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.

Sarmiento & Toggweiler (1984)
Siegenthaler & Wenk (1984)
Physical Complexity:
Carbon-Cycle OGCMs of the early JGOFS Period

Simulated annual sea-air flux of pre-industrial CO₂
(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

OCMIP-2: Sea-to-Air Flux of Total CO₂ in 1995
(Biol. + Sol. + Anthro.)

DATA: from Takahashi et al. (1999)
Models were run with specified atmospheric CO$_2$ boundary conditions.

No future change in ocean circulation.

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

![Graph showing $pCO_2$ sensitivity](image)

- JGOFS coarse res. OGCM
- Pre-JGOFS 3Box Model
- Pre-industrial
- Maximum efficiency of biological pump
- Today's efficiency of biological pump
- Reduction of surface nutrients

Climate sensitivity depends on model architecture!

(Adapted from Archer et al., 2000)
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

N-based ecosystem model

(Oschlies & Garcon, 1999)

(Oschlies, 2002)
Physical Complexity:
Model-derived Estimates of Export Production

(Oschlies, 2001)
Physical Complexity: Model-derived Estimates of Export Production

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Physical Complexity: Model-derived Estimates of Export Production

(Oschlies, 2001)

sensitivity to diffusion

eddy permitting (1/3)°
eddy resolving (1/9)°

(Oschlies, 2001)
Physical Complexity: What about Eddies?

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

- 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

Ledwell et al. (1998)

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

Centr. Diff. adv./Biharm. mix.

t = 2 years

depth (m)

coarse-res.OGCM
(4/3 degree)

eddy-perm.OGCM
(1/3 degree)

K_ρ (cm²/s)

effective K_ρ

explicit K_ρ

Ledwell et al. (1998)
(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

- CO₂, O₂
- low lats high lats
- particulate and dissolved organic matter
- inorganic nutrients
- Z(euphot. zone)
- (1)
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 CO₂!
Applicability of Concepts: Biological Pump and Air-Sea Exchange

- Z(euphot. zone)
- Z(winter mixed layer)

CO₂, O₂

Particulate and dissolved organic matter

Low lats vs. high lats
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

Z(euphot. zone)
Z(winter mixed layer)

CO₂, O₂

(1) newly-remineralised dissolved inorganic matter

(3a) newly-remineralised dissolved organic matter

particulate and dissolved organic matter

low lats high lats
Applicability of Concepts: Biological Pump and Air-Sea Exchange

CO₂, O₂

low lats

high lats

Z(euphot. zone)

Z(winter mixed layer)

newly-generated inorganic matter deficit

newly-remineralised dissolved inorganic matter

particulate and dissolved organic matter

(3a)

(3b)

(1)

(2)
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.
Only weak relation between biotically effected air-sea exchange and biological production rates.

(Oschlies & Kähler, subm.)
## Conclusions Part II: Applicability of Concepts

<table>
<thead>
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<th>Box models</th>
<th>$Z_{\text{euph}} = Z_{\text{ML}}$</th>
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## Conclusions Part II: Applicability of Concepts

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| OGCMSs     | $Z_{euph} \neq Z_{ML}$  
$Z_{ML} = f(x,y,t)$ 
$\Rightarrow Z_{ML_{max}}(x,y)$ | Biotically effected air-sea fluxes differ from NP, EP, NCP. 
$Z_{ML_{max}}$ appropriate reference depth. 
Both organic and inorganic fluxes across $Z_{ML_{max}}$ 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

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?

<table>
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<tr>
<th>Ecosystem model</th>
<th>stoichiometry</th>
<th>Number of adjustable parameters</th>
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<tr>
<td>Restoring</td>
<td>usually Redfield</td>
<td>O(1)</td>
</tr>
<tr>
<td>NPZD-type</td>
<td>usually Redfield</td>
<td>O(10)</td>
</tr>
<tr>
<td>Multiple functional groups, multiple elemental cycles</td>
<td>prognostic</td>
<td>O(100)</td>
</tr>
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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.

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´´.