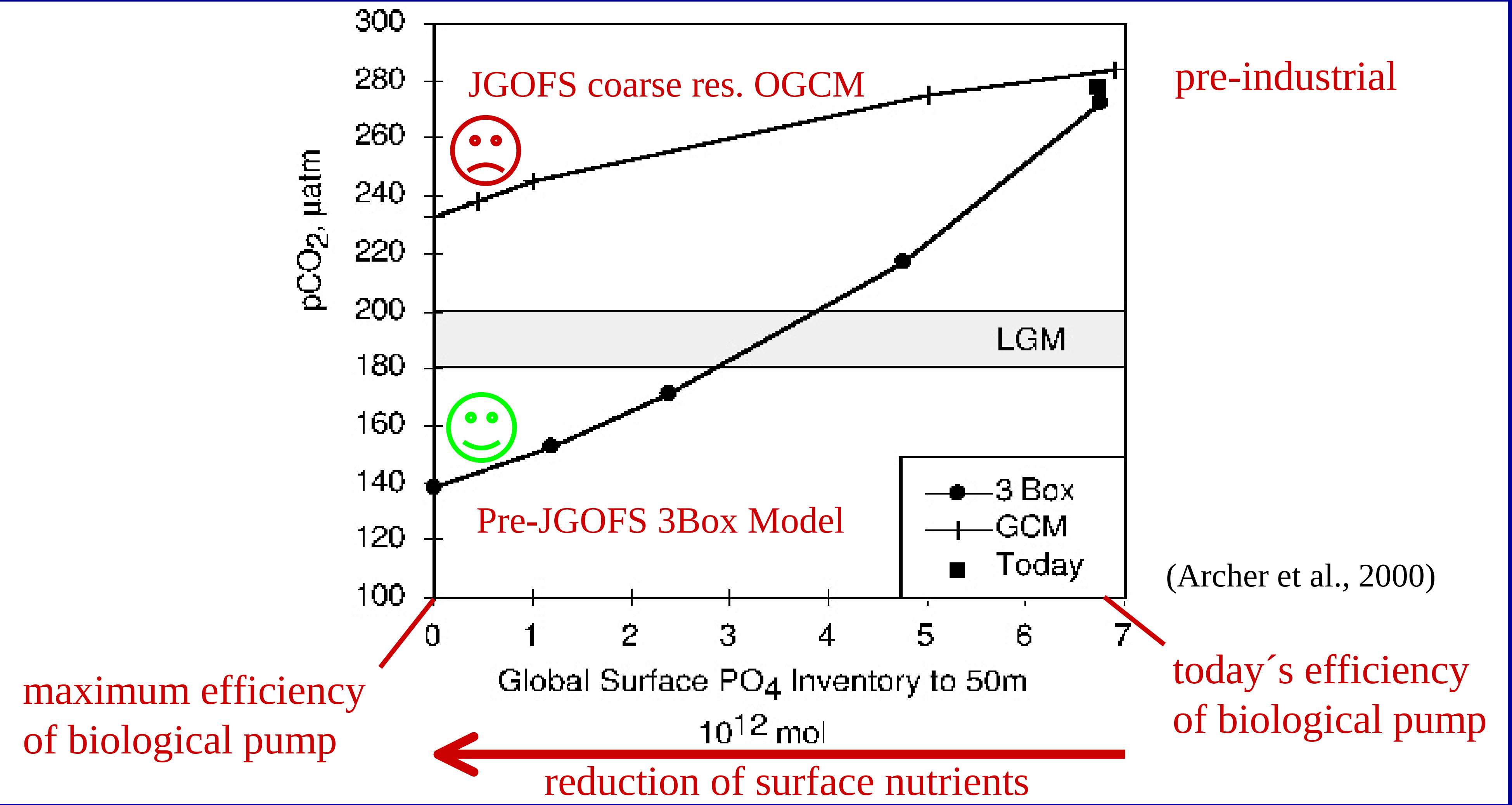


(J. Orr and OCMIP2 group)

- **Good internal agreement in past and present, divergence in future.**

Physical Complexity: Glacial-Interglacial Climate Changes

Simulated atmospheric pCO_2 sensitivity to the biological pump



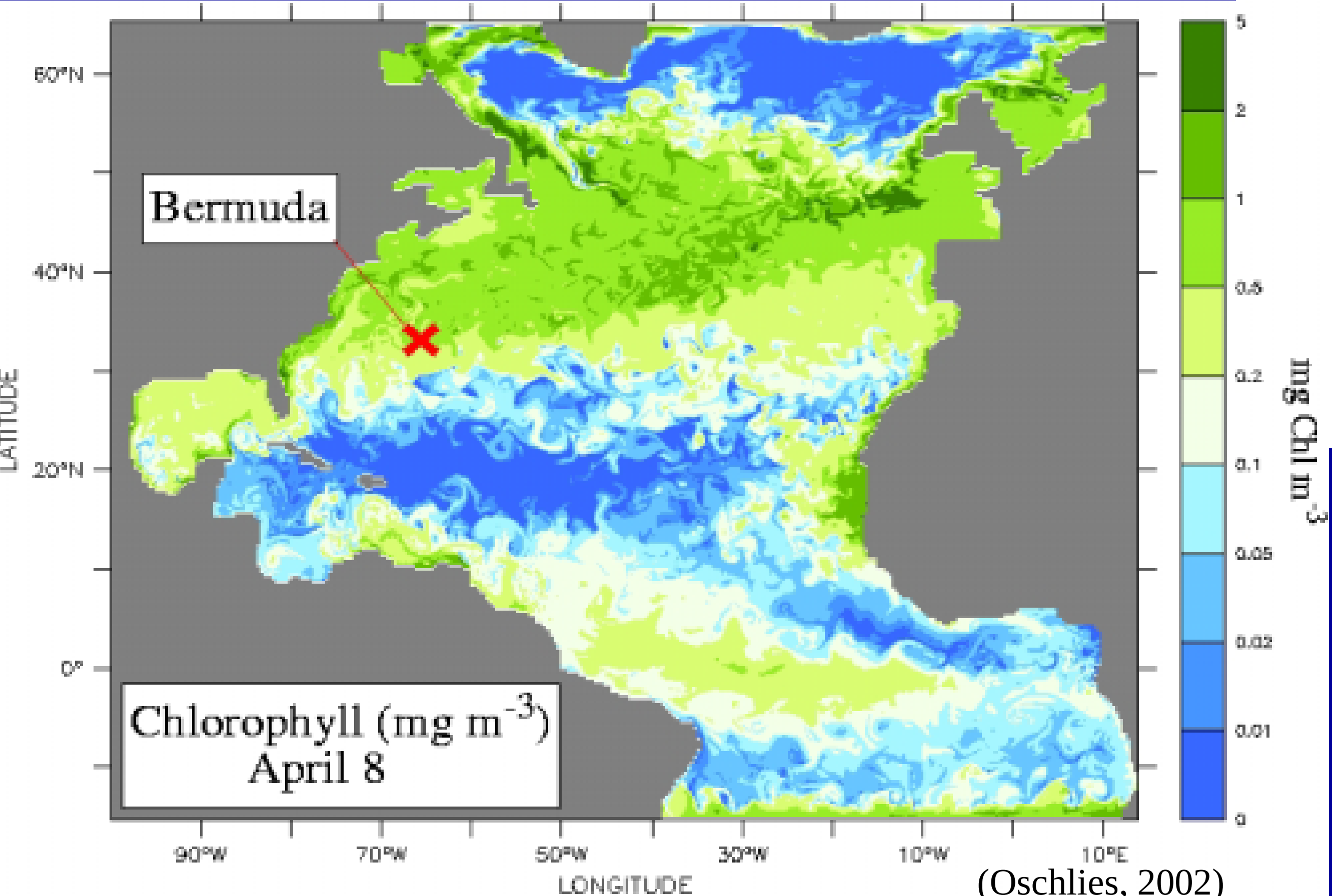
- **Climate sensitivity depends on model architecture!**

Physical Complexity and Climate Sensitivity: Hypotheses

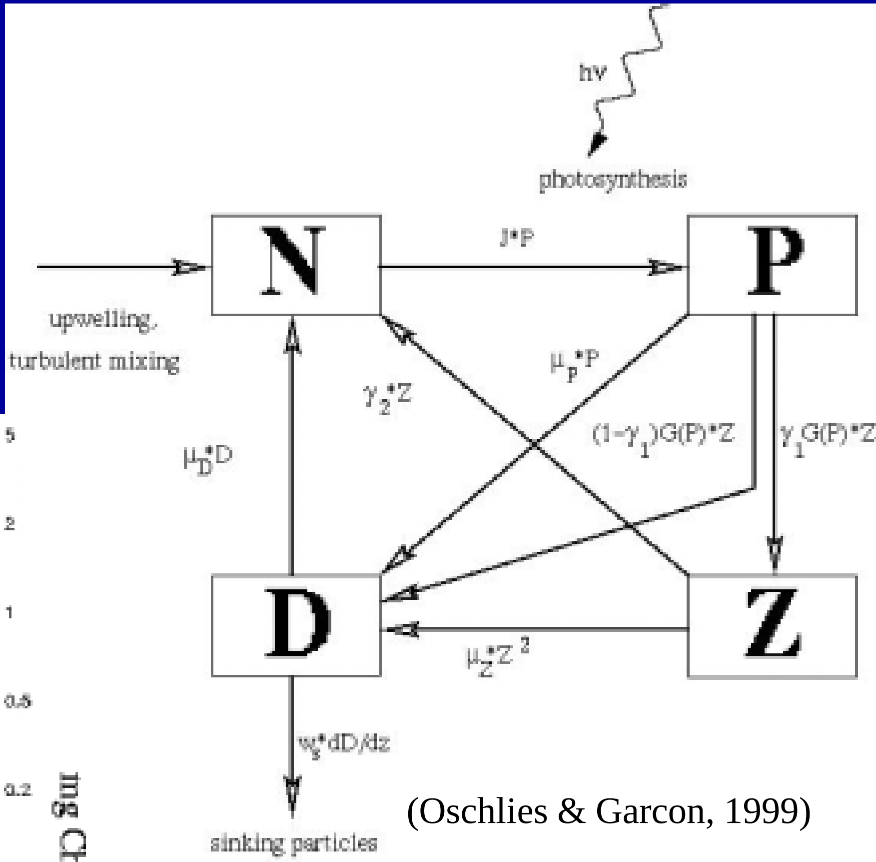
- Poor representation of wind-driven circulation in box models (Follows et al., 2002).
- Overestimated CO_2 equilibration in deep-water formation regions in box models, possibly underestimated in OGCMs (Toggweiler et al., 2003a,b).
- Unrealistically high diapycnal mixing in OGCMs (Oschlies, 2001).

Physical Complexity: Sensitivity Experiments

Spring bloom, eddy-resolving (1/9°) model



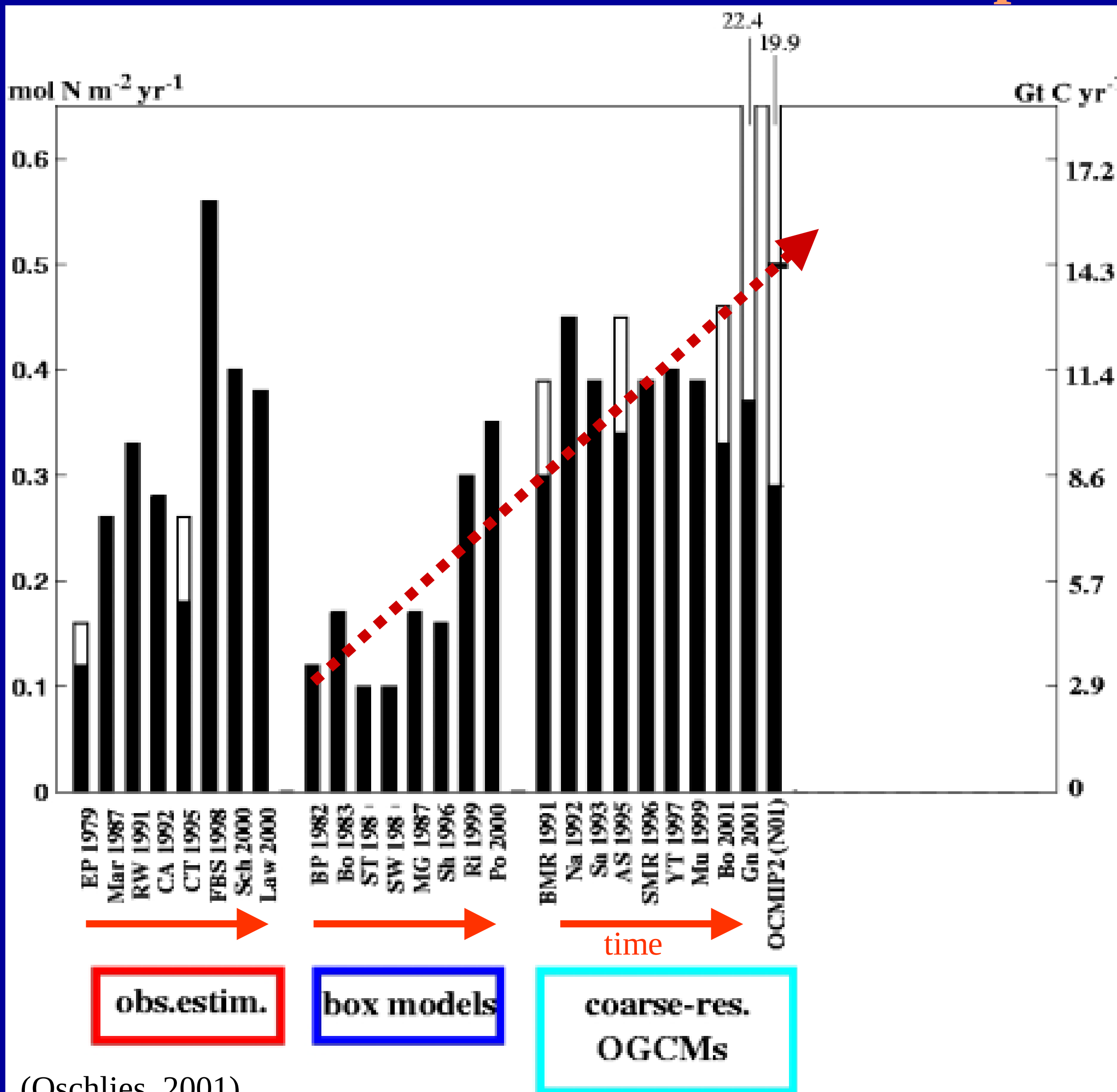
(Oschlies, 2002)



(Oschlies & Garcon, 1999)

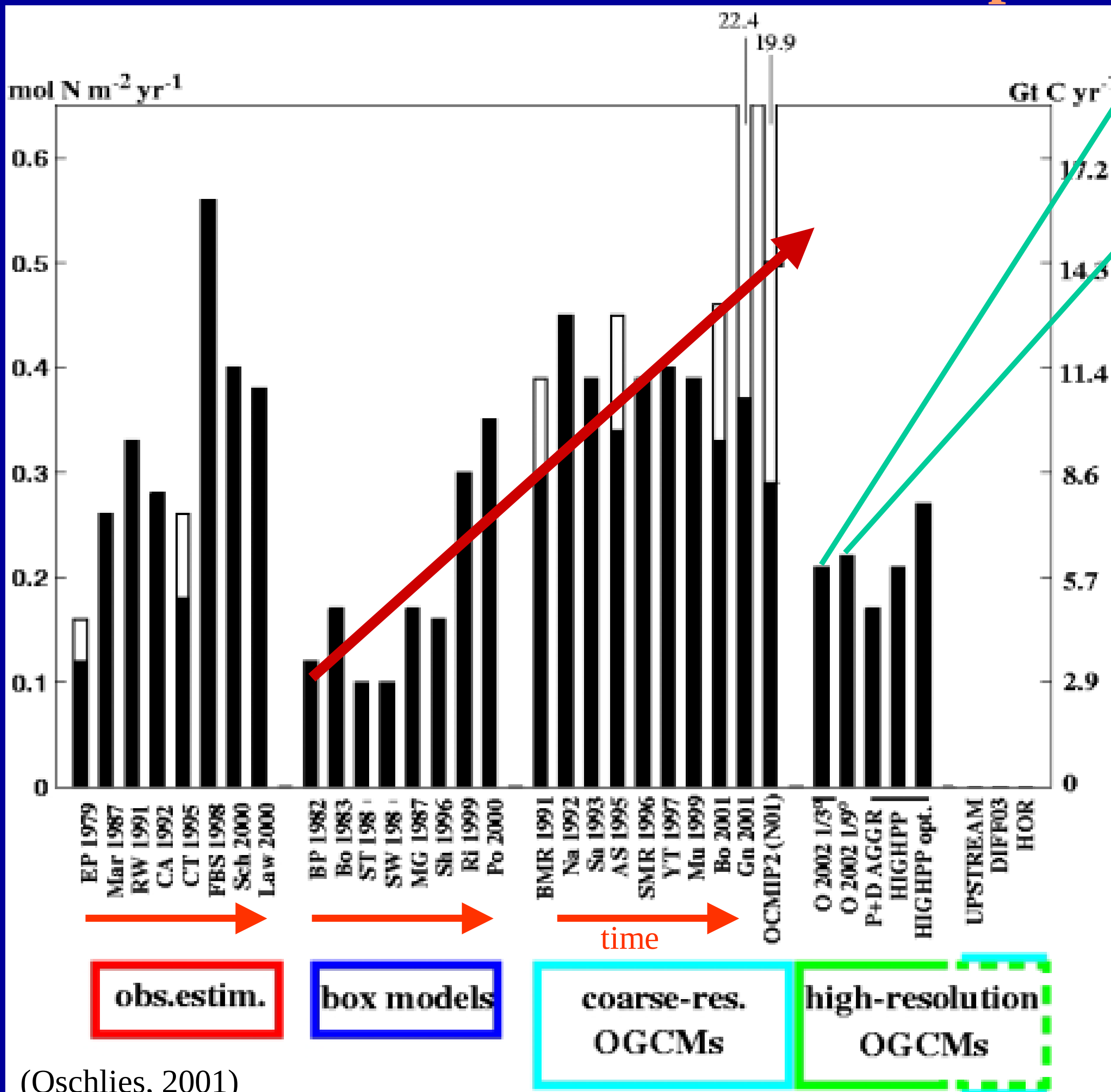
N-based ecosystem model

Physical Complexity:
Model-derived Estimates of Export Production



(Oschlies, 2001)

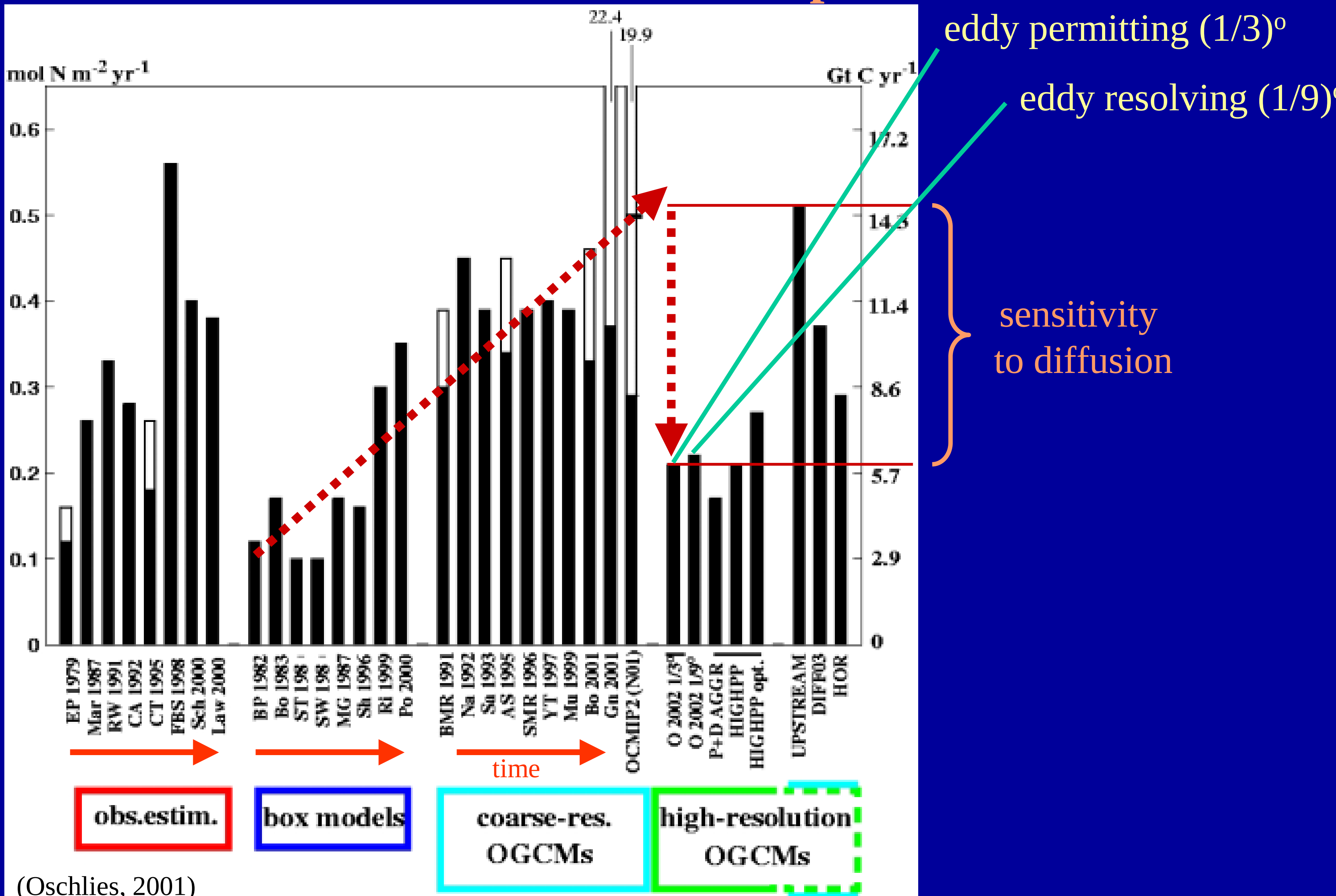
Physical Complexity: Model-derived Estimates of Export Production



eddy permitting (1/3)º

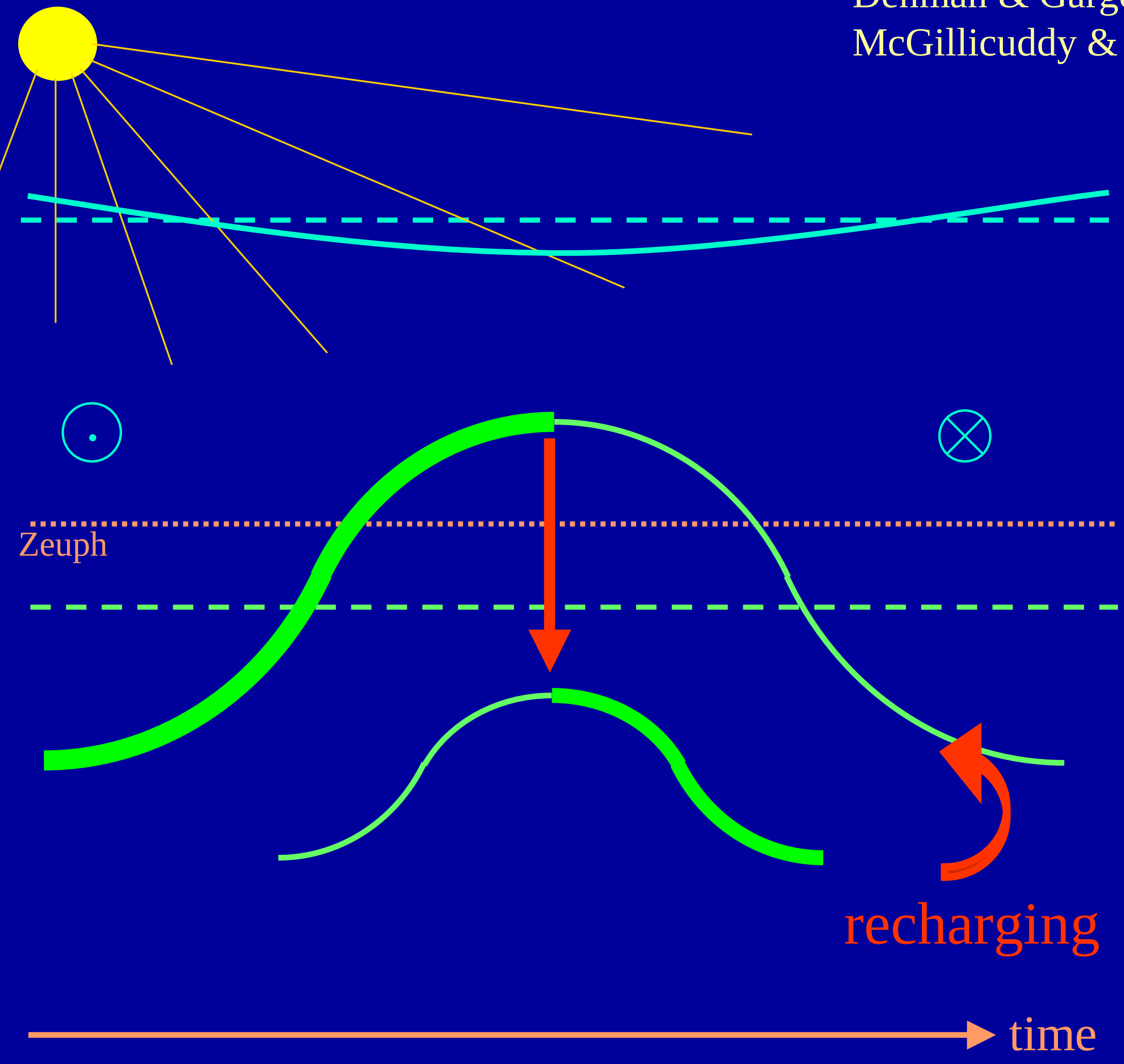
eddy resolving (1/9)º

Physical Complexity: Model-derived Estimates of Export Production



Physical Complexity: What about Eddies?

Eddy-pumping process (Jenkins, 1988; Falkowski et al., 1991; Denman & Gargett, 1995; Dadou et al., 1996; McGillicuddy & Robinson, 1997; ...)

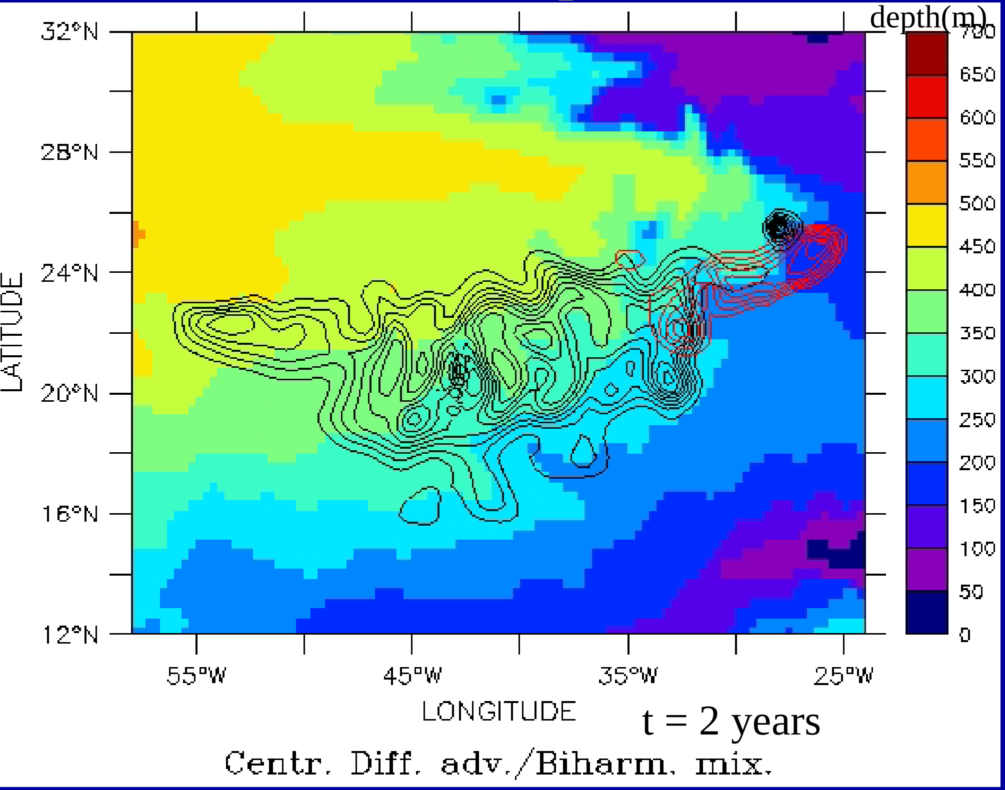


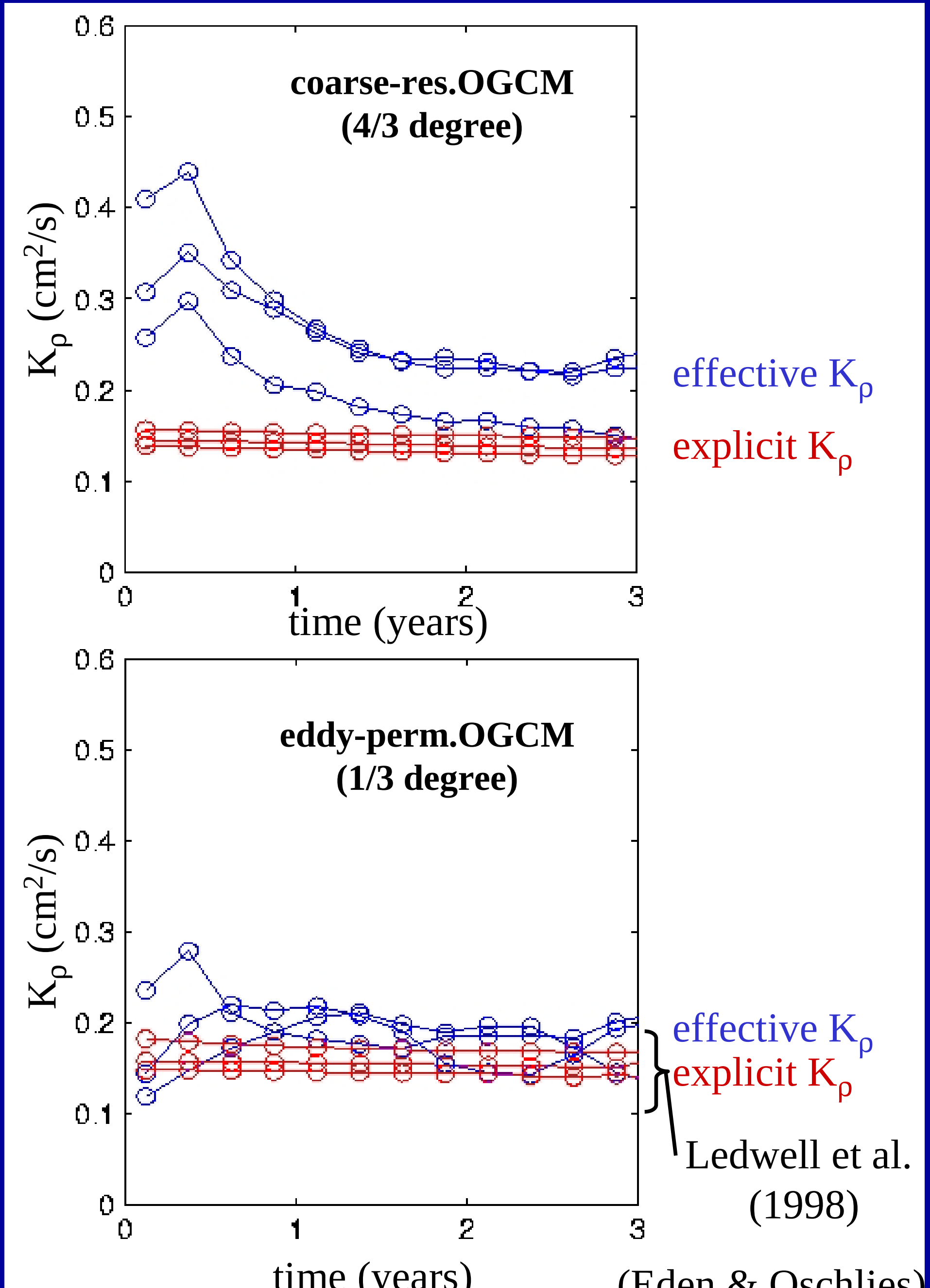
- Sinking is diapycnal process.
- Recharging of nutrients on shallow isopycnals matters.
- Recharging requires diapycnal nutrient transport.
- Bottleneck is diapycnal transport rather than isopycnal uplift!

(Oschlies, 2002)

Physical Complexity:
What is the right amount of diapycnal diffusion?

Simulation of Ledwell et al.´s (1993) Tracer Release Experiment





(Eden & Oschlies)

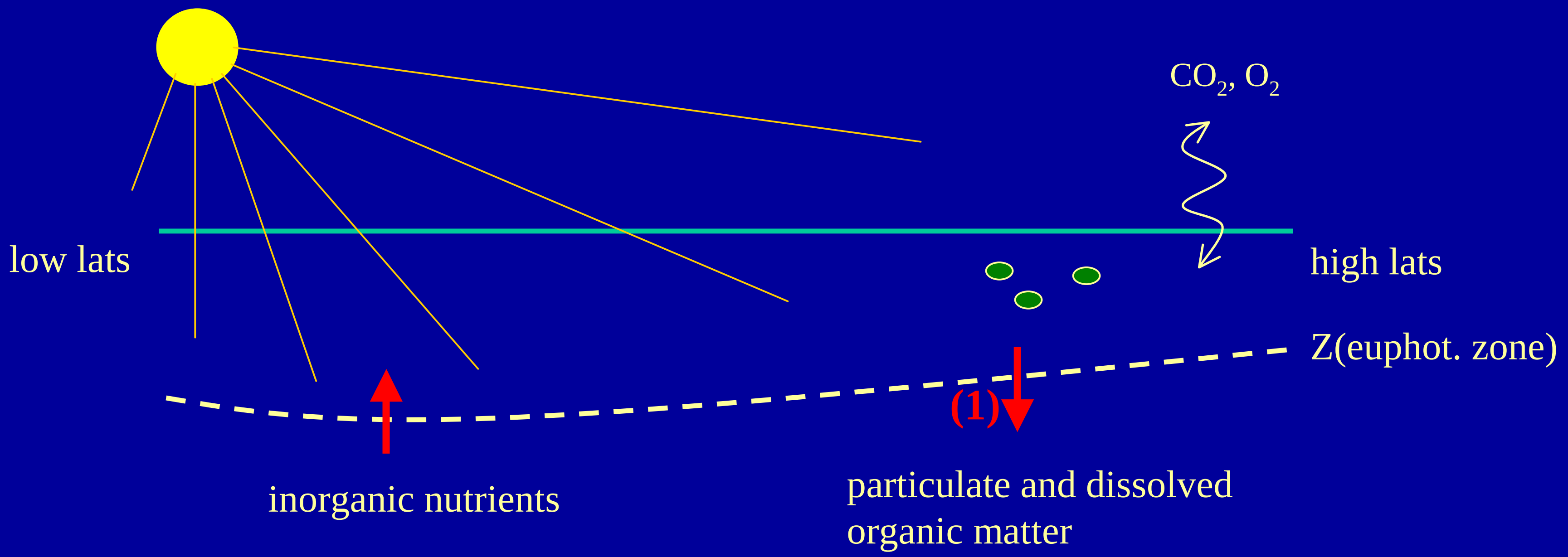
Conclusions Part I: Physical Complexity

- JGOFS period: from box models to eddy resolving models.
- Climate sensitivity depends on model architecture!
- Many coarse-resolution OGCMs are too diffusive.
  (In this aspect, box models may be better!)
- Need realistic description of diapycnal processes
  (small-scale mixing, eddy-induced diapycnal fluxes, double diffusion, sinking, active vertical migration,...).
- Need accurate numerics (advection!).

Part II: Applicability of Concepts

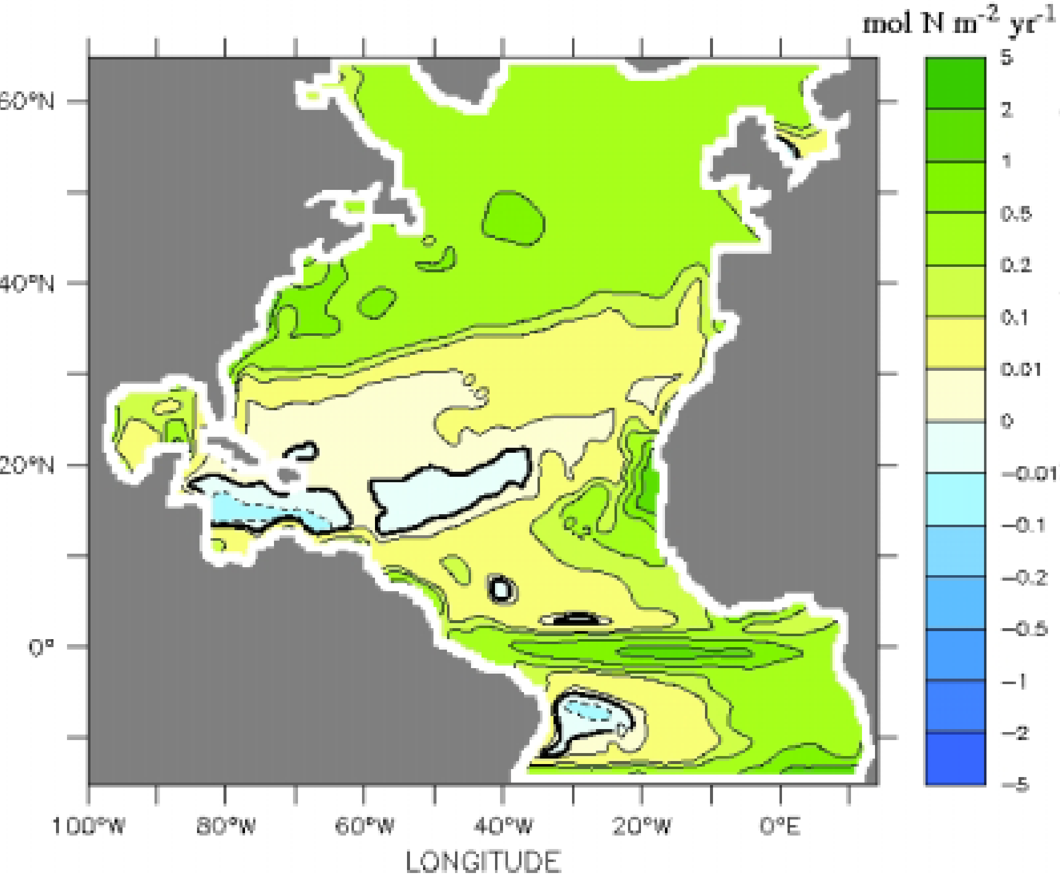
- Can we relate biotically effected air-sea fluxes of CO_2 and O_2 to biological production rates?
  - New production
  - Export production
  - Net community production

Applicability of Concepts: Biological Pump and Air-Sea Exchange

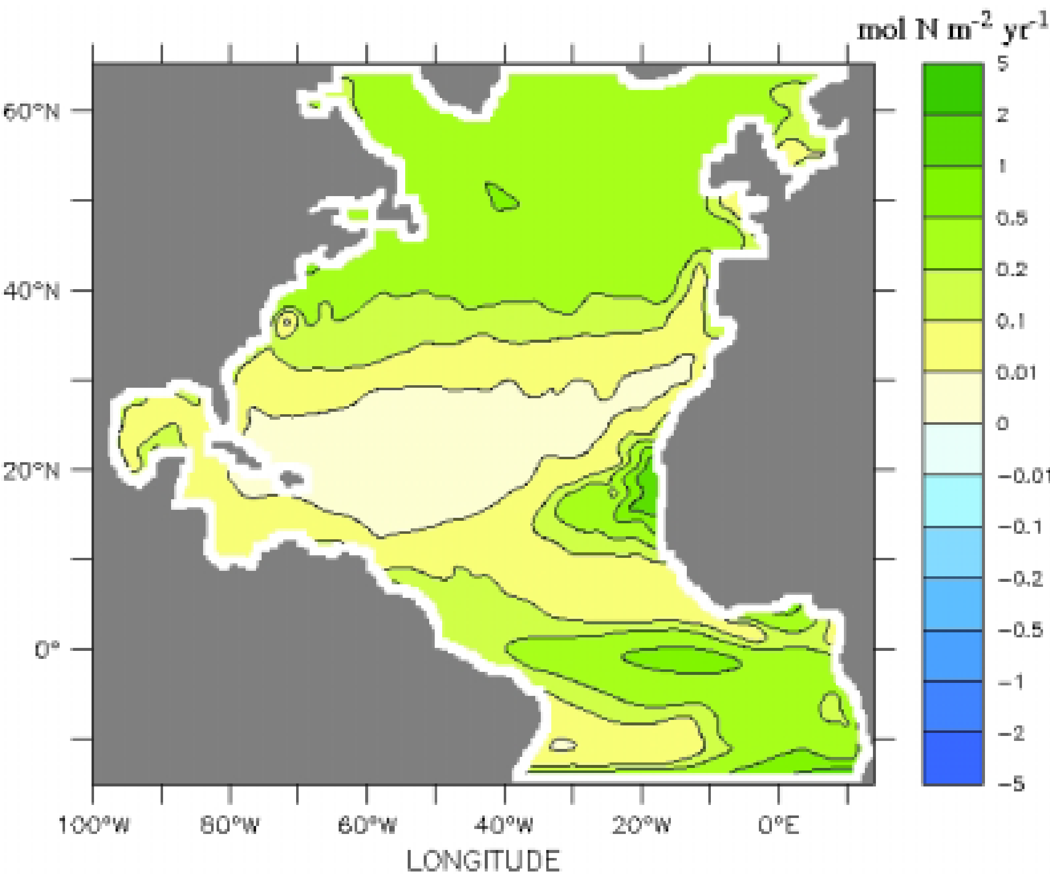


Applicability of Concepts:
Simulated Net Community Production and Air-Sea Exchange

Net community production (0-Zeuph)

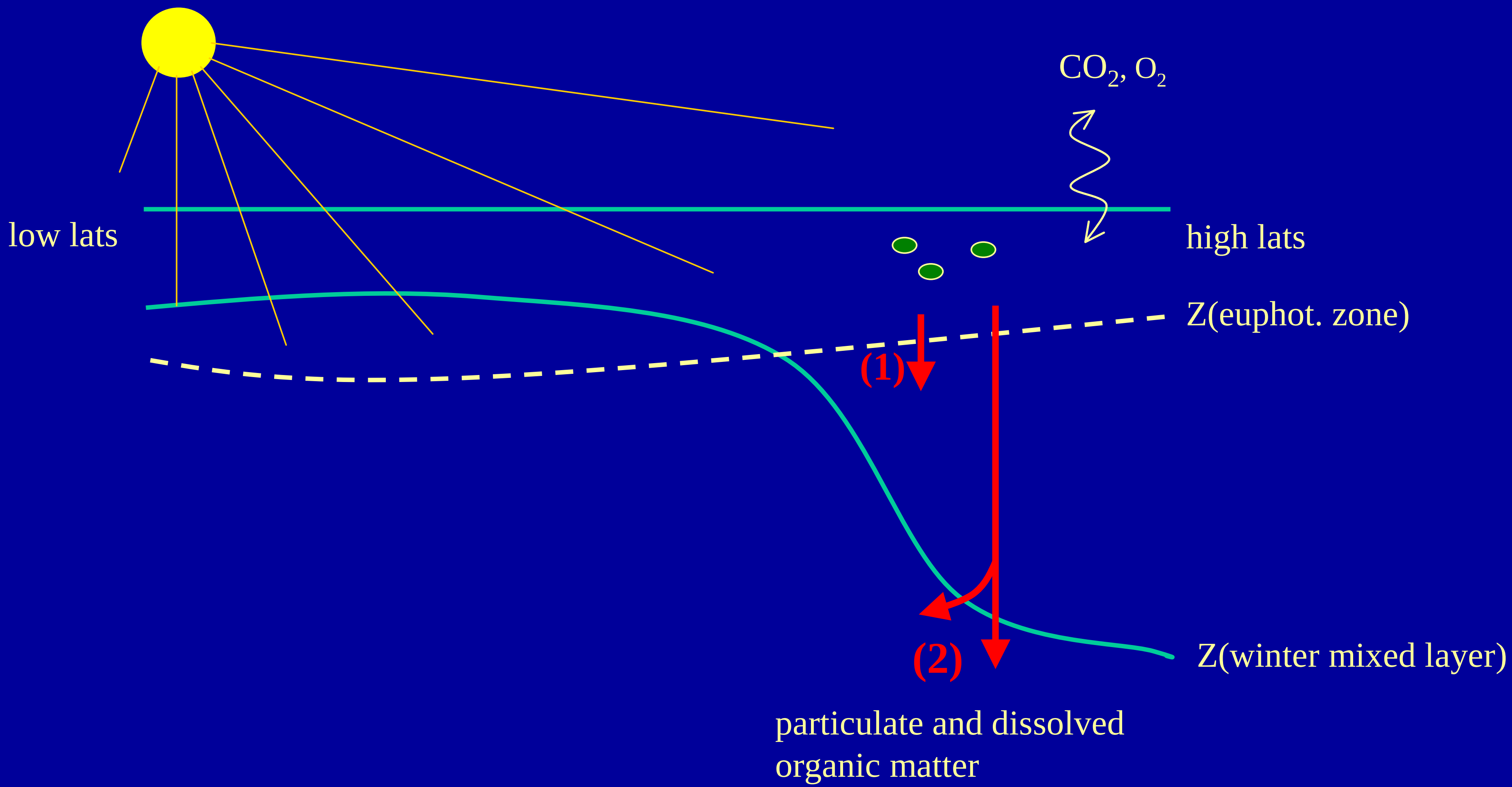


Biotically effected air-sea flux



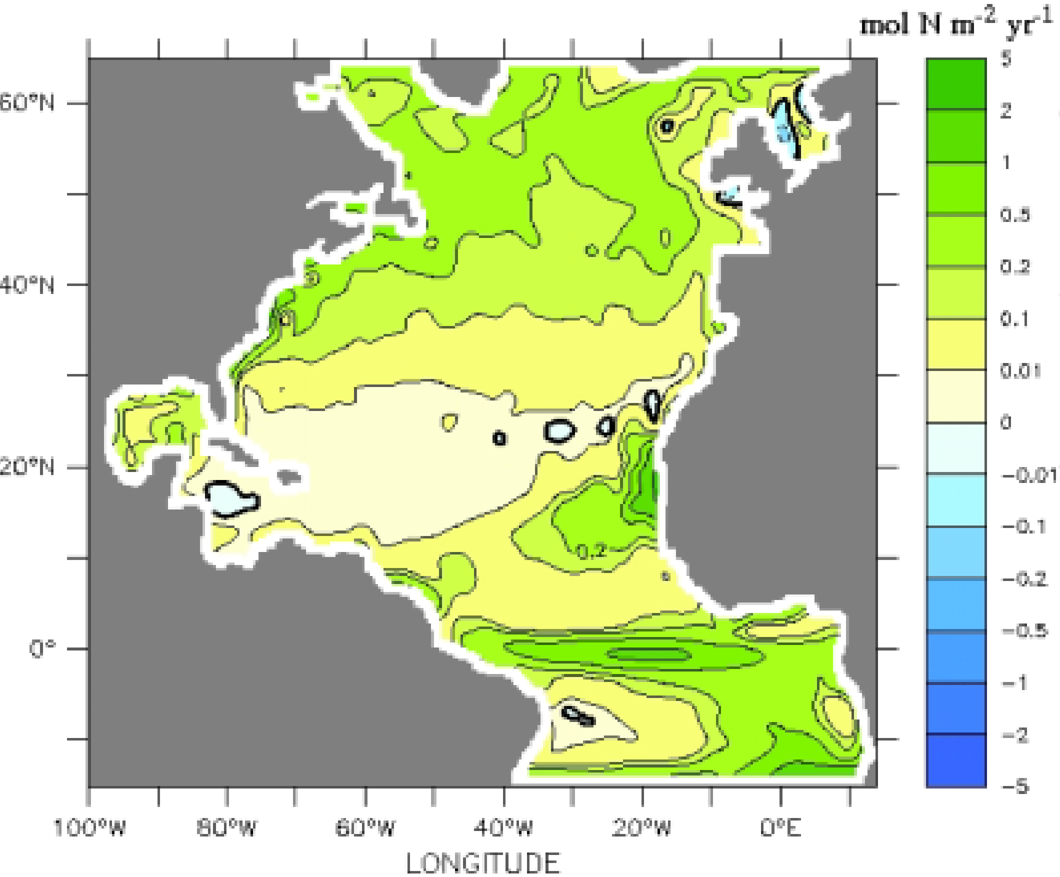
- Net heterotrophy does not imply biotically effected outgassing of CO_2 !

Applicability of Concepts:
Biological Pump and Air-Sea Exchange

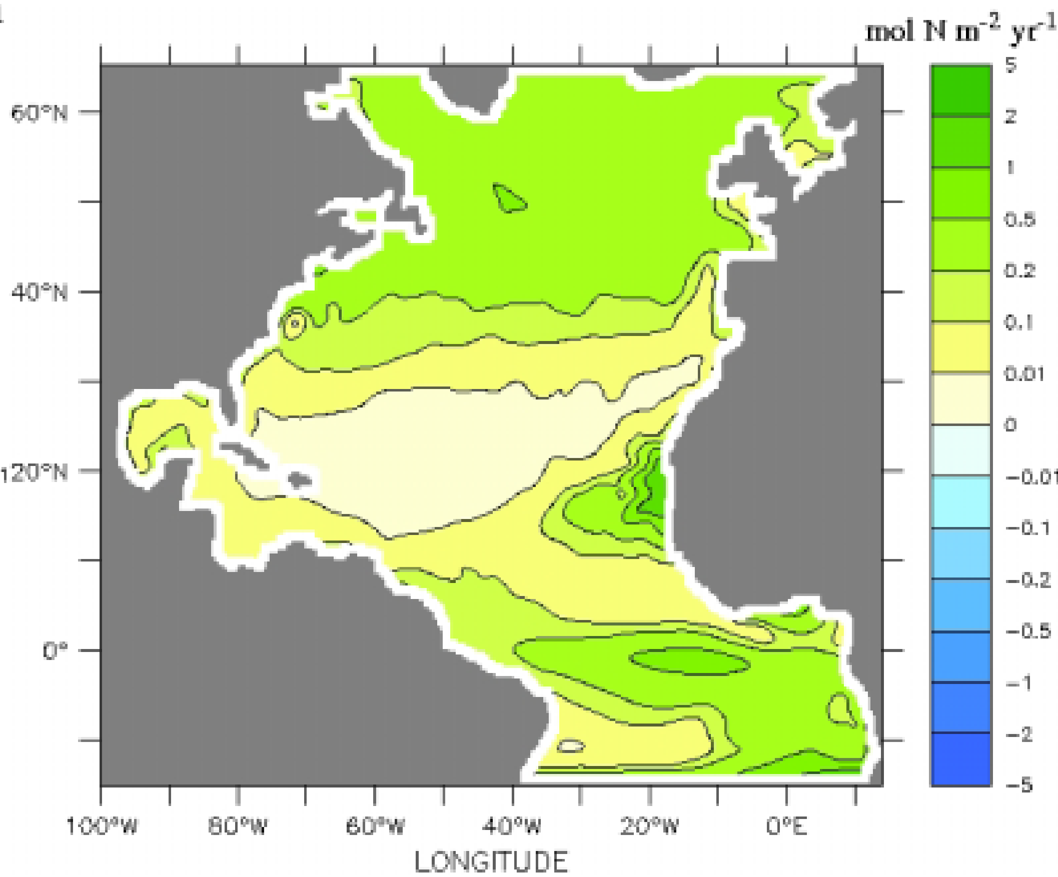


Applicability of Concepts:
Simulated Net Community Production and Air-Sea Exchange II

Net community production (0-wiML)

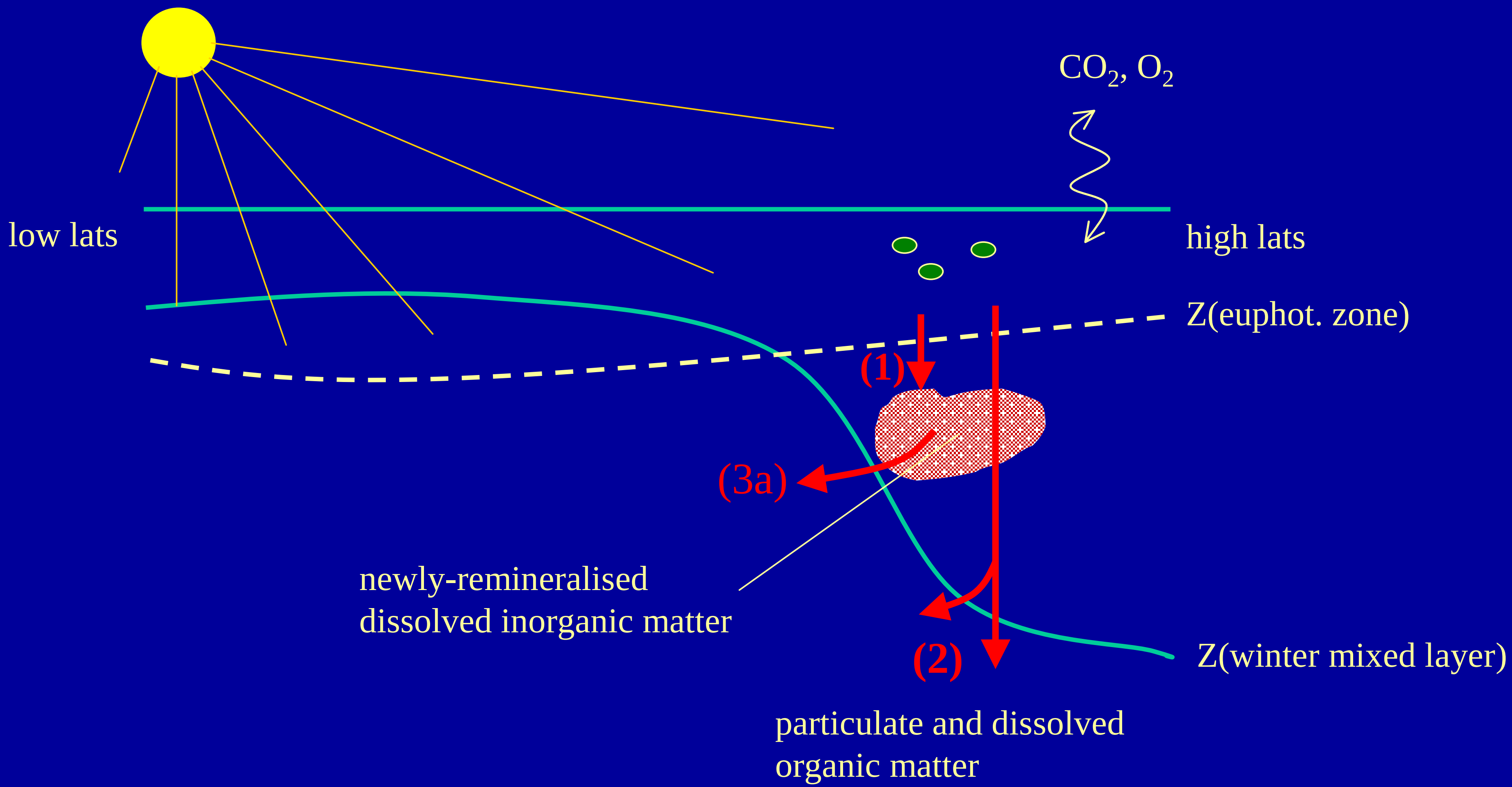


Biotically effected air-sea flux

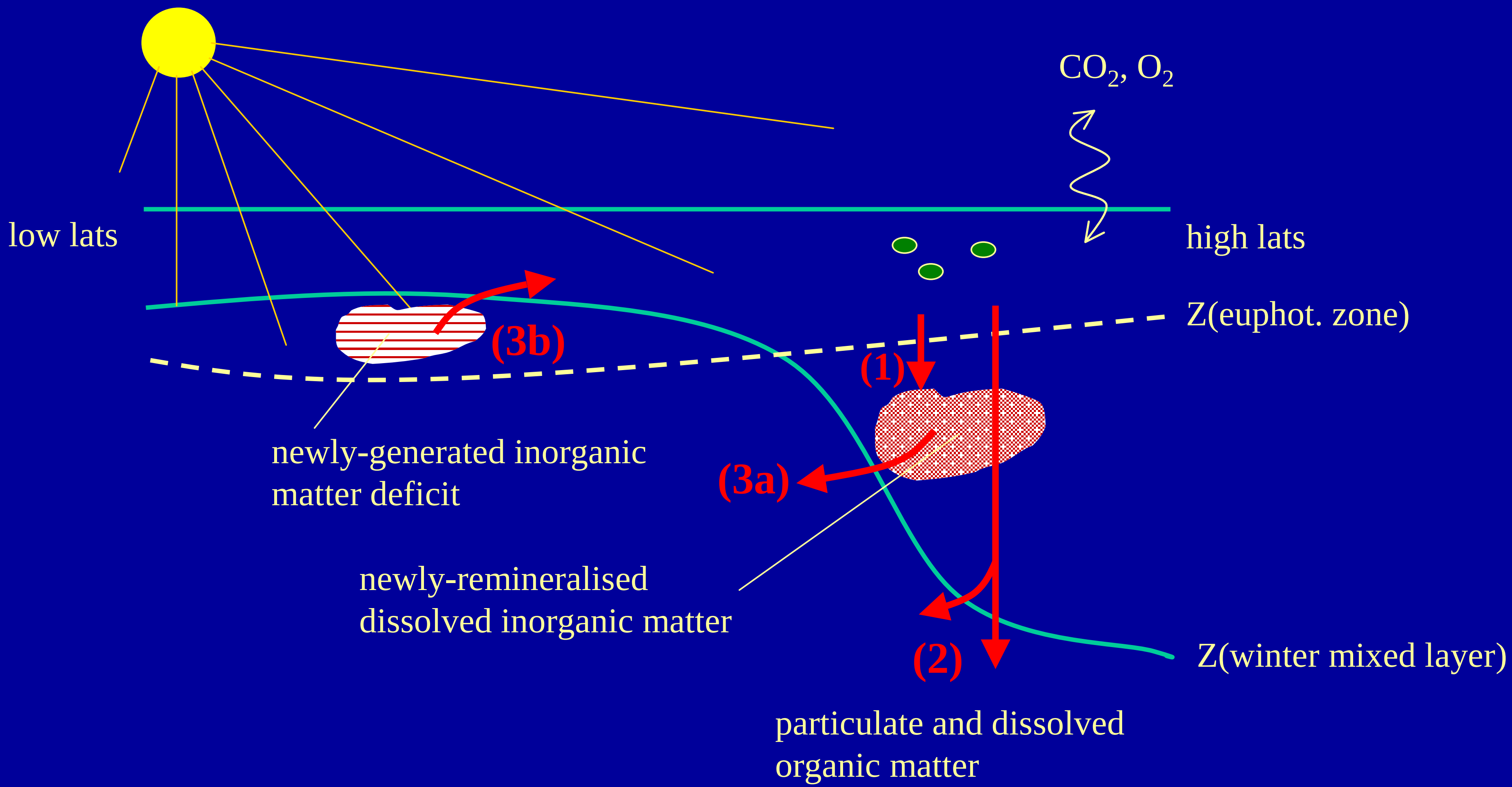


- Winter mixed layer depth is more appropriate reference depth!

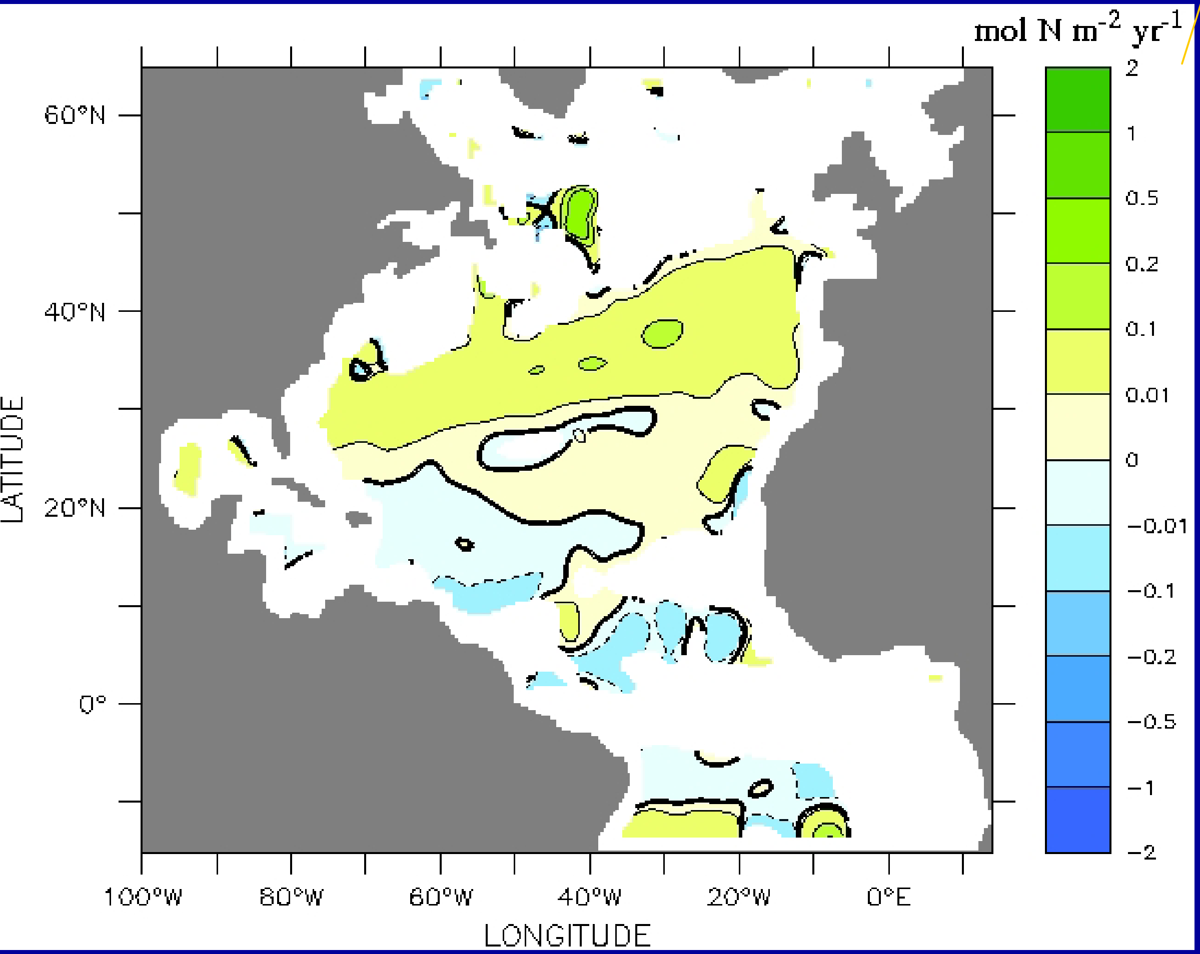
Applicability of Concepts:
Biological Pump and Air-Sea Exchange

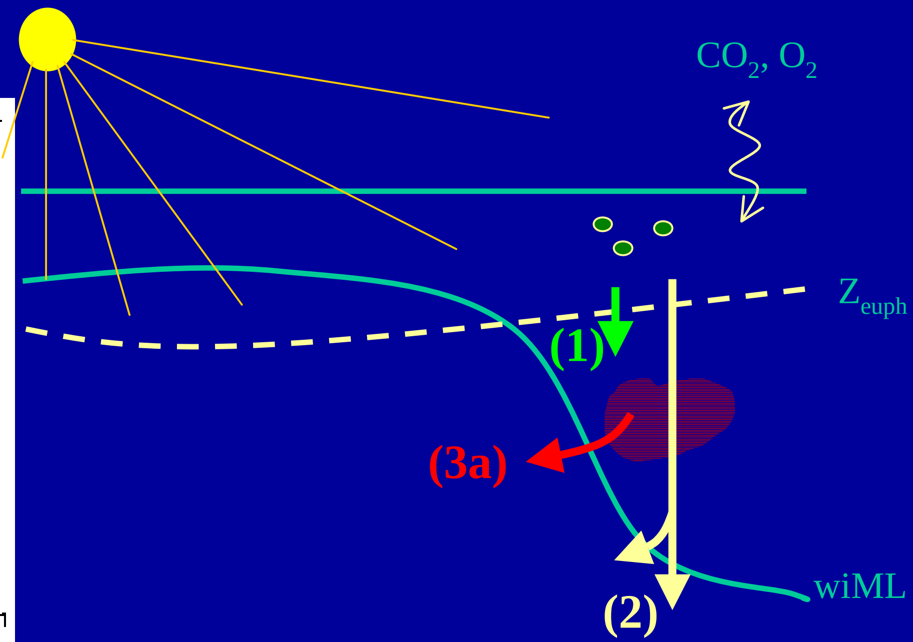


Applicability of Concepts: Biological Pump and Air-Sea Exchange



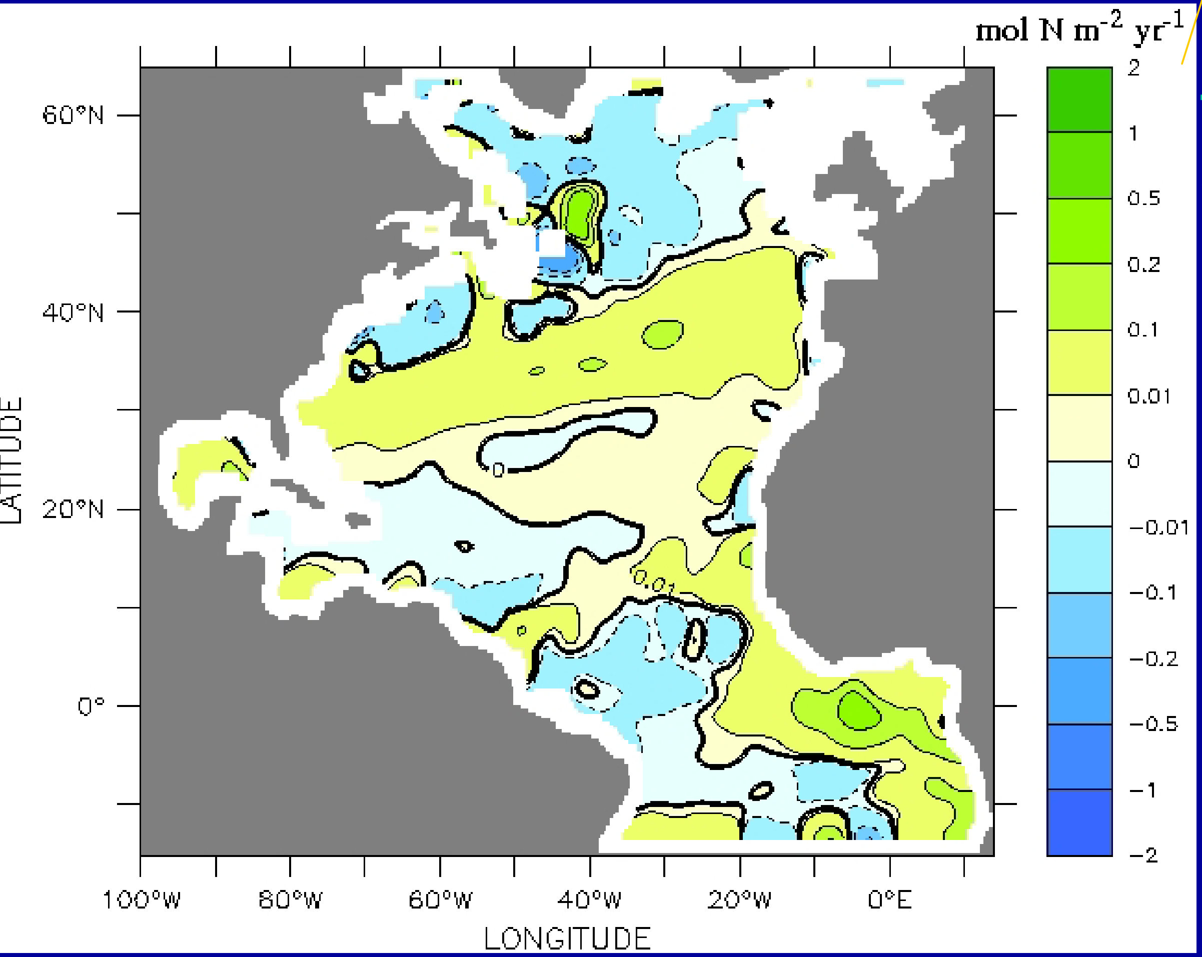
Applicability of Concepts:
Inorganic Contributions to the Biological Pump

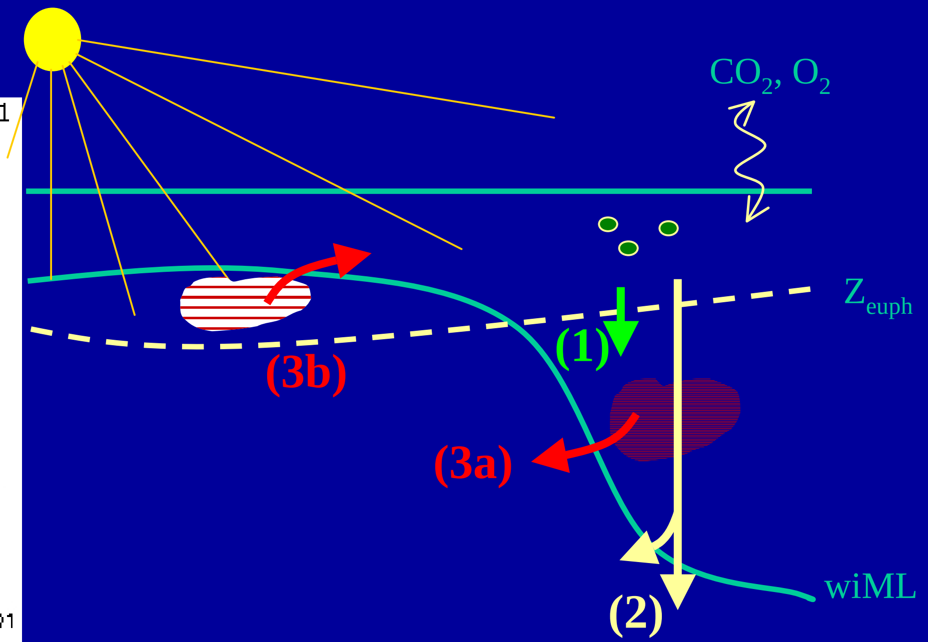




- Subduction of newly-remineralised inorganic matter.

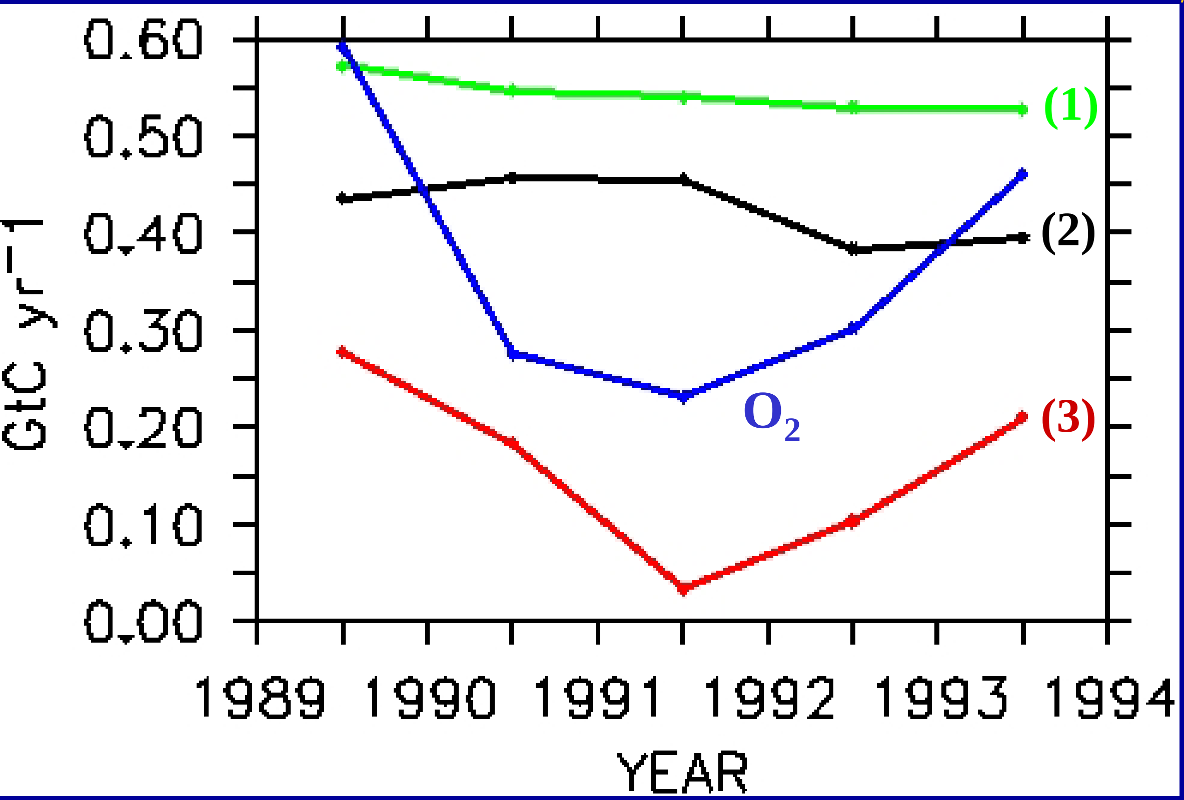
Applicability of Concepts: Inorganic Contributions to the Biological Pump

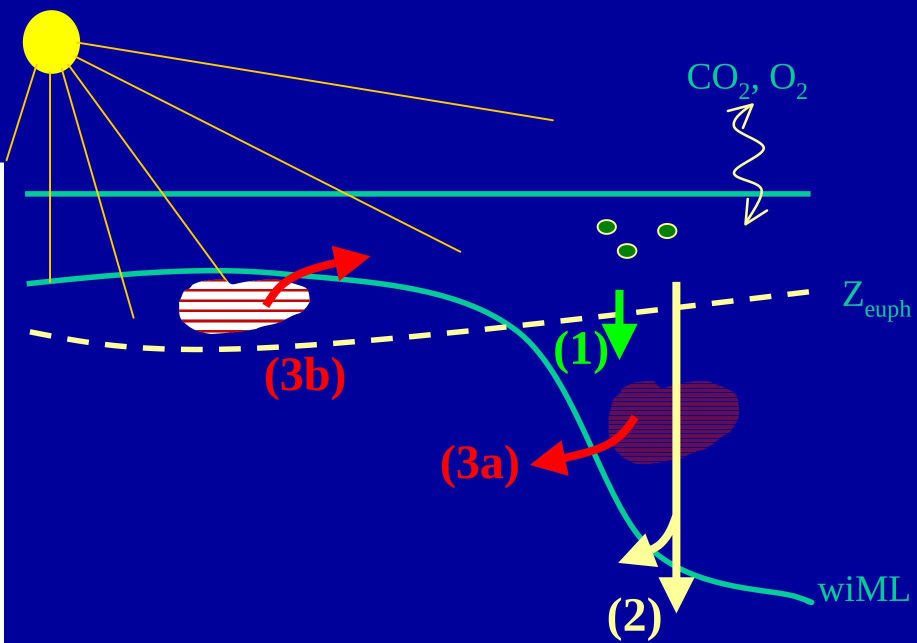




- Subduction of newly-remineralised inorganic matter.
- Induction of newly-generated inorganic matter deficits.

Applicability of Concepts: Simulated interannual Variability associated with the Biological Pump





- Only weak relation between biotically effected air-sea exchange and biological production rates.

(Oschlies & Kähler, subm.)

Conclusions Part II: Applicability of Concepts

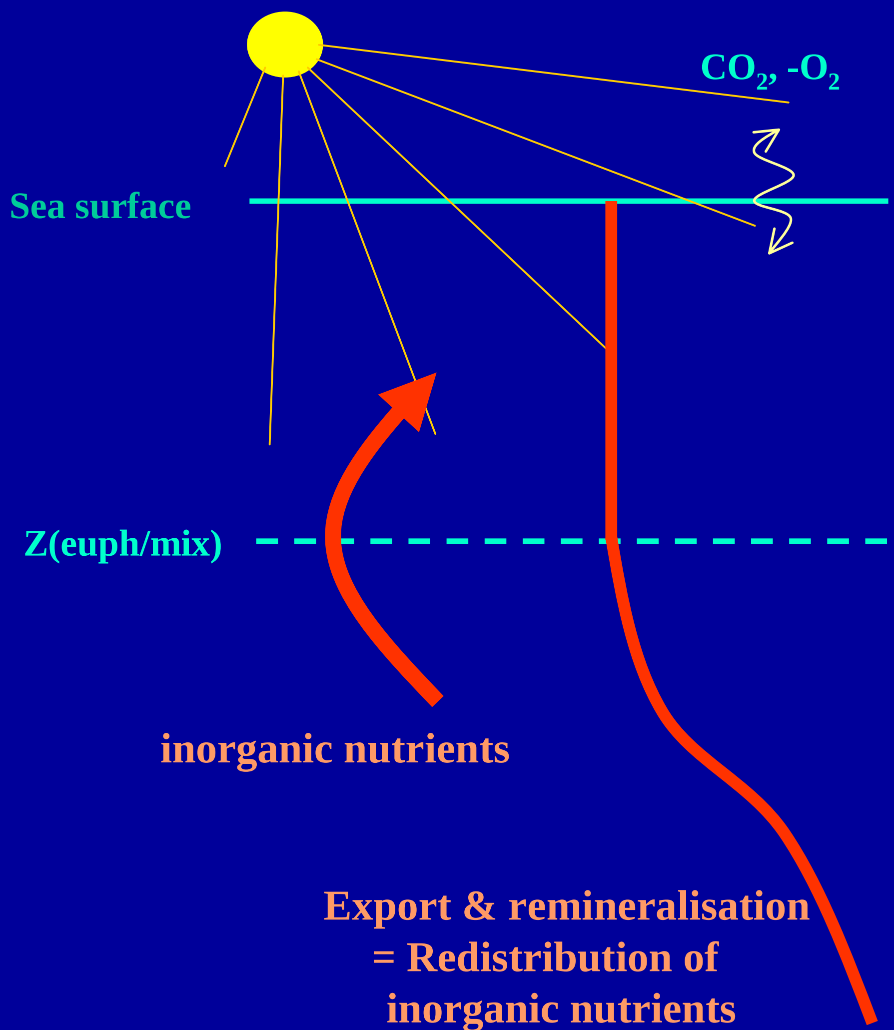
Box models	$Z_{euph} = Z_{ML}$	Biotically effected air-sea fluxes given by NP, EP, NCP. Concepts apply!
OGCMs		

Conclusions Part II: Applicability of Concepts

Box models	$Z_{euph} = Z_{ML}$	Biotically effected air-sea fluxes given by NP, EP, NCP. Concepts apply!
OGCMs	$Z_{euph} \neq Z_{ML}$ $Z_{ML} = f(x,y,t)$ => $Z_{MLmax}(x,y)$	Biotically effected air-sea fluxes differ from NP, EP, NCP. Z_{MLmax} appropriate reference depth. Both organic and inorganic fluxes across Z_{MLmax} matter!

- Caveat: Redfield stoichiometry!

Part III: Ecological Complexity: (i) Nutrient-Restoring Models



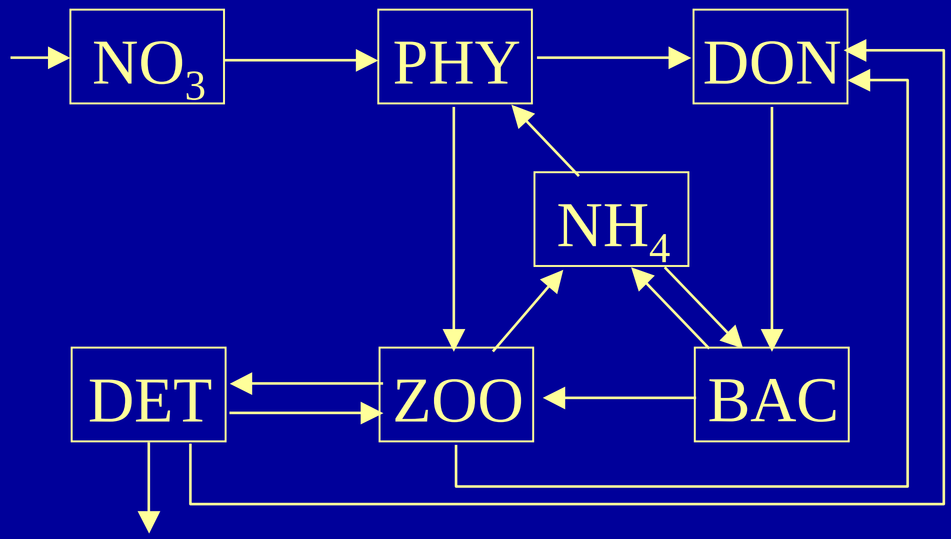
2 - 4 Parameters:

- nutrient uptake rate
- remineralisation profile

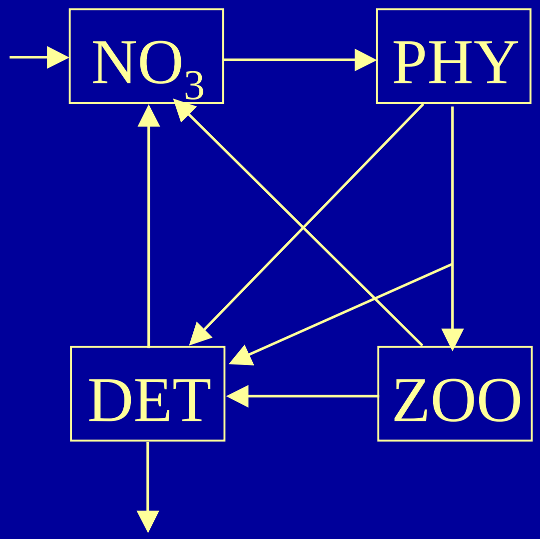
Examples:

- Bacastow & Maier-Reimer (1990,91)
- Najjar et al. (1992)
- OCMIP 1 & 2

Ecological Complexity: (ii) NPZD-type Models



(Fasham et al., 1990)



NPZD = Nutrient-Phytoplankton-Zooplankton-Detritus

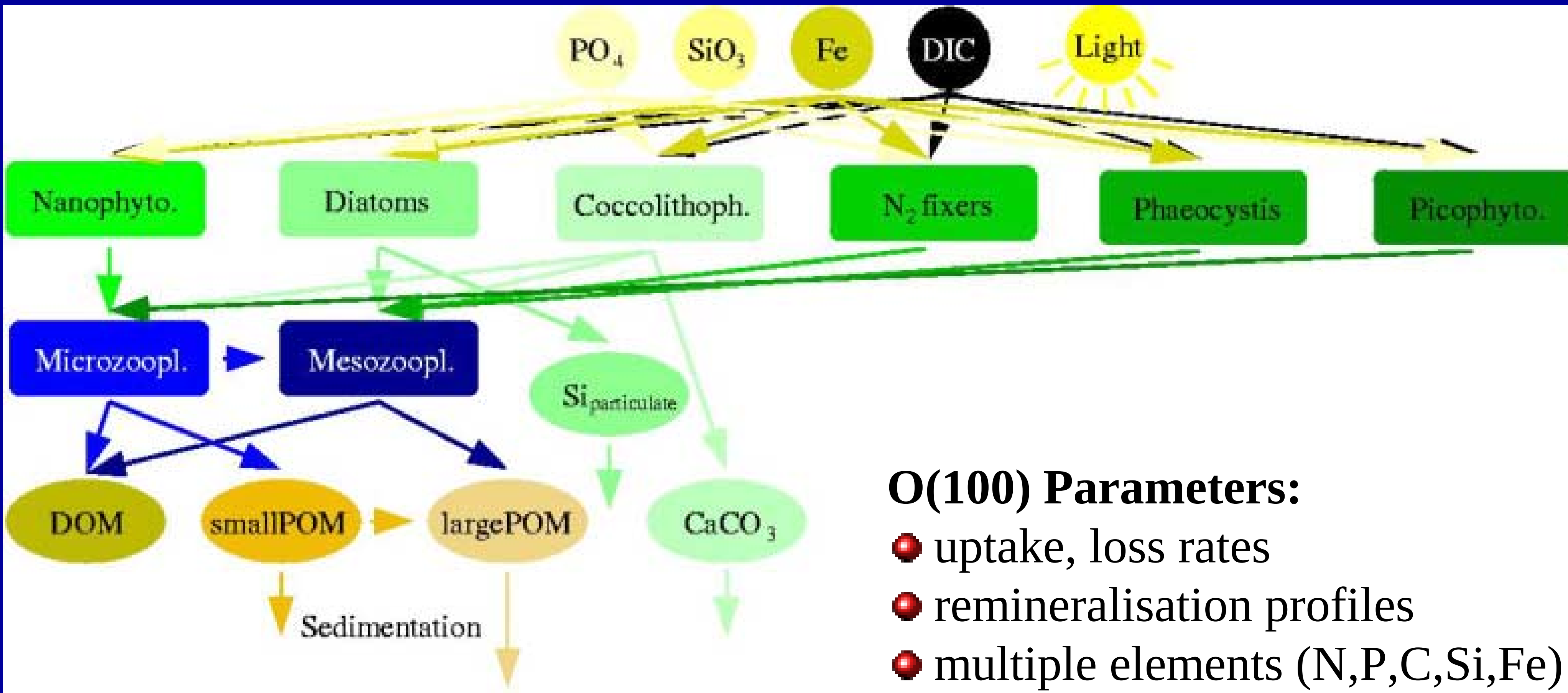
10-30 Parameters:

- uptake, loss rates
- remineralisation profile

Examples:

- Basin scale
  (Sarmiento et al., 1993; Fasham et al. ,1993; Chai et al., 1996; McCreary et al., 1996)
- Global Ocean
  (Six & Maier-Reimer, 1996)
- eddy-permitting basin scale
  (Oschlies and Garcon, 1998, 1999)
- eddy-resolving basin scale
  (Oschlies, 2002)

Ecological Complexity: (iii) “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. (in press)
- “Green Ocean Model“ consortium

Ecological Complexity: How far have we gotten?

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)

- ``Intuitively´´: More complex models are more realistic.

Ecological Complexity: How far have we gotten?

Parameter estimation studies (so far NPZD-type only)

(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;....)

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

Ecological Complexity: 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.
    - JGOFS time-series sites, satellite data.
    - Paleo data.

  ↓ Time & space scale

- Do not disregard alternative model structures
  (e.g., based on size, energy, membrane surfaces, ...)

Conclusions: How far have we gotten?

- Physical complexity: probably OK.
  - eddy resolving models, smaller scale process models
  - improved parameterisations for coarser resolution models (isopycnal / diapycnal mixing)
- Applicability of concepts: OK with some care.
  - Increased model complexity requires more complex analysis strategies / concepts.
- Ecological complexity: Not so clear, yet.
  - Do we yet have the right model structures?
  - Be ambitious: Search for ``Kepler´s laws´´ rather than for ``Ptolomaic epicycles´´.